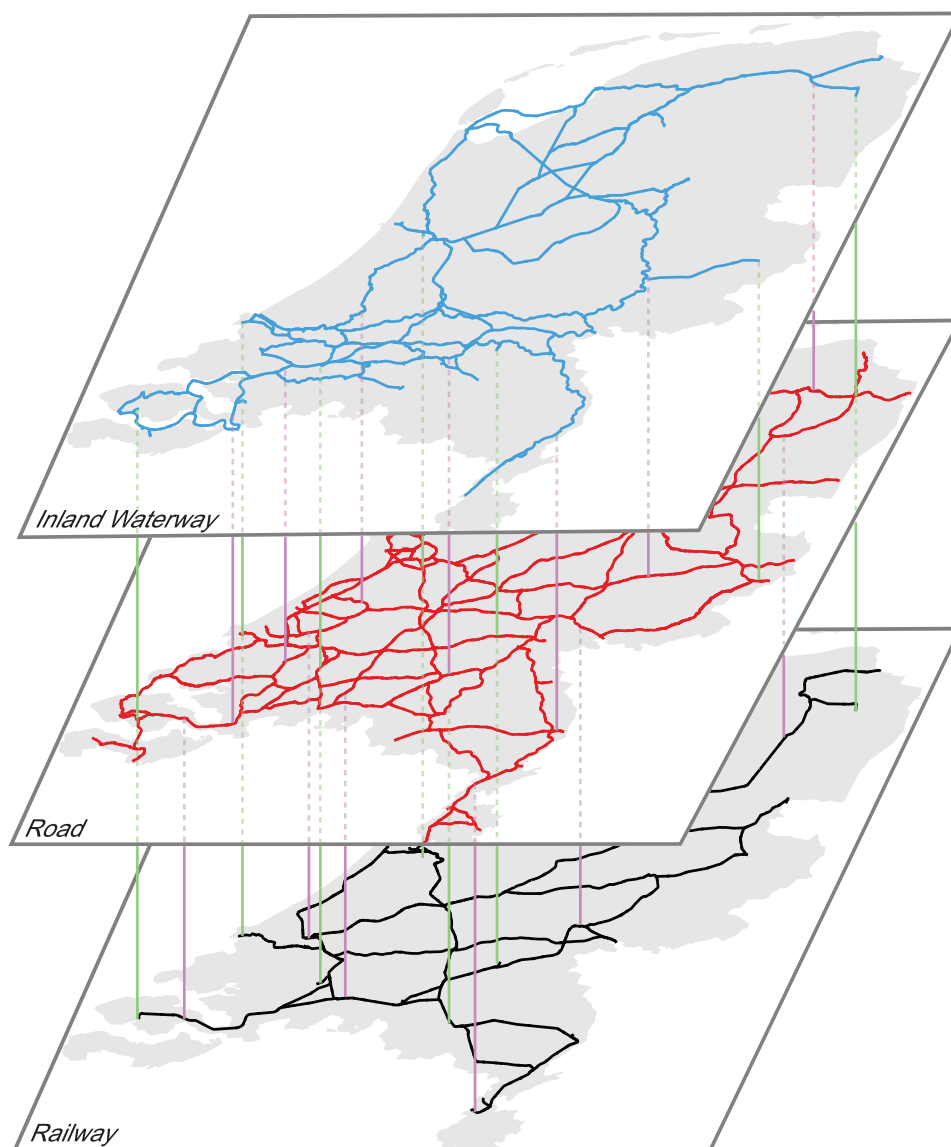


Robustness Analysis of the Dutch Synchromodal Freight Transport Network

Simulating Disruptions on a Macroscopic Graph Model

W. J. L. van Dam



Rijkswaterstaat
Ministry of Infrastructure and the
Environment

 **TU Delft**

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by

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Rijkswaterstaat
Ministry of Infrastructure and the
Environment

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Preface

This thesis presents the result of my master graduation project, conducted at Rijkswaterstaat (Ministry of Infrastructure and the Environment) in Delft. It is the final part of my studies at Delft University of Technology, completing my Master of Science in Electrical Engineering. I had the opportunity to research the robustness of the Dutch synchromodal freight transport network. At the start of my research it quickly became apparent that a large research gap existed for the robustness of synchromodal and multimodal transport networks. This made it a complex subject, as there was little earlier research to build upon and it was difficult to decide what should be researched and what not. I enjoyed this challenge very much and I am pleased with the results I was able to achieve.

My thanks go out to my supervisors: Alfred Pellemans, Zhidong He and Piet Van Mieghem, for their time and help. I want to thank Piet Van Mieghem and Gerrit-Jan van den Toorn for offering me the opportunity to research the robustness of the synchromodal freight transport network. I like to thank Lea Kuiters and Nora Schmorak for their input during our monthly meetings together with Alfred Pellemans and Zhidong He. Furthermore, I want to thank the colleagues at Rijkswaterstaat, with special thanks to the colleagues at SVM-lab for the fun discussions and many enjoyable lunches. My thanks also goes out to the many people not mentioned here explicitly, that offered their time and advice to help my research further along than it would otherwise be. Last, but surely not least, I would like to thank my wife Loes for her patience and exceptional support during this demanding period of my studies.

*Wirdmer van Dam
Delft, September 6, 2017*

Abstract

Freight transport is an essential component of the economy, as among other things it ensures the availability of finished goods to consumers. Synchronomodal transport is a new transport method that aims to use real-time and flexible switching among different modes of transport according to the latest logistics information, to utilise the different modes of transport efficiently. But what are the effects of disruptions of the infrastructure used by synchronomodal transport on freight transport? As some recent disruptions in the Netherlands have shown, the negative effects can be considerable. The effects of disruptions on the functioning of multimodal transport networks have scarcely been researched. This research gap is addressed in this thesis, by analysing the robustness of the Dutch synchronomodal freight network, comprising of the inland waterway, road, railway and container terminal infrastructure.

First an overview is given of the elements of the synchronomodal transport infrastructure. Apart from the infrastructure elements of each mode of transport, two important characteristics are identified: the interconnection and the interdependence. Container terminals are the interconnection between different modes of transport, as they facilitate the transshipment of containers. Infrastructure elements whose functioning influences multiple modes of transport (e.g. bridges) are the interdependence between different modes of transport. Subsequently, this overview of infrastructure elements is used to make a macroscopic graph model in which all relevant infrastructure elements are represented. Using the random removal of graph elements, the robustness of the synchronomodal network is analysed. Three case studies are used to study the Dutch synchronomodal network: the corridor between Rotterdam and Antwerp, the corridor Rotterdam and Duisburg, and the domestic freight transport in the Netherlands.

The robustness analysis of the three case studies lead to the following conclusions. Of the three modes of transport, the modality road is the most robust. The inland waterway modality is less robust and the rail modality is the least robust. It should be noted that the rail modality provides a relatively cheap alternative and offers the capabilities to transport containers further into Europe than the inland waterways. The ability to transship containers between different modes of transport (i.e. interconnection) has a significant positive effect on the robustness. The interdependence has a smaller negative effect on the robustness. Generally, the new alternative paths offered by the addition of a mode of transport (even without interconnection) outweigh the negative effects of the interdependence.

These findings make it clear that the use of the synchronomodal transport method, increases the robustness of the freight transport network. During this research, many possibilities for future research were identified. As the research gap for analysing the robustness of a synchronomodal transport network was very large at the start of this research, many things can still be researched after this research. The importance of freight transport warrants additional research on this topic. According to this research, due to mode-free booking and the real-time and flexible switching among different modalities, synchronomodal transport offers a robust freight transport method.

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List of Abbreviations

AON	All-or-nothing
CEMT	<i>Conférence Européenne des Ministres de Transport</i>
EU	European Union
GIS	Geographic Information System
I	Interdependence
ID	Identification
IWW	Inland Waterway
mtwy	Motorway
NWB	<i>Nationaal Wegenbestand</i> (database for roads, waterways and railways)
NUTS	Classification of Territorial Units for Statistics (French: <i>Nomenclature des unités territoriales statistiques</i>)
OD	Origin(s)/Destination(s)
Ra	Railway
Ro	Road
ro-ro	Roll-on/roll-off
T	Terminal
TEN-T	Trans-European Transport Network
TEU	Twenty foot Equivalent Unit
VIN	<i>Vaarweg Informatie Nederland</i> (database for waterways)
Wa	Inland waterway

List of Symbols

G	Graph consisting of a set of N nodes and a set of L links
N	Number of nodes in a graph
L	Number of links in a graph
\mathcal{N}	The set of nodes in a graph
\mathcal{L}	The set of links in a graph
l	A link
$w(i \rightarrow j)$	weight of the link between nodes i and j
d_l	Length of the link l
\mathbf{A}	Adjacency Matrix
\mathbf{D}	Demand matrix
\bar{G}	Synchromodal graph without all infrastructure elements
m	Modality, in this research from the set $\{IWW, Road, Rail\}$
C_l	Generalised cost of link l , used as link weight
τ_m	Unit cost per unit of time of modality m
κ_m	Unit cost per unit of distance of modality m
$v_{avg,m}$	Average speed of modality m
t_{lock}	Average time needed to navigate a lock
\tilde{x}	Median
\bar{x}	Sample mean
s	Sample standard deviation
\mathcal{O}	Big O notation

Glossary

All-Or-Nothing	Traffic allocation algorithm in which all traffic between an origin and destination is assigned to the shortest path.
Aqueduct	Bridge structure that carries the waterway over obstacles (also called navigable aqueduct).
Barge	Watercraft used on inland waterways (Dutch: <i>binnenvaartschip</i>).
Bulk	Goods not packaged or loaded individually, can be both liquid and dry.
Capacitated Network	A Network model where there is congestion when the capacity of an infrastructure element is reached.
Cargo	Goods being transported.
Cargo-path	The availability of a railway section for one cargo train every hour (Dutch: <i>goederenpad</i>).
CEMT-class	Classification of European inland waterways.
Centroid	The centroid of a polygon is located at the centre of mass of that polygon.
Challenge	A set of elementary changes in a graph, corresponds with a disruption in the real world.
Container	A steel box with standardised size used to transport goods (also called intermodal container).
Crow flies distance	The length of the straight line connecting two points.
Directed Graph	The links have a direction associated with them, only allowing movement in that direction.
Disruption	A (negative) change in the behaviour of the components or the environment of a system.
Draught	The depth of a ship or barge in the water.
Elementary Change	Either an addition of a node, a removal of a node, an addition of a link, a removal of a link or a change of a link weight.
Feedback Interdependence	When feedback is allowed, disruptions of a node in subgraph G_1 caused by the disruptions of a node in subgraph G_2 can in turn cause a disruptions of another node in subgraph G_2 .
Flood barrier	Waterway element able to prevent flooding upstream.
Freight transport	The process of transporting goods from origin to destination.
Graph	A mathematical model consisting of nodes (i.e. vertices) and links (i.e. edges) that are related to each other in some way.
Hinterland	The area where goods transported through the port have their origin or destination.

Impound	Confining water within an enclosure or within certain limits.
Infrastructure	The physical structures used for freight transport.
Intermodal Container	See <i>Container</i> .
Link	One of two types of element in a graph, connecting two nodes at its endpoints (also called edge).
Lock	Waterway element facilitating the movement of barges between different water levels.
Macroscopic model	Traffic model in which individual vehicles are aggregated into flows.
Mesoscopic model	Traffic model that fits between macroscopic and microscopic models.
Method M	Simulation of random removals method using length of link based probability of failure and removing all graph elements not contributing to the synchronomodal network after each challenge.
Method U	Simulation of random removals method using an uniform probability of failure.
Microscopic model	Traffic model in which individual vehicles are studied.
Modal split	The way cargo is distributed over different transport modes.
Modality	See <i>transport mode</i> .
Mode-free booking	Request cargo to be transported, without specifying a mode of transport that should be used.
Multimodal	Use multiple mode of transports to move cargo from its origin to its destination.
Network	An abstract representation of the infrastructure consisting of connected parts so that movement is possible between or along the parts.
Node	One of two types of element in a graph, point which can be connected to other points using links (also called vertex).
NUTS	A division of the economic territories of the European Union for statistical analysis purposes.
Planar graph	A graph that can be drawn in such a way that no links intersect each other without a node.
Quay	A structure which makes the (un)loading of barges possible.
Reliability	A measure of the probability of challenges occurring in a system.
Resilience	A measure of a system's ability to quickly recover from challenges.
Robustness	A measure of a system's ability to keep a certain functionality despite challenges.
Roll-on/roll-off	Cargo which can be driven on and off transport vehicles.
Scale-free Graph	A graph with a degree distribution following a power law.
Ship	A large, sea-worthy watercraft.
Simple Path	A simple path has no repeating nodes between origin and destination.
Subgraph	A graph whose nodes and links form subsets of the nodes and links of another graph.
Supergraph	A graph consisting of two or more subgraphs.
Symmetric Directed Graph	For each directed link, another link going in the opposite direction is also present in the graph.
Synchronomodal transport	A logistics concept using real-time and flexible switching among different modes of transport according to the latest logistics information.

Terminal (container)	Structure facilitating the transshipment of containers between different modes of transport.
Transport mode	The means by which cargo is transported (e.g. road, sea, air).
Twenty Foot Equivalent Unit	Unit of cargo capacity, based on the volume of a 20-foot long container.
Tonne-Kilometre	Unit measure of freight transport, the transport of one tonne of cargo over a distance of one kilometre.
Uncapitated Network	A Network model where capacity and congestion are not considered.
Unimodal	Use one mode of transport to move cargo from its origin to its destination.
Weir	Waterway element able to regulate the flow of water (Dutch: <i>stuw</i>).

Introduction

Freight transport is an essential supply chain component and a vital component of the economy, as it ensures the efficient movement and timely availability of raw materials and finished goods [19, 82]. The amount of cargo that is transported in Europe increases [96] which warrants an optimised use of infrastructure to limit congestion and emissions. Less congested modes of transport, like the inland waterways and railways, need to be utilised more. While congested modes of transport, like roads [55], need to be utilised less. Synchronomodal transport is a transport method (or logistics concept) with the goal to utilise multiple modes of transport efficiently in the hinterland¹ [63].

In this chapter, the problem that is researched in this thesis is described. In Section 1.1, the problem definition is presented. In Section 1.2, the current research gap is described. Subsequently, the scope of the research is determined in Section 1.3. In Section 1.4, the research questions, which follow from the problem definition and scope, are presented. The methodology used to answer these research questions is described in Section 1.5. Finally, the outline of the rest of this thesis is presented in Section 1.6.

1.1. Problem Definition

Currently, most cargo in the Netherlands is transported by road, but this transport mode has the highest emission per tonne-kilometre and is the most congested [49, 55]. As other transport modes (i.e. inland waterway, railway, short-sea) lead to less undesired collateral effects, a modal shift is desired. This modal shift can be achieved with the implementation of synchronomodal transport. The core of synchronomodal transport is real-time and flexible switching among different modes of transport according to the latest logistics information, to utilise the different modalities efficiently [5, 44, 64, 89, 99]. The Top Sector Logistics (Dutch: *Topsector Logistiek*) has the goal to save 55 million truck-kilometres per year using synchronomodal transport [46].

Before synchronomodal transport becomes a reality, several aspects of freight transport need to be ready for this new transport method. Information about the current state of the infrastructure needs to be gathered and shared with transport operators (data infrastructure). There must be alternative transport routes possible (e.g. container terminals) for transport operators to choose from (transport infrastructure). And customers must book their cargo mode-free, so that transport operators can choose a modality in a synchronomodal fashion. This also enables transport operators to bundle cargo flows and use other modalities than the road efficiently.

The transport infrastructure (e.g. inland waterways and roads) is the main focus of this research. This infrastructure is managed by multiple authorities, of which Rijkswaterstaat is the government body responsible for the design, construction, management and maintenance of the national road infrastructure and the national waterway infrastructure [69]. Rijkswaterstaat has a department *Synchronomodal Transport and Shipping*, which together with other parties aims for an efficient use of the transport infrastructure. It was hypothesised

¹The hinterland is the back-country of a port, the area where goods transported through the port have their origin or destination [94].

that the Dutch transport infrastructure is already able to facilitate synchromodal transport in a robust network [100]. Rijkswaterstaat wants this to be researched. The robustness of the main infrastructure of roads, railways and inland waterways is defined as a *national interest* [56]. Robustness is a measure of a system's ability to keep a certain functionality despite changes in the behaviour of its components or its environment [2, 10, 37, 41, 97]. The problem definition can be summarised as follows:

Is the Dutch freight transport infrastructure a robust network suited for synchromodal transport?

1.2. Research Gap

The research gap found in literature is presented in this section. The related research is described in more detail in Chapter 3. The robustness of the road network in the Netherlands has been extensively researched [39, 85, 87]. But this research for an unimodal network cannot simply be applied to the synchromodal network, due to the dissimilarities of the different modalities used for synchromodal transport. The added complexity of multimodal networks has been recognised and some research has been done on the robustness of multimodal transport networks [13, 84]. This research does not consider synchromodal transport and focuses on the identification of critical components of the network. Furthermore, no research has yet investigated the interdependence between the networks of different modalities in a freight transport system. Thus a significant research gap remains for analysing the robustness of a synchromodal transport network.

1.3. Scope

The problem definition presented in Section 1.1 is a broad problem. To finish the research in the available time frame, the problem definition should be limited to a clearly defined scope. Due to the significant research gap for the robustness of multimodal freight transport systems, much ground work (e.g. collect data, determine best method) has to be done. This limits the scope of this research, which is described in this section.

Freight transport can be classified based on the type of cargo being transported. The types of cargo distinguished in this research are dry bulk, liquid bulk, (intermodal) containers, roll-on/roll-off (ro-ro) and other cargo [32, 106]. Earlier research on synchromodal transport and current synchromodal transport services focus on the cargo type containers [44, 89]. Although the definition of synchromodal transport does not technically limit itself to a certain cargo type [5, 44, 64, 89, 99], primarily containers are envisioned for synchromodal transport due to their relatively low transshipment cost [100]. Only containers are considered in this research, similar to earlier research on synchromodal transport.

Freight transport can take place on different modes of transport [82]. In the Netherlands containers can be transported by inland waterway, road, railway or short-sea. Short-sea is not used for domestic freight transportation in the Netherlands [105]. Although short-sea shipping could be a viable mode of transport for some geographic areas, it is not considered in this research as short-sea shipping is very dissimilar to the other modes of transport. The following modes of transport are considered in this research: inland waterway, road and railway.

For research on freight transport, two main categories can be distinguished for traffic models. Microscopic models study individual vehicles, while macroscopic models aggregate individual vehicles into flows to study a transport network [113]. Due to the complexity of microscopic models and the high computational time requirements of such a model, a macroscopic traffic model is used to describe synchromodal transport in this research. Although microscopic models are a more accurate representation of the real world, the validity has been a point of discussion as complex models often suffer from a lack of transparency [83].

Robustness is a measure of a system's ability to keep a certain functionality despite changes in the behaviour of its components or its environment [2, 10, 41]. This research focuses on disruptions leading to the complete unavailability of infrastructure elements for freight transport. Examples of such disruptions are given in Subsection 2.3.6.

Furthermore, the research scope is limited to the Dutch freight transport infrastructure. Due to the amount of transported containers in the Netherlands with an origin or destination in another country [102], a small part of the infrastructure in Germany and Belgium is considered as well. This is described in more detail in

Section 1.5, where the method used for this research is presented. An overview of the geographic scope is shown in Figure 1.1.

1.4. Research Questions

The main research question of this research is defined as follows:

How robust is the synchromodal transport infrastructure, comprising of the inland waterway, road, railway and container terminal infrastructure, for the transport of intermodal containers in the Netherlands?

The research required to answer this research question is divided into three research sub-questions. When these sub-questions are answered, the main research question can be answered.

1. What are the different elements of the synchromodal transport infrastructure and how do these elements affect synchromodal transport on the different modalities?

A clear overview of all the different elements of the synchromodal transport infrastructure does not exist at the start of this research. Before a network model is made of the synchromodal transport infrastructure, it is important to have an extensive understanding of this infrastructure. For each of the three modes of transport, the different infrastructural elements and their affect on synchromodal transport should be described.

2. How do the infrastructural elements and the other properties of the synchromodal transport system need to be taken into account in a network model to give a relevant representation of the synchromodal transport system?

Once the first sub-question is answered, a network model of the infrastructure can be made. Taking the scope of this research into account, the infrastructural elements and the other properties (e.g. traffic allocation) need to be represented by a network model.

3. How can the robustness of the synchromodal network model be analysed and how well does it apply to the robustness of the synchromodal transport infrastructure?

When the second sub-question is answered, the network model can be used to analyse the robustness of the synchromodal network. A methodology must be found to analyse the robustness of the synchromodal network model, as no single robustness metric exists [97]. Subsequently, the validity of the results of this methodology for the robustness of the synchromodal infrastructure needs to be discussed.

1.5. Method

The three sub-questions presented in the previous section give a brief overview of the structure of this research. In this section, the method used in this research is described in detail. First, a literature study was executed regarding the infrastructure of each transport mode, synchromodal freight transport, graph theory and the robustness of networks. During the literature study the problem definition and research questions were defined. A graph network model was made for the synchromodal transport infrastructure. Representing the transport infrastructure with a graph model has been done in earlier research [3, 9, 82, 115]

To research the robustness of the Dutch infrastructure, three geographic regions were defined. For international freight transport, two corridors were defined: the Rotterdam-Duisburg corridor and the Rotterdam-Antwerp corridor. In these two corridors a large part of the internationally transported containers are transported, as can be seen in Figure 7.1 on Page 68. For the transported containers with both their origin and destination in the Netherlands, the third geographic region was defined: the Netherlands. An overview of these three geographic regions is shown in Figure 1.1.

The third geographic region (the Netherlands) was divided into 40 smaller regions, which are called NUTS-3 regions (see Figure 1.1). The NUTS (French: *Nomenclature des Unités Territoriales Statistiques*) classification of Europe is a division of the economic territories of the European Union for statistical analysis purposes [16]. The data for the number of containers transported in the Netherlands available in this research, specifies the number of containers transported between these 40 regions [75]. The freight demand of each region has been

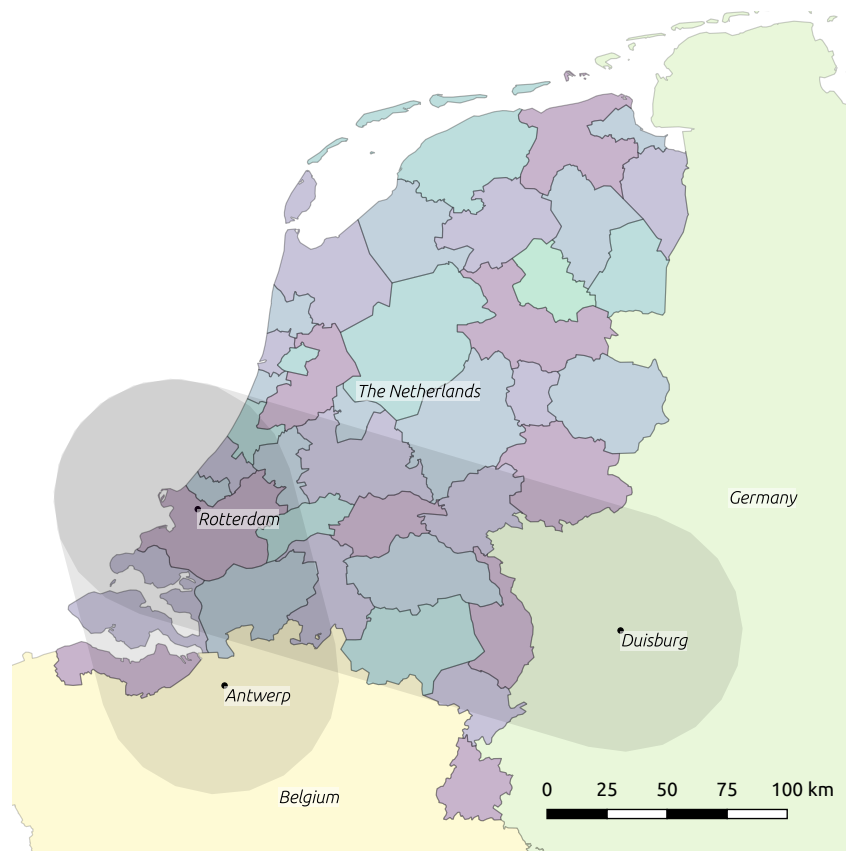


Figure 1.1: Image of the Netherlands divided into 40 regions (NUTS-3), with the corridors Rotterdam-Duisburg and Rotterdam-Antwerp shown.

aggregated into the centroid of each region². This method is also used in earlier research on freight transport networks [88, 115]. As the precise origins and destinations are unknown, only the national road infrastructure was explicitly considered in this research. The underlying road infrastructure was implicitly considered in the links between the centroids and the national roads.

As the geographic scope of the three regions is quite large, the robustness of the synchromodal infrastructure in these regions was not immediately analysed. First, a smaller representative example of a synchromodal network was defined (see Section 5.6). Two variants of this network were proposed: a corridor variant (similar to the first two geographic regions: the Rotterdam-Duisburg and Rotterdam-Antwerp corridors) and a regions variant (similar to the third geographic region: the Netherlands). This example network was used to help answer the third research sub-question. As *the* robustness metric does not exist [97], a simulation-based approach was used. The robustness is concerned with the effects of disruptions, thus disruptions were simulated on the synchromodal graph and the functioning of the graph was studied (similar to robustness analyses done in related research, e.g. [1, 38, 108]). Using the example network the procedure to simulate disruptions and analyse the results was determined.

The three geographic regions were defined as the case studies of this research, to distinguish this more practical part of the research from the more theoretical part. The answers found for the three sub-questions were used to analyse the robustness of the synchromodal infrastructure in these three regions. With that, the main research question was answered and this research was concluded.

²The centroid of a polygon is located at the centre of mass of that polygon.

1.6. Thesis Outline

After this introduction, the rest of the thesis is structured as follows. First an introduction to the topic synchromodal transport is given in Chapter 2. In this chapter the underlying terminology, the different transport methods and some aspects and statistics of freight transport in the Netherlands are described. Subsequently the related research is presented in Chapter 3. The related research is split into research on modelling the freight transport system and analysing the robustness of networks.

In Chapter 4, the first research sub-question is answered. The different elements of the synchromodal transport infrastructure are described and two important aspects of the synchromodal infrastructure are described: the interconnection and the interdependence. Furthermore, the available data detailing the infrastructure in the Netherlands is discussed.

The synchromodal transport graph is presented in Chapter 5. This chapter answers the second research sub-question. The topology of the graph is described, the link attributes and traffic assignment is presented, the validity of the graph model is discussed and finally a representative example of a synchromodal network is presented.

The third research sub-question is answered in Chapter 6. In this chapter the robustness analysis using simulations of disruptions is described. Next, the effects of certain choices for the graph model and the simulations are analysed. Similar to the previous chapter, the validity of the simulation results is discussed.

In Chapter 7, the case studies are presented. The case studies are: the Rotterdam-Antwerp corridor, the Rotterdam-Duisburg corridor and the Netherlands. Some general statistics of the graphs of these case studies are presented and the simulations that are done are described. Subsequently, the results of these simulations are presented in Chapter 8. In this chapter these results are also discussed. Finally, in Chapter 9 the conclusions are presented and the possibilities for further research are discussed.

To aid readers of this thesis, a list of abbreviations (Page xix), a list of symbols (Page xxi) and a glossary (Page xxiii) are added to this document.

2

Synchromodal Freight Transport

This chapter aims to give an introduction to the topic synchromodal transport. First, the underlying terminology used in this topic is explained in Section 2.1. The transport method synchromodal transport and other transport methods are discussed next in Section 2.2. Lastly, in Section 2.3 some aspects and statistics of freight transport in the Netherlands are described.

2.1. Underlying Terminology

For transport an infrastructure is needed, this is sometimes called a network. In Subsection 2.1.1, these terms are discussed in detail. When goods are transported they become known as cargo or freight. These two terms are explained in more detail in Subsection 2.1.2. The different types of cargo are described in Subsection 2.1.3. Cargo can be transported by different modes or modalities. Each modality has its own infrastructure and its own transport vehicles. The different modes of transport are further explained in Subsection 2.1.4. Companies requiring transport services are called shippers and companies offering these services are called carriers [21].

2.1.1. Infrastructure and Network

The terms infrastructure and network are often used interchangeably to describe the collection of structures making (freight) transport possible. In this research a distinction is made between the two terms. Infrastructure is used to describe the physical structures used for freight transport. While network is used to describe a model of the physical structures. A network is a large system made up of connected parts, so that movement or communication is possible between or along the parts [24]. A network is thus an abstract representation of the infrastructure. An example of a network is a graph, which is a mathematical structure consisting of nodes which are connected or related to each other by links (this is further explained in Chapter 3).

2.1.2. Freight and Cargo

The goods that are transported by any vehicle can be labelled as both freight and cargo. A distinction can be made between the two terms based on the type of vehicle being used. Freight is then used for goods transported by train or by truck, while cargo is used for goods transported by ship or by plane [27]. The terms differ in their origin. Cargo comes from Spanish *cargar* while freight comes from Middle Dutch *vracht*. The term freight not only indicates transported goods, but can also indicate the commercial transport of goods or the price charged for the transport of goods. The term cargo is unambiguous in its meaning, only indicating transported goods [25, 26].

For clarity, the two terms are used as follows in this research: cargo is used to indicate the goods being transported, while freight is used to indicate the process of transporting goods. For example: freight transport is the process of transporting cargo from an origin to a destination.

2.1.3. Classification of Cargo

Cargo can be classified into different types of cargo. There are multiple classifications of cargo types [8, 54, 112]. In this research the following classification is used, as this corresponds to the classification used by governmental institutions gathering statistical information [32, 106]:

- **Liquid bulk:** liquid goods which are not packaged or loaded individually, for example in containers or on pallets, but are poured in the cargo hold of a vehicle. Gaseous products also fall into this category. Examples of liquid bulk cargo are crude oil, rubber and (liquefied) natural gas.
- **Dry bulk:** goods in granular or particulate form which are not packaged or loaded individually, but are dropped in the cargo hold of a vehicle. E.g. minerals, coal or wood chips.
- **(Intermodal) Containers:** steel boxes, with standardised sizes, used to transport goods across different modes of transport without handling the goods themselves. Unlike the amount of bulk which is usually measured in tonnes, the amount can also be measured in TEU (Twenty Foot Equivalent Unit). E.g. 20 ft (1 TEU) or 40 ft (2 TEU) containers.
- **Roll-on/roll-off (ro-ro):** cargo which can be driven on and off transport vehicles, usually measured per unit. E.g. cars, buses or trucks.
- **Other:** including, but not limited to, break bulk (also called general cargo), goods not in bulk nor packaged in containers. E.g. barrels, wood or bags of cacao.

2.1.4. Modes of Transport

Transport modes are a vital component of transport systems as they are the means by which cargo is transported [82]. In this subsection the different modes of transport, or modalities, are compared based on several properties, such as vehicle capacity, speed and sustainability. In Table 2.1 an overview of this comparison is shown.

Road Transport

Road transport has become the dominant mode of transport on land in the world [82]. The road infrastructure is the most dense infrastructure of all modes of transport in the European Union [96]. This makes door-to-door transport possible with this modality. This also means road transport is often used for the initial or last leg of the journey when other modalities are used [49]. The road infrastructure is shared with passenger transport, limiting its capacity and increasing the travel time during rush hour. The relatively high probability of accidents lowers the reliability of road transport [49].

Trucks are used as a vehicle to move cargo from an origin to a destination. Trucks are limited in the amount of cargo they can transport (approximately 2 TEU). While limited in volume, road transport is still relatively cheap for distances up to 700 km as cargo does not have to be transferred between modes [49]. But the limited volume results in relatively high emissions per tonne-kilometre (see Subsection 2.3.4) and high maintenance costs of road infrastructure. Trucks are able to transport all types of cargo, except some very large break bulk.

Rail Transport

Rail transport is used less as a mode of transport in the Netherlands than road transport (see Subsection 2.3.1). The rail infrastructure is far less dense than the road infrastructure. This means other modalities are often needed for the first or last leg of the journey [49]. The railways are partially shared with passenger transport, which limits capacity and leads to the need of scheduling a journey in advance. Scheduled shuttle services offer high speed and high reliability [49].

To transport cargo from origin to destination trains are used as a vehicle. Trains are able to transport more cargo than trucks (about 90 TEU in the Netherlands [59]). Trains are relatively fast and able to transport heavy (bulk) cargo [49]. Rail transport is more sustainable than road transport [82], especially considering electrified rail transport where the electricity can be generated using renewable energy sources. Another strength of rail transport is transport over longer distances. For longer distances rail transport is relatively cheap, but for short distances the high trans-shipment costs result in a high cost per tonne-kilometre [49]. Trains can transport all types of cargo, except very large break bulk which cannot fit on a freight waggon.

Transport Mode	Economical	Speed	Sustainability	Vehicle Capacity	Cargo Types	Infrastructure
Road		-	-	-	+	++
Rail	-		++		+	+
Sea	++	--		++	++	--
Waterway	+	--		+	++	
Air	--	++	--		-	-
Pipeline	-	+	+	+	--	-

Table 2.1: Comparison of modes of transport using several properties: economical, speed, sustainability, vehicle capacity, cargo types and infrastructure [49, 82].

Sea Transport

Most cargo imported in and exported from the European Union (EU) is transported by sea [96]. The sea and ocean infrastructure is sparse, as the number of ports is limited. The ports are also the limiting factor in the capacity of transport by sea. The first and last leg of the journey is often done with hinterland transport, using other modes of transport [49]. Short-sea shipping is used to transport cargo between ports in the EU [96].

Ships are used to transport cargo from port to port. These ships can be very large (up to 19,000 TEU), but this limits the number of ports which can be visited. Sea is a slow transport mode, but also relatively cheap [49]. For short-sea shipping smaller ships are used (300-1000 TEU). There exist specialised ships for all cargo types [82].

Inland Waterway Transport

With the Rhine–Meuse–Scheldt delta in its borders, inland waterways¹ are an important transport mode in the Netherlands. After road transport, inland waterway transport is the most used transport mode in the hinterland of the Netherlands (see Subsection 2.3.1). The infrastructure is climate dependent, as the draught of waterways is variable [49]. This can be countered with the use of weirs (see Section 4.1). Transport via other modalities can be needed to reach an origin or destination. The waterways are much less congested than road and rail, but the possibilities of expanding capacity are limited [49].

To transport cargo, barges² are used as a vehicle. Barges are smaller than sea-faring ships, but similarly have a low speed [49]. Barges can transport higher volumes than other hinterland transport modes, as they can transport up to 500 TEU [7]. As barges can transport a high volume of cargo, its environmental impact per tonne is relatively low (see Section 2.3). Barges can transport all types of cargo. As coasters (small sea-faring ships) can go up some rivers, there is an overlap between inland waterway transport and (short-)sea transport.

Air Transport

Cargo can also be transported by air. The infrastructure of airports is more dense than the sea infrastructure, but still less dense than road and rail infrastructure [49]. This means other modalities are often needed for the initial or last leg of the journey. The infrastructure is mostly shared with passenger transport, except cargo facilities at airports which are usually separated from passenger transport.

To transport cargo by air primarily airplanes are used. Airplanes have the advantage of speed, which offsets the many disadvantages [82]. Airplanes are relatively expensive and are not fit for heavy, large volume cargo [49]. Airplanes also have a large environmental impact. Many types of cargo could be transported by air, but in practice this is limited to time-critical or expensive goods due to the high costs.

¹In this thesis also referred to as waterways

²A flat-bottomed boat

Pipeline Transport

Pipelines can also transport cargo. Special about this transport mode is that pipelines act as both the infrastructure and vehicle for transport. Pipelines mainly transport oil and natural gas, but are able to transport other liquid or gaseous goods [82]. The advantages are speed (continuous transportation), safety and low environmental impact, while the disadvantages are high construction cost and the limitation to a single product (or expensive cleaning costs when switching products) [49]. The risk of a pipeline spill with the subsequent environmental impact is another disadvantage.

2.2. Freight Transport Methods

Freight transport methods define how the different modes of transport are used to transport cargo. In this section the transport methods available in literature are described. First, *synchromodal transport* is described in Subsection 2.2.1. Then the other transport methods that are defined in literature, are presented in Subsection 2.2.2.

2.2.1. Synchromodal Transport

Synchromodal transport is a relatively new concept in freight transport, originating in the Netherlands. It was first defined in an open letter from the Strategic Logistics Platform (*Strategisch Platform Logistiek*) [47]. In this letter synchromodal transport is defined using three features:

- Cargo and destination are no longer linked to one mode of transport. The transport mode used is determined by the available capacity of vehicles and infrastructure, together with the type of cargo.
- In this transport mode, growth of the amount of cargo leads to a better accessibility and sustainability as the transport sector will automatically use waterway and rail modes more when cargo volume grows.
- New management centres will facilitate the bundling of flows of goods, the synchronisation of services and the balance of transport modes. [47]

Synchromodality is subsequently summarised as the synchronisation of the transport demand of individual transport companies with the complete multimodal transport system [91]. In later academic sources [5, 44, 64, 89, 99] it is agreed that the core of synchromodality is real-time and flexible switching among different modalities according to the latest logistics information, to utilise the different modalities efficiently. To make this possible customers book cargo "mode-free", i.e. the transport mode is not specified in advance [67]. From origin to destination cargo can use one or multiple transport modes, depending on availability. For multiple transport modes, transfer terminals are needed to switch modality.

The motivation for this new transport mode is the need to promote a modal shift (from road to other modes), as freight transport is partly responsible for negative effects like high emission and congestion [55, 67]. As cargo is booked mode-free, transporters are able to bundle the flows of goods. This makes the use of ships and trains feasible as their high capacity can be used efficiently. Combining modalities also results in a robust freight transport network consisting of multiple modes of transport [100].

Although some sources [44, 89] limit synchromodal transport to one cargo type (containers), the definition of synchromodal transport does not impose this limitation. All cargo types can be transported in a synchromodal fashion. But in practice switching modality is easiest for containers, as the goods themselves are not handled (see Subsection 2.1.3). For other cargo types the cost of switching modality is thus higher [100], but the journey from origin to destination can still be planned synchromodally.

2.2.2. Other Transport Methods

Before synchromodal transport, other transport methods have been envisioned. These different transport methods sometimes have an overlap in their definitions, but each method has an emphasis on other aspects of freight transport. In this subsection the other transport methods available in literature are briefly described.

- Unimodal transport uses a single mode of transport from origin to destination. Typically this refers to transport by truck [44], but other modes can also be used in an unimodal fashion.

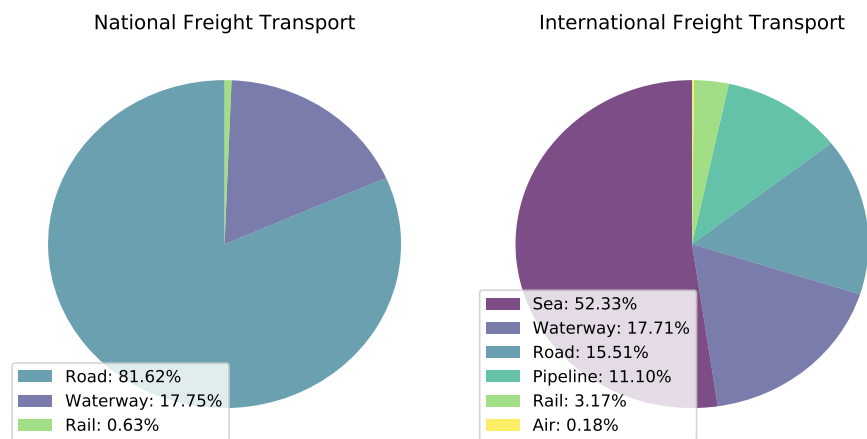


Figure 2.1: Modal split of national and international freight transport in the Netherlands [102].

- Multimodal transport is defined as the carriage of goods from origin to destination by at least two different modes of transport [89, 95]. The emphasis of this method is on the use of multiple transport modes, the cargo can be any type.
- Intermodal transport is a particular type of multimodal transport. The cargo is still transported by at least two different modes of transport, but the cargo is transported in a single transport unit (an Intermodal Transport Unit) [20, 95]. The goods themselves are not handled when changing mode of transport.
- Co-modal transport focuses on the efficient use of different modes of transport, both in an unimodal and multimodal fashion. The emphasis of co-modal transport is an optimal and sustainable utilisation of resources [44, 89].
- Combined freight transport is intermodal transport where the major part of the journey is by modes of transport other than by road. Only the initial or final leg is carried out by road and is as short as possible [95]. The emphasis of combined freight transport is to minimise the use of the road infrastructure.

2.3. Freight Transport in the Netherlands

In this section, some aspects of freight transport in the Netherlands are described. The statistics presented in this section are for the year 2015, unless stated otherwise. First the modal split of freight transport is discussed in Subsection 2.3.1. The sea ports of the Netherlands are described in Subsection 2.3.2 and some transport corridors located in the Netherlands are described in Subsection 2.3.3. In Subsection 2.3.4, statistics of the environmental impact of freight transport are presented. The application of synchromodal transport is discussed in Subsection 2.3.5. And finally, some large incidents of the last decade affecting freight transport are described in Subsection 2.3.6.

2.3.1. Modal Split of Freight

In 2015, freight transport in the Netherlands consisted of 632 million tonnes of national transport and 1136 million tonnes of international transport [102]. These figures illustrate the importance of international trade for the Netherlands. The modal split is quite different for national and international freight transport, as can be seen in Figure 2.1. For national transport, primarily the roads are used. While for international transport, the importance of the sea ports shows in the modal split. As transport by air is severely limited in weight (see Subsection 2.1.4), its share is very small. From and towards the Port of Rotterdam more than 12 million containers were transported in 2014 [29]. The modal split of these containers (excluding sea transit) is 51% by road, 11% by rail and 38% by waterway [29].

	Hamburg	Bremerhaven	Wilhelmshaven	Amsterdam	Rotterdam	Zeeland Seaports	Antwerp	Ghent	Zeebrugge	Duinkerke	Le Havre
Dry bulk	31.5	8.3	4.4	44.2	87.7	10.1	13.8	16.7	1.3	21.7	1.6
Liquid bulk	14.0	2.0	20.6	42.8	224.6	12.2	66.7	3.7	6.8	4.3	40.1
Containers	90.6	55.2	4.3	0.6	126.2	0.4	113.3	0.3	15.6	3.0	25.5
Ro-ro	0.0	0.0	0.0	0.4	22.0	0.7	4.7	2.1	13.5	16.3	0.0
Other	1.7	8.0	0.0	8.5	5.7	9.7	10.0	3.6	1.2	1.4	1.2
Total	137.8	73.4	29.0	96.5	466.4	33.1	208.4	26.4	38.3	46.6	68.3

Table 2.2: Cargo throughput in million tonnes per commodity in the Hamburg - Le Havre range [58].

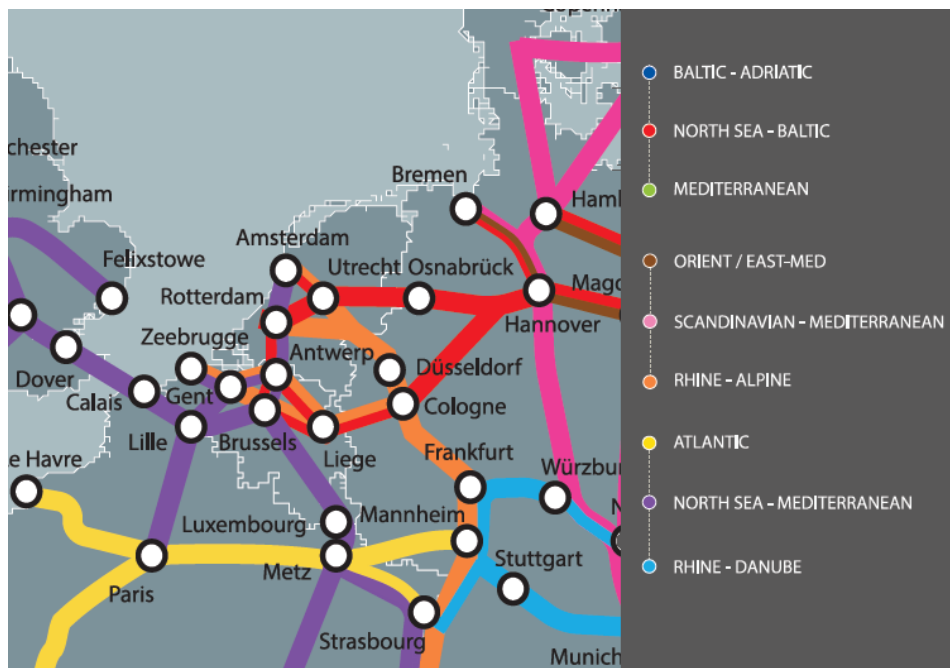


Figure 2.2: The Trans-European Transport Network (TEN-T) corridors in and around the Netherlands [17].

2.3.2. Dutch Sea Ports

As stated in the previous subsection, Dutch sea ports are important for international freight transport. Dutch sea ports are often compared with other ports in the Hamburg - Le Havre range, as these ports share (parts of) their hinterland. A comparison of the amount of cargo throughput per cargo type is shown in Table 2.2. The Port of Rotterdam is by far the largest port in this range. This can be largely attributed to the amount of dry and liquid bulk. The large amount of liquid bulk likely explains the significant pipeline share in the international model split (Figure 2.1).

The three largest Dutch sea ports are Amsterdam, Rotterdam and Zeeland Seaports. Dry and liquid bulk are handled by all three, while containers and ro-ro are almost exclusively handled by the Port of Rotterdam. The throughput of containers in the Port of Rotterdam amounts to 126.2 million tonnes or 12.2 million TEU [58]. Of the 12.2 million TEU, 3.7 million TEU is transferred sea-to-sea and 8.4 million TEU is transferred sea-to- or from-hinterland (with modal split: road 4.5 million TEU, rail 0.9 million TEU and waterway 3.0 million TEU) [55]. The road share has decreased in previous years, while the waterway and rail share has increased.

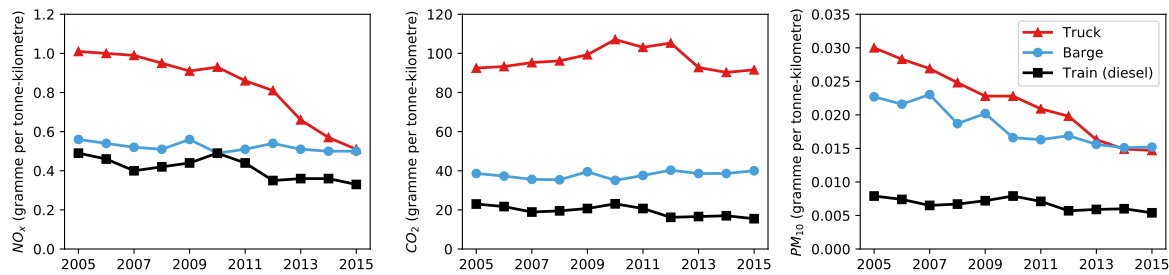


Figure 2.3: Emission of NO_x , CO_2 and PM_{10} in gram per tonne-kilometre for trucks, barges and diesel trains in the years 2005-2015 [55].

2.3.3. Transport Corridors

In the freight transport network of both the Netherlands and the European Union transport corridors are defined by government organisations. Although freight transport takes place on a large amount of different paths, corridors can be defined encompassing a large part of total freight transport. One such definition of corridors for the European Union can be found in the Trans-European Transport Network (TEN-T), see Figure 2.2. Of the nine TEN-T corridors defined in the European Union, three run through the Netherlands. This reflects the important role the Netherlands has in European freight transport.

2.3.4. Environmental Impact

In Subsection 2.1.4, the environmental impact of different transport modes has been discussed. In this subsection, some statistics are presented for three modalities: waterway, road and rail (diesel). In Figure 2.3, the emission of NO_x (nitrogen oxides), CO_2 (carbon dioxide) and PM_{10} (particulate matter, Dutch: *fijnstof*) is shown for the years 2005-2015. Diesel trains have the lowest environmental impact, while trucks have the highest impact. Remarkable is the decline in NO_x and PM_{10} emissions for trucks, equalling barges in recent years. For CO_2 emissions, barges still have a smaller impact compared to trucks.

2.3.5. Sychromodal Transport

Sychromodal transport is not only a theoretical freight transport method, but is currently used in the Netherlands. There are several organisations offering sychromodal transport services. Some examples are European Gateway Services [86], TEUbooker [92] and Lean & Green [42]. To change modality inland container terminals are used. There are dozens of inland container terminals in the Netherlands [14, 60, 61, 81]. Most of the organisations focus on container transport from and towards the Port of Rotterdam, which corresponds with the importance of the Port of Rotterdam for this cargo type (see Table 2.2). As companies increasingly make use of sychromodal transport services, sychromodal transport seems to have found a place in Dutch freight transport.

2.3.6. Large Incidents on Dutch Infrastructure

Large incidents on the infrastructure can disrupt normal freight transport operations. In the Netherlands, several large incidents have happened in the last decade. Some examples of large incidents are given in this subsection, together with the negative effects the incidents had on freight transport.

On the 5th of January, 2011, there was a large fire at a chemical firm located in the port of Moerdijk [53]. Due to the fire, the neighbouring waterway *Hollands Diep* was closed for all shipping. Large clouds of smoke caused by the firefighting had additional effects on the infrastructure, as the neighbouring motorway and railway were closed. This meant the incident disrupted three different modalities at the same time.

On the 11th of October, 2016, The bridge *Merwedebrug* crossing the waterway *Boven Merwede* was closed for heavy road traffic (weighing more than 3.5 tonnes) [68]. During an inspection fatigue was discovered in the metal beams of the bridge causing the closure. As it is a multi-span bridge (see Section 4.1) [79], the repairs only had a small effect for freight transport on the waterway. The repairs took two months, disrupting freight

transport on the motorway during this period.

On 29th of December, 2016, a barge navigating in heavy fog damaged the weir (Dutch: *stuw*, see Section 4.1) at Grave [78]. The weir at Grave is combined with a bridge crossing the waterway. As the extend of the damage could not be immediately determined, the bridge was closed for all traffic. The next day the bridge could be reopened for all traffic. The damaged weir caused the water level in the waterway upstream to drop to the point barges could not navigate the waterway anymore. This disruption of freight transport lasted for several weeks, until a temporary dam was build substituting the weirs function.

3

Related Research

The related research is presented in this chapter. This chapter aims to give the necessary background to answer the research questions and to give the state of the art of research on the robustness of freight transport systems. The modelling of the freight transport system in earlier research is discussed in Section 3.1. The focus of this section is to model the freight transport system as a graph. In Section 3.2, related research on the robustness of freight transport networks is discussed. As the related research on this subject is limited, also research on the robustness of other networks is discussed in this section.

3.1. Modelling the Freight Transport System

The freight transport system has been researched extensively. Research on freight transport systems often calls for a model of the freight transport system. In earlier research the freight transport infrastructure has often been represented by a graph [3, 9, 82, 115]. A graph $G = (\mathcal{N}, \mathcal{L})$ is a data structure which can be used to represent a network. The set \mathcal{N} consists of N nodes (or vertices), which are connected by a set \mathcal{L} of L links (or edges). The connections of a graph can be represented by an adjacency matrix \mathbf{A} , which consists of elements a_{ij} that are one or zero depending on whether there is a link between nodes i and j . A link L between nodes i and j can be directed or undirected and has a link weight. The link weight $w(i \rightarrow j)$ is often a positive real number representing the importance of that link [98].

Freight transport networks have several characteristics which distinguish them from many other networks [31]. In graphs of transport networks the nodes and links represent precise positions in the three dimensional Euclidean space. The number of links spanning large distances is limited, as the exchange of traffic at crossing links is often possible (interrupting the link with a node). Furthermore, the addition of links is costly which limits these networks to not be scale-free¹. Although the road network is sometimes assumed to be planar², empirical evidence has shown that road networks are non-planar [30].

In this section several graph models used in earlier research are presented. These are split into several aspects. In Subsection 3.1.1, the representation of infrastructure elements as nodes and links in a graph model is discussed, this is the graph topology. How to model the interdependence between different modalities (see also Section 4.5) in a graph is described in Subsection 3.1.2. A link weight can reflect one or several attributes of the connection it represents, this is further described in Subsection 3.1.3. Finally, the allocation of traffic in the graph model is discussed in Subsection 3.1.4.

3.1.1. Graph Topology

The first decision in modelling the infrastructure as a graph, is how the infrastructure elements are represented by the nodes and links (see Chapter 4 for the different infrastructure elements). Often in previous research point-like elements (e.g. intersections, terminals or cities) are represented by nodes and line-like

¹A scale-free graph is a graph with a degree distribution following a power law.

²A planar graph is a graph that can be drawn in such a way that no links intersect each other without a node.

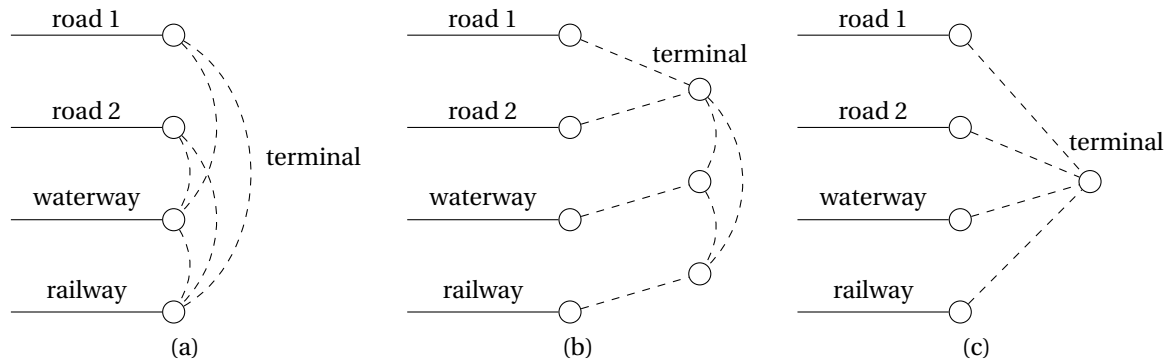


Figure 3.1: Three methods to model an intermodal terminal in a graph model [88, 115].

elements (e.g. routes, roads or railways) are represented by links. The level of detail being represented in a graph is different from research to research. In this subsection these differences are further examined.

A graph can be used to give a high-level representation of the infrastructure of an intermodal freight system [9]. Nodes represent cities and links represent the routes between these cities. To include transfer costs when the modality changes, each city is represented by one node per modality in this research. This city representation is called the multiple node method. These nodes are then connected to each other making transshipment possible.

Some rules to model the infrastructure have been proposed [82]. Nodes represent the terminals and intersections and links represent the connections between the nodes. Additionally, nodes can be added for aesthetic reasons (to keep the graph representation comparable to the real infrastructure) or nodes can be added when attributes of a segment change (e.g. change in the number of lanes of a road).

The intermodal freight transport system (consisting of road, waterway and railway) in the United States has been modelled [88]. Each infrastructure layer is modelled based on a database of the infrastructure, which consists of points connected by lines. In this research, data about cargo flows between zip codes is used. The zip codes are represented by nodes located at the centroid³ of the zip code area, connected to the relevant infrastructure layer(s). Two methods on how to connect intermodal terminals to the network are discussed [88]. The first method is the bi-modal connections model, where each intermodal transfer is represented as a single network link between two modes of transport (see Figure 3.1(a)). In the other method a transfer terminal is represented by multiple gates (one gate per modality), which are interconnected (see Figure 3.1(b)).

The optimal hub location problem of terminals for freight transport has been modelled and solved by a heuristic approach [3]. The model is applied to the Iberian Peninsula for two modalities: road and railway. Each infrastructure layer is represented by a directed graph $G_i = (\mathcal{N}_i, \mathcal{L}_i)$, $i = 1, 2$, where \mathcal{N}_i is the set of nodes in network i and \mathcal{L}_i is the set of links connecting the nodes. The set of nodes consists of intersections, cities and terminal locations. The set of links consists of links connecting these nodes. The origins and destinations are represented by nodes \mathcal{N}' , which are connected to the infrastructure with links \mathcal{L}' . The terminals are represented by transfer links \mathcal{L}^t (the bi-modal connections model [88]). Flows through terminals are expected to be bi-directional, thus two directed links are used to represent a terminal connection. A directed super-graph $G = (\mathcal{N}, \mathcal{L})$ is build, with the set of nodes \mathcal{N} consisting of \mathcal{N}_1 , \mathcal{N}_2 and \mathcal{N}' and the set of links \mathcal{L} consisting of \mathcal{L}_1 , \mathcal{L}_2 , \mathcal{L}^t and \mathcal{L}' .

A general framework for modelling intermodal transport systems has been formulated [45]. Similar to other research [3], each modality is represented by a directed graph. The intermodal transport network can then be represented as one directed super-graph. Terminals can also have a storage node, a node where containers can be stored temporarily before continuing their journey [45]. Nodes can be categorised into: origin nodes, destination nodes and transfer nodes. The links connect the nodes when a path exists in the system and thus simplifies the more complex physical arrangement of the infrastructure.

The multimodal freight system (road, railway, waterway and terminal) has been modelled to optimise terminal locations [115]. The centroids of NUTS-3 regions (a statistical subdivision of Europe) are used as origins

³The centroid of a polygon is located at the centre of mass of that polygon.

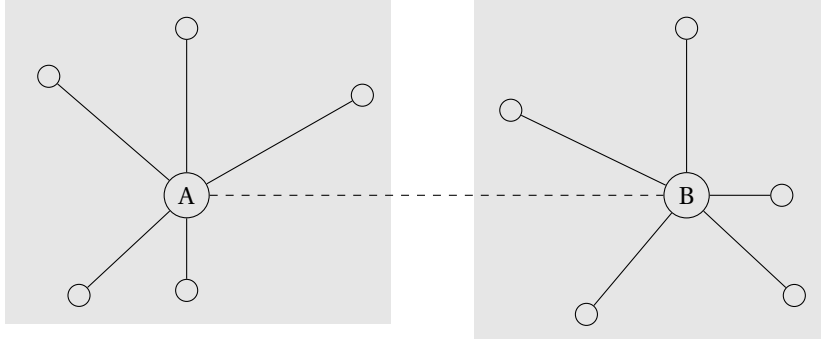


Figure 3.2: The hub-and-spoke system of modelling regions [6]. All origins and destinations in the two regions are connected through two hubs (A and B).

and destinations. These centroids represent the cargo demand of the entire region. The nodes in the model represent the ends of the infrastructure connections (e.g. segments of roads), the terminals and the centroids of NUTS-3 regions. Links are classified as geographic links, transshipment links, pre/end haulage links and access/egress links. The geographic links represent infrastructure sections; transshipment links connect terminals to the appropriate geographic links; pre/end haulage links connect centroids to the terminals; and the access/egress links connect centroids directly to infrastructure sections of the road. The terminals are modelled as a single node connected directly to the infrastructure (see Figure 3.1(c)).

The intermodal freight system has also been modelled to design road-rail intermodal transport solutions [6]. In this research, regions are modelled using the hub-and-spoke system (see Figure 3.2). In each region (grey area) one terminal is selected as a hub (nodes A and B), through which the majority of cargo passes. The other origins and destinations (unlabelled nodes) in a region are connected to this hub using road transport. The hubs are subsequently connected using road or rail transport. The hubs in this research are comparable to the centroids discussed earlier, except the initial and last part of the journey are explicitly modelled in the hub-and-spoke system.

3.1.2. Interdependence

Interdependence is a dependency between the infrastructure of different modalities (see Section 4.5). For example bridges are structures which can affect multiple modalities. To the best of this author's knowledge, earlier research on freight transport systems has not considered this interdependence between modalities. Consequently, the general graph theoretical approach in modelling this interdependence is presented in this subsection. The implications of this interdependence for the robustness of the graph are discussed in Section 3.2.

Considering interdependence in robustness analysis is important, as multiple complex networks are often coupled together [12]. A method to model the interdependence in a graph has been proposed [98]. This methodology will be described here. Consider two interdependent networks A and B , represented by a graph $G_A = (\mathcal{N}_A, \mathcal{L}_A)$ and a graph $G_B = (\mathcal{N}_B, \mathcal{L}_B)$. The interdependence between a node in network A and a node in Network B is represented by an interdependency link, which can be directed. The adjacency matrix of an interdependent network consisting of m different networks has the block structure:

$$A = \begin{bmatrix} A_1 & B_{12} & \cdots & B_{1m} \\ B_{12}^T & A_2 & \cdots & B_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ B_{1m}^T & B_{2m}^T & \cdots & A_m \end{bmatrix} \quad (3.1)$$

The block A_j is the adjacency matrix of the graph G_j . The blocks B represent the interdependency between network layers. In our example, each element $(B_{12})_{kl}$ is either one or zero depending on whether there is an interdependency link between node k in G_A and node l in G_B . When interdependency links are undirected, the B blocks are symmetrical matrices.

3.1.3. Link Attributes

A link between nodes i and j has a link weight $w(i \rightarrow j)$. This link weight can reflect one, multiple or a linear combination of attributes of the connection it represents. In freight transport graphs the link weight is often used to determine the least-cost path between origin and destination, this least-cost does not necessarily represent a monetary cost. It is also possible that a link is specified by a vector $\vec{w}(i \rightarrow j)$ that consists of positive components, each reflecting a metric (e.g. monetary cost, delay, capacity) [98]. In this case a multi-constrained routing algorithm can be used. A link attribute can be used as a constraint, for example the capacity of a link. In this subsection several of the link weights used in earlier research are discussed.

The graphs discussed in the previous section are geometric graphs, as the nodes and links represent geometric objects. Consequently, using the distance of a link in the calculation of the link weight is often done in earlier research [3, 9, 82, 115]. Using the distance in determining the least-cost path between origin and destination, results in the geographic shortest path. Although solely the distance can be used as the link weight, additional or other factors can be considered as well.

One such factor can be the monetary cost of freight transport [3, 9, 36, 45, 115]. This monetary cost can be defined per tonne-kilometre, so that the cost is higher for longer links or when more cargo is transported. A different monetary cost can be defined for each type of commodity [3], each modality [3, 115] and for terminal links (as transshipment has a cost) [45, 115]. The environmental impact of using a link can be a factor as well [6, 115], often using a monetary cost per emission to relate it to the monetary cost factor of freight transport. Another factor can be the amount of traffic on a link [82], making a link less appealing when more traffic is on a link.

Apart from factors reflecting the attractiveness of a link, there are also factors that impose a constraint on a link. Such a factor is the capacity of a link [45, 82]. The capacity limits the amount of traffic that can use a specific link. Another factor is the state of a link, a Boolean variable indicating if a link can be used or not [3]. This can be used to study the effect of adding or removing links, while preserving the structure of the graph.

Link specific impedances can be used to reflect the generalised cost of different routes [88]. First native link impedance functions are defined for each modality. These functions are based on several link attributes, such as: distance, traversal speed, divided highway or not and railway importance. Next, the native impedances for each modality are scaled so that one mile on the best type of link would incur one impedance penalty unit. Finally, these native impedances are made relative using relative modal impedance factors. The impedances are not used to estimate a generalised cost, but are only used to force realistic route selection.

A generalised cost function for the link weight has been proposed [115]. The links are split into four categories: geographic links, transshipment links, access/egress links and pre-/end-haulage links. Access/egress links are the links connecting centroids directly to the road infrastructure and pre-/end-haulage links are the links connecting centroids to a terminal. For each type of link, a generalised cost function is defined for moving one unit of a commodity. This generalised cost can depend on several variables, for example on the unit mode-related cost, the distance of a link, the average mode-related speed or the mode related CO_2 emission. The transshipment link has a dynamic cost, depending on the amount of cargo transshipped.

3.1.4. Traffic Assignment

The goal of a freight transport system is the movement of cargo from origins to destinations. To evaluate the freight transport system, it can be necessary to know the location of vehicles or vehicle flows in the graph. There is a complex set of factors influencing the actual paths taken by vehicles, such as commodity type and carrier/shipper decisions [88]. To assign traffic to the network many different models are presented in earlier research. A distinction can be made between traffic routing and traffic assignment. Traffic routing is concerned with a limited number of vehicles and their behaviour, while traffic assignment is mainly concerned with the system-wide behaviour of traffic in a transport network [82]. This can also be described as microscopic for individual vehicles and macroscopic for traffic flows.

One method is to find the optimal paths by minimising the sum of the link weights and assigning the traffic to this path (all-or-nothing assignment) [3, 36, 45, 82]. Depending on the link attributes used in the link weight, the optimal path can be dissimilar between models. This method for traffic assignment is the basis

for more complex methods. An example of a more complex method is using a capacity constraint in the traffic assignment [82]. Traffic is assigned to the optimal path until the capacity is reached, at which point the next optimal path that is available is used. Another method assigns percentages of the traffic demand to multiple paths, when these paths are almost equally likely [88].

The link weight of the transshipment links can depend on the amount of cargo transshipped [115]. Traffic assignment thus influences the optimal path. An all-or-nothing (AON) algorithm is used to model the traffic. The weight of the transshipment links is updated, after which the AON algorithm is run again. This is repeated until the difference of the transshipment cost in two adjacent runs is less than a predefined tolerance. The capacity is assumed to be unconstrained [115].

3.2. Robustness of Networks

In this section related research on the robustness of freight transport networks is discussed. As the amount of related research on this subject is limited, some research on the robustness of other networks is also discussed in this section. Network robustness, reliability and resilience are all related to disruptions in a network. As a consequence, these terms are sometimes used interchangeably. To avoid ambiguity in this research, the terms are defined here.

Robustness is a measure of a network's response to perturbations or challenges [37, 97]. A system is robust when it keeps certain desired system functionality despite changes in the behaviour of its components or its environment [2, 10, 41]. Thus a freight transport network is robust when it can keep functioning when elements of the network are disrupted. Its function can be described as meeting the cargo demands in the network.

A disruption is a change in the behaviour of the components or environment of a system. A perturbation or challenge is a change in a graph model. A perturbation or challenge is defined as a set of elementary changes in a graph network [97]. The elementary changes in a graph are: addition of a node or link, removal of a node or link, change in the link weight.

Reliability and resilience are different from robustness. A reliable network (almost) never has any disruptions, while a resilient network is able to recover rapidly from a disruption [15]. Or in general, reliability is a measure of how much you can rely on something and resilience is the ability of something to recover from a change [48]. A freight transport network is thus reliable when the failure of an element almost never occurs and it is resilient when a failure of an element is fixed rapidly.

First, some general research on robustness of networks is discussed in Subsection 3.2.1. Research on the robustness of interdependent networks is presented in Subsection 3.2.2. Next, some research on passenger and unimodal freight networks is discussed in Subsection 3.2.3. And finally in Subsection 3.2.4, the limited research on intermodal transport networks is presented.

3.2.1. Robustness

A robustness metric (or statistic) is a measure of the robustness of a graph. There is no robustness metric which is valid for all types of graphs, although a framework for such a metric has been proposed [97]. In earlier robustness analyses different graph metrics (e.g. elasticity [90], algebraic connectivity [107]) have been used to reflect the robustness of graphs in different situations. These metrics can be split into three categories of increasing meaningfulness but also increasing computational difficulty: worst case statistics, average statistics and probabilistic statistics [41].

The connectivity of a graph is a worst case statistic and is equal to the number of nodes or links that have to be removed to disconnect a graph. A graph is connected when there is a path between every pair of nodes. The average connected distance is an average statistic. It is the average distance of the shortest paths between each pair of connected nodes in the graph. This statistic in combination with the fragmentation can be used to study the effects of random node failures and intentional attacks on random and scale-free networks [1]. The network resilience is an example of a probabilistic statistic. It is the largest number of node failures so that the graph is still connected with a certain probability [52].

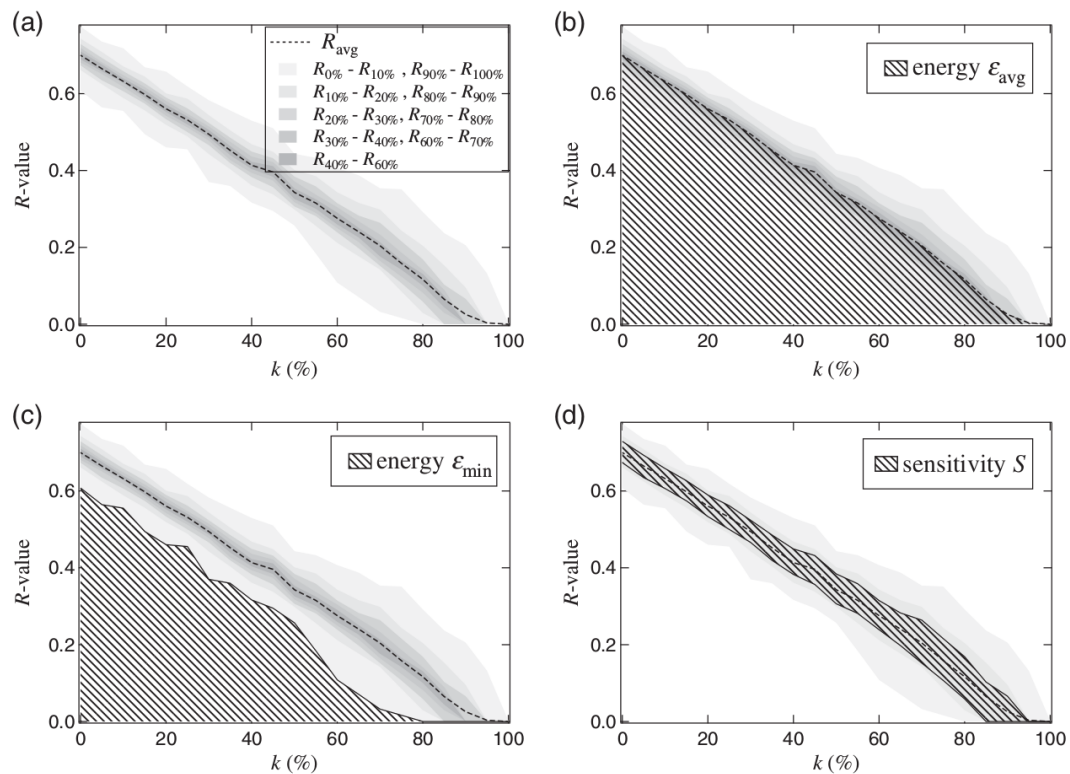


Figure 3.3: Robustness envelopes, with k as percentage of attacked nodes. (a) percentiles, (b) average energy, (c) minimum energy and (d) sensitivity [93].

Although *the* robustness metric does not exist, a framework for such a metric is proposed [97]. The R -value (normalised to the interval $[0, 1]$) is proposed as the robustness value of a graph. It is assumed that any network challenge can be decomposed as a sequence of elementary changes of the graph. Six elementary changes exist: adding a node, removing a node, adding a link, removing a link, rewiring a link and changing the link weight. The degradation of the R -value caused by the elementary changes can then be studied. It is proposed to calculate the R -value using a weighted linear combination of several metrics that characterise the graph. The resulting robustness envelopes can be analysed using the average energy, the minimum energy and the sensitivity [93]. These are shown in Figure 3.3.

The robustness of a graph can be analysed by examining the effects of removing nodes and links in the graph [1, 13, 38, 108]. Removing nodes and links simulate the failures of infrastructure elements in the network. As there is no metric accurately describing the robustness of all graph networks, this methodology provides a general approach to analyse the robustness of graphs. Depending on the network being analysed, only links, only nodes or links and nodes could be removed. Furthermore, for the sequence of removals one of several strategies can be used (e.g. random failure or targeted attack). To compare graphs of different sizes, the fraction of elements that have been removed can be used as a measure [1].

Two robustness simulation variants can be distinguished: static robustness and dynamic robustness [10]. In static robustness analysis, elementary changes can be made without having to redistribute any quantity being transported on the network. In dynamic robustness analysis this redistribution should be taken into account. Static robustness analysis can be analytically treated, but dynamic robustness analysis almost always has to rely on numerical simulations [10].

3.2.2. Interdependent Networks

It is shown in Section 4.5 that there is an interdependence between the infrastructure of different modalities. Considering interdependence in robustness analysis is important [12]. To reflect the interdependence in a graph model, nodes in different networks are connected with dependence links [34, 35, 38]. These depen-

dence links can be bidirectional, reflecting that disruptions of either node results in the disruptions of the other node [34]. A distinction can be made between feedback and no-feedback interdependence [35]. When feedback is allowed, disruptions of a node i in graph G_1 caused by the disruptions of a node j in graph G_2 can in turn cause a disruptions of a node k in graph G_2 . While for no-feedback interdependence such spreading of disruptions is not allowed.

To simulate the effects of a failure in an interdependent network, a node can be randomly removed. This can then cause a cascade of failures. Instead of randomly removing a node, the initial failure can also be part of a targeted attack. The robustness of interdependent scale-free networks has been researched under targeted attacks [38]. The results of this research implies that interdependent networks are difficult to defend using traditional defence strategies such as protecting the high degree nodes.

The theoretical framework has been applied to several real-world interdependent networks, the analysis of an interdependent power and gas pipeline network [108] will be discussed as an example. Two aspects of robustness are researched: edge attack strategies and critical components [108]. Both networks are represented as an undirected graph and the functional characteristics of each infrastructure are taken into consideration. The interdependence is represented by dependence links. The simulation process consists of several steps: when an edge is disrupted, the load will be redistributed in that network. If the load exceeds the maximum capacity of an element it is removed. This is done until the steady state is reached in the network. Then elements that depend on removed elements are removed from the other network. Now the load in the other network is redistributed and elements that are overburdened are removed. This interplay is repeated when necessary. It is shown that critical components are different for interdependent network than for independent network. In addition, it is shown that degree-based interfaces provide good stability and performance [108].

3.2.3. Transport Networks

Of the three modalities considered in this research (inland waterway, road and railway), primarily the robustness of the roads has been researched [110]. In this subsection some of the research on the robustness of road networks is described. Furthermore, some research on the robustness of (multimodal) passenger transport networks is discussed. As freight and passenger transport regularly use the same infrastructure, research in one field can be relevant to the other.

In traditional highway planning, the volume/capacity (V/C) ratio has been used to identify critical links. In contrast with this localised approach, a system-wide approach has also been proposed [85]. A network robustness index is proposed, which takes network flows, link capacity and network topology into account. The network robustness index of a link is equal to the difference in system-wide cost between that link being disrupted and being functional. The cost can be travel-time, monetary cost or other costs. It is shown that this approach leads to different results than the traditional approach.

In earlier research, the factors influencing the robustness are investigated and the infrastructure is compared to other real-world networks [39]. The road graph is dominated by a single giant component. The degree distribution differs substantially from other real-world networks, which often have a scale-free degree distribution. The Dutch road infrastructure does not have short path lengths (small-world phenomenon) as it is likely a subgraph of a two-dimensional lattice. Although the road graph differs from many real-world networks, some networks are similar such as the power grid. The robustness of the Dutch road network has been evaluated, with a focus on the effect of incidents [87]. The robustness is measured using the vehicle loss hours caused by disruptions.

In other research the robustness of the road, railway and tram networks of Melbourne is analysed [43]. Several metrics are considered to measure the functioning of the system: the degree, the betweenness, the clustering coefficient and the topological integrity. The topological integrity is represented by the probability density function of the probability that the removal of a node i breaks the network into n pieces. Based on these measures, the tram network is considered to have the highest structural performance.

The robustness of metro networks has also been analysed [109]. Several robustness measures are considered. The robustness indicator [23] is a robustness metric for metro networks, which is equal to the number of alternative paths in the network divided by the total number of stations in the network. It increases when alternative paths are offered and it decreases in larger systems. The effective graph resistance [28], which

is the sum of the effective resistance between all pairs of nodes in the network. The effective resistance is the potential difference between two nodes when a unit current is injected at one node and withdrawn at the other. The last measure is a critical threshold, the fraction of nodes that have to be removed so that the remaining network has a largest component that contains a certain percentage of the original network. The first two metrics are analytical, while the last is simulation-based. The simulation was done for both random and targeted attack. The results from the metrics contradict each other, which shows that the robustness is difficult to determine.

A review of the literature regarding the vulnerability of transportation network has recently been made [110]. In the review two limitations of existing research are identified. First, the limited amount of research regarding the vulnerability of multilayer transportation networks. Second, the lack of methods to relate the structure vulnerability to the dynamical functional vulnerability.

3.2.4. Intermodal Freight Transport Networks

The robustness of a synchromodal freight transport network has not been researched at the time of this writing. Other transport methods have been presented in Subsection 2.2.2, some of which share similarities with synchromodal transport. Multiple modalities are used in an intermodal freight transport network, similarly to a synchromodal transport network. Some research has been done on the robustness of an intermodal transport network.

A method using raster-based geographic information system (GIS) techniques can be used to analyse the robustness of an intermodal network [84]. The betweenness is used as a measure of the importance of a link. The betweenness of a node is the sum of all shortest paths in the network that pass through that node. The robustness is researched by removing geographic grid cells that have nodes with the highest values of betweenness and analysing how to diameter and average shortest paths of the network change. The proposed method is applied to the network of major roads and rail in the State of Florida. The results provide some evidence that the road and rail infrastructure is relatively robust to disruptions. But it is noted that it is unclear if the betweenness is the best measure for structural importance of nodes. Furthermore, neither the dynamics of the freight network, nor multiple disruptions in the network are considered.

The impact of disruptions on the dynamics of an intermodal transport network can also be analysed [13]. This analysis is used to identify links which removal have a large negative effect on the network's performance, also referred to as critical links. Using a traffic micro simulation model, the movement of individual transport units in the network is simulated. The effects of a disruption on the transport units is analysed for each link in the network. The effect is measured as the total delay of all transport units caused by a disruption. The method proposed is applied to the intermodal transport network in the North Eastern area of Austria, focusing on the railway and inland waterway networks [13]. Using the proposed method critical links are identified in the Austrian intermodal network. It is noted that deciding the route solely on the transport time might not be sufficient. It is proposed to also consider monetary costs, which would change the preferred routes.

3.3. Concluding Remarks

As discussed in Subsection 3.2.4, the amount of research on the robustness of the intermodal transport infrastructure is very limited. The robustness of synchromodal transport infrastructure has not been researched at all, to the best of this author's knowledge. To support the rest of the research done, the related research is presented in this chapter. Using research on freight transport systems and research on the robustness of networks, a foundation is made for the rest of the research presented in this thesis.

4

The Infrastructure

An overview of the synchromodal transport infrastructure in the Netherlands is given in this chapter. The infrastructure consists of the physical structures used for synchromodal freight transport. The overview of the synchromodal transport infrastructure answers the first research sub-question, which reads as follows:

1. What are the different elements of the synchromodal transport infrastructure and how do these elements affect synchromodal transport on the different modalities?

As defined in the scope of this research, the synchromodal transport network comprises the inland waterway, road, railway and container terminal infrastructure. As a macroscopic traffic model is used (see Section 1.3), not all infrastructure elements are relevant for the model (e.g. parking area and marshalling yard). Only the relevant infrastructure elements are presented in this chapter. First, the inland waterway infrastructure is described in Section 4.1. The road infrastructure is described next in Section 4.2. In Section 4.3, the railway infrastructure is described. The container terminal infrastructure is described in Section 4.4. The container terminals form the interconnection between the different transport modes. The effects of the different elements on synchromodal transport are described for each element. Some elements can affect synchromodal transport on multiple modalities, creating an interdependence between modalities. These elements are described separately in Section 4.5. The available data describing the infrastructure and that is used in this research, is described in Section 4.6. Finally, this chapter is briefly summarised and some concluding remarks are given in Section 4.7.

4.1. Inland Waterway

The Netherlands has an extensive network of (inland) waterways, as can be seen in Figure 4.1. The main transport routes and main waterways are almost 1500 kilometres long, while there are 6000 kilometres of waterways in total [101]. In the European Union, only Germany and Finland have more kilometres of waterway [101]. The geography of the Netherlands lends itself well for waterway transport and this is utilised by freight transport. As described in Subsection 2.3.1, the inland waterway is the second most important inland transport mode in the Netherlands.

The waterways in the Netherlands form a complex network, consisting of many different elements. Only the elements relevant for transport by barge are described in detail in this chapter. For example dykes and dams can also be considered elements of the waterways, but as barges can never navigate these elements they are not considered. A brief overview of the different elements is given in Table 4.1. The elements with the function "facilitate crossing of other infrastructure" are described in more detail in Section 4.5, as these elements often serve multiple modes of transport. For each element, some examples of disruptions and the different effects of a disruption are also described.

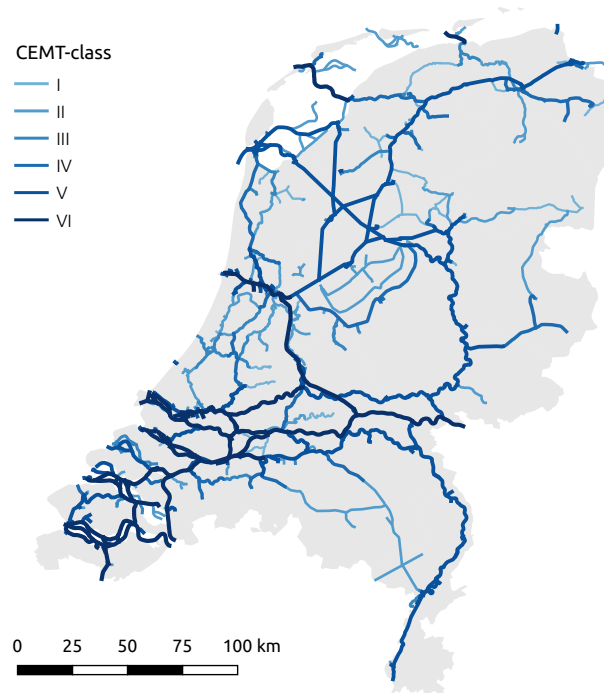


Figure 4.1: Map of the inland waterways with a CEMT-class in the Netherlands [73].

Element	Function
Waterway section	Facilitate movement of barges between other elements.
Waterway intersection	Connect more than two waterway sections.
Bridge	Facilitate crossing of other infrastructure.
Tunnel	Facilitate crossing of other infrastructure.
Water-retaining structure	Regulate the water flow and the water level.
Lock	Facilitate movement of barges between different water levels.
Quay	Makes (un)loading of barges possible.

Table 4.1: The elements of the inland waterway infrastructure in the Netherlands [80].

4.1.1. Waterway Section

The waterway sections form the basis of the inland waterway infrastructure. They form the links between the other elements and therefore facilitate the movement of barges (and seafaring ships when the waterway is large enough). A waterway section can for example be a river, a canal or a lake¹. The water in the waterway section can have a flow. This means that a waterway section can have different properties for up- and downstream. For example, barges moving upstream have a lower speed and higher environmental impact compared to barges moving downstream.

Each waterway section has a CEMT-class (*Conférence Européenne des Ministres de Transport*) [57], which is a classification of European inland waterways. The CEMT-class indicates the maximal dimensions of barges that can navigate the waterway. This is different from the other modalities (road and rail) where a standard size fits on every section. In Appendix D a detailed description of the different CEMT-classes is given. Barges used for the transport of containers belong to CEMT-class III or higher [7]. As the water level is often season dependent, the maximal dimensions of barges can change too.

¹Lakes often have waterways defined as lines corresponding to the navigation channels, but this definition can be ambiguous for barges able to cross the lake using any path.



Figure 4.2: Example of a weir: the weir at Grave [76].



Figure 4.3: Example of a flood barrier: the Maeslantkering [76].

A waterway section can be disrupted in different ways, e.g. the waterway section can become obstructed, the water level can become too low, maintenance work can be done or weather conditions can prevent normal operations. A disruption can limit the maximal dimension of barges that can navigate the waterway section. Furthermore, a disruption can increase travel time or decrease capacity (number of barges) of the waterway section. A large disruption can incapacitate the entire waterway section, making transport impossible.

4.1.2. Waterway Intersection

Waterway intersections are points where three or more waterways meet and the exchange of barges is possible. This exchange is not always possible between all waterways connected to an intersection. As two waterways can connect almost parallel to an intersection, creating a nearly 180° corner. Limited by the dimensions of the barge or the amount of traffic on the waterways it can be difficult or impossible to make such a turn. A waterway intersection can be disrupted in the same way a waterway section can be disrupted. The disruption also has similar effects, e.g. limit maximal dimension of barges, increase travel time or decrease capacity. Due to the crossing of barges, a collision between barges is more likely than on a waterway section though.

4.1.3. Water-Retaining Structure

To regulate the flow of water and the water level water-retaining structures are used. Only elements that can be navigable are discussed here. Water-retaining structures can be split into two categories: weirs and flood barriers. In general, weirs are closed more often than flood barriers. Consequently, weirs always have a lock alongside, while flood barriers do not always have a lock alongside.

Weir

Weirs (Dutch: *stuwen*) are used to regulate the flow of water in rivers and make the river navigable for barges. A weir is a movable barrier across a waterway, an example is shown in Figure 4.2. When a weir is closed, the water upstream is impounded and rises. This makes sure the draught² is enough for barges to navigate the waterway. A weir also regulates the speed of the water flow, effectively changing a river from a *water slide* to *stairs* [80]. As barges cannot navigate a closed weir, there is always a lock next to a weir. When a weir is closed, the travel time and capacity decreases as the lock has to be used.

A weir can be disrupted in different ways, of which the damaged weir in Grave is an example (see Subsection 2.3.6) [78]. When the lock alongside is in normal operation, disruptions can have less effects. When the flow of water requires the weir to impound the water and the weir fails this function, all freight transport is disrupted. The lock has no effect in this situation and all upstream waterway sections not separated by other weirs or locks can be disrupted. When the flow of water does not require the weir to impound the water and the weir is disrupted, freight transport is only disrupted when the lock is disrupted as well.

²The depth of a ship or barge in the water.

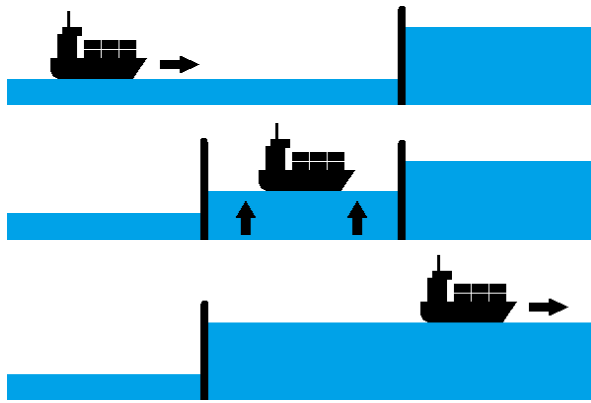


Figure 4.4: Schematic view of the operations of a lock, from top to bottom: one door of the chamber is open and the ship can enter the chamber; both doors are closed and the water level in the chamber rises; the other door opens and the ship can leave the chamber. The process is reversed for moving ships down to the lower water level.



Figure 4.5: Lock at Lith (2 chambers) with a weir to the right [76].

Flood Barrier

A flood barrier prevents the flooding of land upstream, as it protects the land against storm surges and spring tides. A flood barrier is shown in Figure 4.3. Flood barriers are movable, only closing when the water level is expected to be too high. In the Netherlands multiple flood barriers have been constructed as part of the Delta Works (Dutch: *Deltawerken*). The Delta Works are various construction projects to protect the southwest of the Netherlands against the sea. Most flood barriers in the Netherlands are navigable when opened.

When a high water level requires the flood barrier to close and it fails this function, the subsequent natural disaster (flooding of land) would most likely make regular freight transport unimportant. It is more likely that a flood barrier is closed, e.g. due to a high water level or maintenance work. When there is a lock alongside the flood barrier, freight transport can continue (albeit with longer travel time and lower capacity). When there is no lock (for example at the *Maeslantkering*), all freight transport would be impossible.

4.1.4. Lock

To move barges from one water level to another, locks (Dutch: *sluizen*) are used (see Figure 4.5). Locks can be used in combination with a weir, making the passage of barges possible when the weir is closed. Locks can also be used close to waterway intersections, to disconnect the water level in different waterways. A lock consists of one or more chambers, with gates isolating a chamber from neighbouring water. A chamber can have additional gates, making the size of the chamber variable. Multiple chambers can be arranged in series or in parallel, to either increase the possible water level difference between waterways or to increase the capacity of the lock system. A lock has a dual function, allowing barges to navigate a water level difference and blocking the flow of water. The operations of a lock are explained in Figure 4.4.

A lock can for example be disrupted by a malfunction in the control system. Or one or more doors of the chamber can fail. The effects of a disruption can be increased travel time, decreased capacity or water flowing freely. The consequences of this last effect are similar to the effects of a weir disruption. When there is a single chamber, disruptions have a larger effect than when there are multiple parallel chambers. Although some disruptions (e.g. malfunction in the control system) could disrupt all chambers simultaneously.

4.1.5. Quay

A quay is a structure on the border of land and water which makes the (un)loading of barges possible. It can be seen as a special type of mooring location, as barges can moor at a quay. A port or inland container terminal consists of one or multiple quays together with the infrastructure to (un)load cargo. Quays located in sea ports can often (un)load both barges and seafaring ships. A malfunction of the crane at a quay is an example of a disruption. A disruption can result in the (un)loading of less or no barges at that quay.

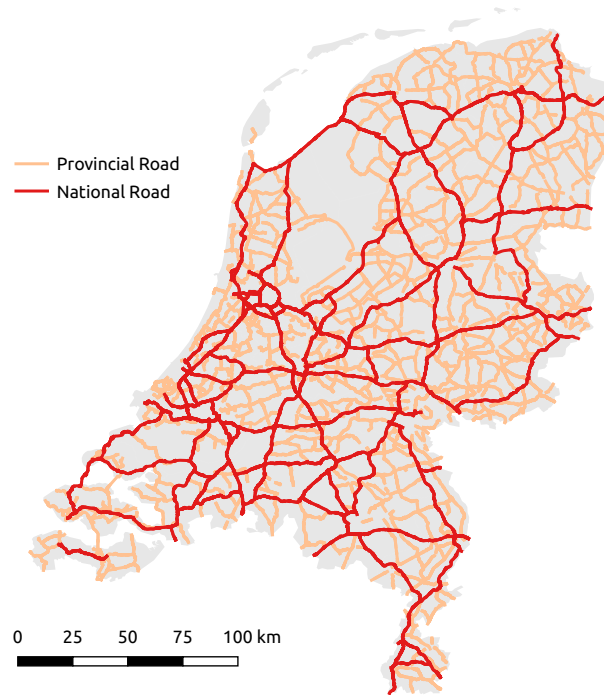


Figure 4.6: Map of the roads managed by Rijkswaterstaat (National Roads) and the provinces (Provincial Roads) in the Netherlands [72].

Element	Function
Road section	Facilitate movement of trucks between other elements.
Road intersection	Connect more than two road sections.
Bridge	Facilitate crossing of other infrastructure.
Tunnel	Facilitate crossing of other infrastructure.
Railway crossing	Facilitate crossing of other infrastructure.
(Un)loading Area	Makes (un)loading of trucks possible.

Table 4.2: The elements of the road network in the Netherlands.

4.2. Road

Of the three infrastructure layers considered in this research, the road network is the most extensive. The network of national and provincial roads are shown in Figure 4.6. National roads are managed by Rijkswaterstaat, while provincial roads are managed by one of the twelve provinces in the Netherlands. Apart from these roads, also an extensive network of smaller roads managed by municipalities and regional water authorities exists. In 2016, the total length of national roads was 5,340 km, the total length of provincial roads was 7,759 km and the total length of other roads 126,025 km [104]. Compared to the other modalities, the road network is thus indeed the most extensive.

The roads in the Netherlands form a complex network, consisting of different elements. Only the elements relevant for freight transport are described in detail in this chapter. A brief overview of the different elements is given in Table 4.2. The elements with the function "facilitate crossing of other infrastructure" are described in Section 4.5, as these elements often consist of multiple modalities. For each element, some examples of disruptions and the effects of disruption are described.



Figure 4.7: Road intersection Gouwe, exchange of vehicles is not possible between all directions [76].



Figure 4.8: Road intersection Prins Clausplein, exchange of vehicles is possible between all directions [76].

4.2.1. Road Section

The basis of the road network is formed by the road section. Road sections connect all other elements and facilitate the movement of trucks and other vehicles. The size of a road section can range from a small road where trucks cannot pass each other to a motorway (a multilane, dual carriageway with controlled access). The number of lanes and the presence of a division between opposing lanes of traffic can be used to indicate the size of a road section. A road section also has a maximum speed, which often is higher when the number of lanes is higher. Other structures can be build over the road (e.g. wildlife crossing), creating a height restriction for vehicles on the road. These height restrictions do not affect most freight transport, as the maximum height allowed primarily effects special freight transport.

Examples of disruptions are maintenance work, accidents between vehicles and bad weather conditions. Unlike the waterway, traffic congestion is a regularly occurring disruption due to the high intensity of vehicles. This high intensity is caused by the large amount of freight transport (see Subsection 2.3.1) and passenger transport on the road network, especially during rush hour. Due to traffic congestion, travel time increases and capacity decreases. When a road has a division between opposing lanes of traffic, it is possible that a disruption only effects a single direction of traffic.

4.2.2. Road Intersection

Road intersections are points where more than two road sections meet and the exchange of vehicles is possible. At busy intersections, traffic is usually regulated with the use of signal lights or a roundabout. When there is a grade separated intersection where different road sections meet (e.g. a motorway with another road), a combination of intersections and slip roads are used to connect the road sections. The exchange of vehicles is not always possible between all roads connected to an intersection. For example on the intersection shown in Figure 4.7 it is not possible, while it is possible on the intersection shown in Figure 4.8.

A road intersection has similar disruptions as a road section. Due to traffic crossing, the capacity of an intersection is usually lower than that of the connected road sections. This means traffic congestion is more likely at road intersections. Accidents are also more likely due to vehicles crossing each other. Another effect is that traffic congestion on one road section, can propagate through the intersection to other road sections. This way one disrupted traffic flow can disrupt other traffic flows as well.

4.2.3. (Un)loading Area

Trucks have to be loaded and unloaded to transport cargo. The infrastructure needed for this depends on several aspects, for example cargo type. For containers the needed infrastructure differs for when a container needs to be emptied or when a container needs to be unloaded from the truck. (Un)loading areas can be found in ports, inland container terminals, and origins/destinations of cargo. When an (un)loading area is disrupted (e.g. by a malfunctioning crane), cargo cannot be loaded, unloaded or transhipped to another modality.

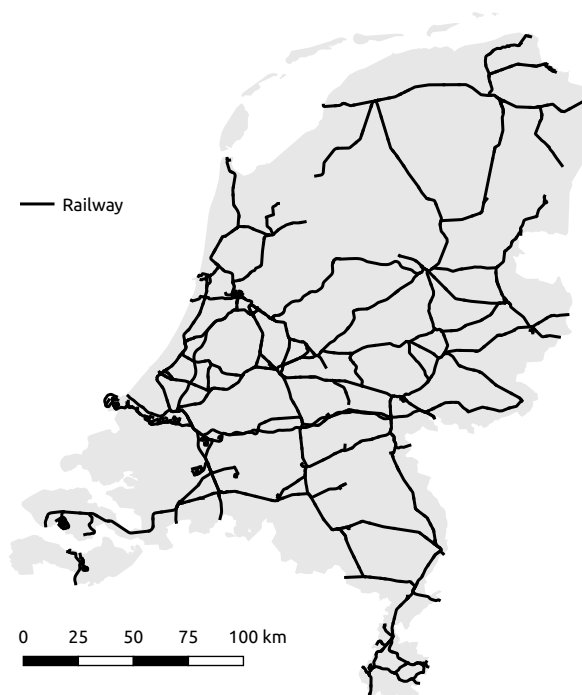


Figure 4.9: Map of the railways in the Netherlands [70].

Element	Function
Rail section	Facilitate movement of trains between other elements.
Rail intersection	Facilitate movement of trains between multiple rail sections.
Bridge	Facilitate crossing of other infrastructure.
Tunnel	Facilitate crossing of other infrastructure.
Railway crossing	Facilitate crossing of other infrastructure.
Freight station	Facilitate the loading and unloading of trains.

Table 4.3: The elements of the rail network in the Netherlands.

4.3. Railway

The rail network is used the least for freight transport in the Netherlands (see Subsection 2.3.1). The complete rail network can be seen in Figure 4.9. The amount of cargo transported by rail is low due to the amount of passenger transport taking place by rail in the Netherlands. Although the dedicated freight railway *Betuwelijn* from Rotterdam to the German border partly mitigates this problem. This is the only mode of transport of which no infrastructure is managed by Rijkswaterstaat. In the Netherlands ProRail [66] is responsible for managing the railway infrastructure. In 2016, the railways had a total length of 3,058 kilometres of which about 75 % has an electrification system [103]. With an electrification system, the power needed to move a train can be produced elsewhere.

The many elements of the railways in the Netherlands form a complex network. Only the elements relevant for freight transport are described. An overview of the considered elements is shown in Table 4.3. The elements with the function "facilitate crossing of other infrastructure" are described in Section 4.5. For each element, some examples of disruptions and the different effects of a disruption are described.

4.3.1. Rail Section

A large difference between railways and the other modalities is that on a rail section a train is bound to use a specific railway track. At certain points a train can switch track using railway switches. It is thus possible to define the tracks as rail sections and the switches as rail intersections. Due to the available databases (see Section 4.6), this is not done in this research. Instead railway lines are rail sections and the rail intersections are the points where multiple railway lines meet. Thus a rail section can consist of one or more (parallel) tracks. To regulate the movement of trains and avoid accidents, railway signalling is used indicating the availability of a track. Furthermore, the amount of trains that can use a rail section is predetermined. The number of cargo trains that can use a certain railway is defined in the number of cargo-paths (Dutch: *goederenpaden*). The number of cargo-paths define the number of cargo trains that can use that railway per direction per hour. As small disturbances have to be taken into account, only 75% of the capacity is booked, resulting in 18 cargo-trains per direction per day [65].

On a rail section there are many conditions that can disrupt freight transport. For example the switches or signalling can suffer a malfunction, the track can be obstructed or the electrification system can fail. The effects of disruptions can be increased travel time and decreased capacity. When the electrification system fails, diesel trains can theoretically still use the rail section. When a rail section consists of multiple tracks, it is also possible that only one of the tracks is disrupted. Then the rail section is not completely disrupted.

4.3.2. Rail Intersection

The rail intersections are points where more than two rail sections meet (see previous Section), these points can also be called junctions. The different rail sections are connected with the use of railway switches. To avoid trains crossing each other's paths when moving in opposite directions, rail intersections can use flyovers creating a grade separated junction.

A rail intersection has similar disruptions as a rail section. But the risk of a collision between two trains is higher on an intersection which is not grade separated. Similar to the road intersection, a disruption on one rail section can propagate through the rail intersection to other rail sections. For example a train that is not able to continue its journey past an intersection, now also obstructs a track on another rail section.

4.3.3. Freight Station

To transport cargo trains have to be loaded and unloaded. The infrastructure elements that make this possible are the freight stations. Due to the electrification system above the track, (un)loading containers is hard for an electrically powered train. Using diesel powered locomotives to (un)load trains solves this problem, although more complex solutions like a moving electrification system have been envisioned [40]. When a freight station is disrupted, less or no cargo can be loaded, unloaded or transshipped to another modality.

4.4. Interconnection

To enable freight transport over multiple modalities, the modalities described in the previous sections are connected to each other. The interconnection between modalities is dissimilar for different cargo types, as each cargo type needs specific structures to be transshipped. Only the interconnection relevant for containers is discussed in this section. For containers, the transshipment is done in container terminals (sometimes called inland ports). An overview of these container terminals in the Netherlands is given in Figure 4.10. Multiple sources [14, 60, 81] were used to come to an overview as complete and up-to-date as possible.

Container terminals can be classified by the modalities that they connect. Due to the large extend of the road infrastructure in the Netherlands, all container terminals are connected to the road infrastructure. This means that an (un)loading area is always an element of a container terminal. When a waterway is connected to the terminal, a quay is also an element of a container terminal. Similarly when a railway is connected to the terminal, a freight station is also an element of a container terminal. Three types can then be distinguished: the rail terminal, the waterway terminal and the trimodal terminal. The rail and waterway terminals connect roads to the railway and waterway respectively. At a trimodal terminal all three modalities are connected to each other. The container terminals connected to the waterways in the Netherlands are all connected

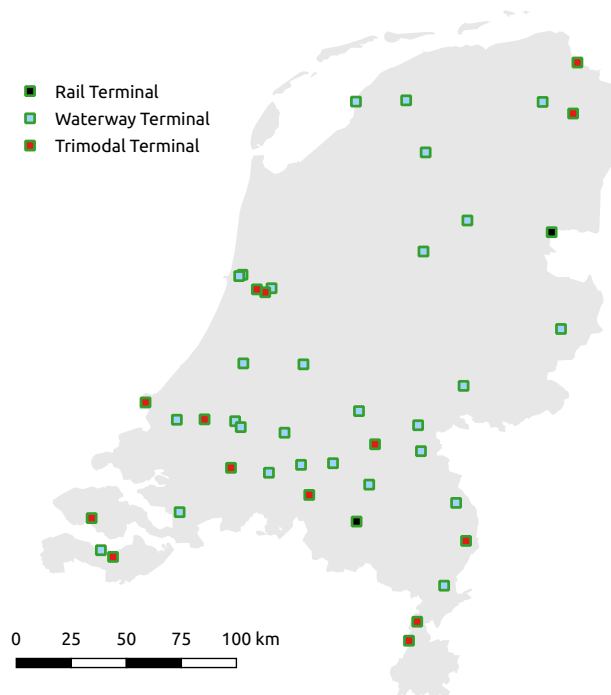


Figure 4.10: Map of the container terminals in the Netherlands. [14, 60, 81]



Figure 4.11: Container port (Port of Rotterdam) [76]. Notice the size difference between the seafaring ship and the barges alongside.



Figure 4.12: Container terminal TCT Venlo [86].

to waterways with CEMT-class III or higher [14, 60, 81]. At a container terminal containers can be stored (temporarily) before being shipped to another location.

4.4.1. Container Port

From and towards the container ports in the Netherlands, all transport modes can be used to transport cargo. These can thus be seen as trimodal container terminals. When also considering sea transport as a modality, these container terminals are actually quadrimodal. An example of a container port is shown in Figure 4.11. Due to the large scale of ports, disruptions can have a wide range of effects. In the worst case (part of) the port cannot be used for freight transport and cargo would have to be transported to other ports.

4.4.2. Inland Container Terminal

As mentioned in the previous subsection, all transport modes can be used to transport containers from and towards ports. But in the hinterland, most companies only have a connection to the road network. In part due to environmental considerations, transporting nearly all cargo by truck is undesirable (see Subsection 2.3.4). Using container terminals, other modalities than the road can be used for the main part of the journey. An example of an inland container terminal is shown in Figure 4.12. A disruption can limit the throughput of a container terminal. When no other inland container terminals are available, the complete journey would have to be done by truck.

4.5. Interdependence

The three modalities (waterway, road and railway) cross each other regularly in the Netherlands. At each crossing a civil engineering structure is needed (e.g. bridge, tunnel, railway crossing), so that vehicles can cross without accidents. It is also possible to use a ferry to transport cars and trucks across a waterway. Ferries are not considered in this research as ferries are only used on a small scale in the Netherlands. Nonetheless, they can form an essential part of the freight transport infrastructure in other countries. When a single civil engineering structure is disrupted, this can thus affect multiple modalities. This is the interdependence between the modalities. The infrastructure elements that facilitate the crossing of other infrastructure were listed for each modality in Tables 4.1 to 4.3. In this section, these elements will be described in more detail.

4.5.1. Bridge

A bridge is a civil engineering structure which spans over constructions, valleys or other infrastructure. A classification of bridge types can be made based on the infrastructure located on top of the bridge: road bridges, rail bridges, water bridges (also called navigable aqueducts) and other bridges (e.g. wildlife crossing). A road bridge is shown in Figure 4.13 and a navigable aqueduct is shown in Figure 4.14. Bridges can be further distinguished by whether they are movable or fixed. A fixed bridge imposes a height limitation on the infrastructure below, while an opened movable bridge imposes either no height limitation or a significantly higher height limitation (than when closed) on the infrastructure below. Opening a bridge creates a delay for both the vehicles on the bridge and the vehicles under the bridge.

When only one modality of the three modalities considered in this research (waterway, road and railway) is associated with a bridge, there is no interdependence between modalities. However, the bridge still imposes a size restriction on the vehicles passing the bridge. When multiple sections of one modality are associated with a bridge, there is a dependence between these sections. When two or all modalities are associated with a bridge, there is an interdependence between modalities. In this case a disruption can affect multiple modalities.



Figure 4.13: Road bridge Vossemeerse crossing the Scheldt-Rhine Canal [76]. Figure 4.14: Navigable aqueduct Leppa [76].



Figure 4.15: Tunnel passing under Dordtse Kil [76].



Figure 4.16: Railway crossing [76].

Bridges are often complex civil engineering structures that can be disrupted in many different ways. When a bridge is movable there are even more possible disruptions. An example of a disruption is the *Merwedebrug* (see Subsection 2.3.6). Other examples of possible disruptions are: high water level³, malfunction of the control system of a movable bridge or maintenance work on the bridge. The many disruptions can also have a wide range of effects, for either the infrastructure on or under the bridge or both. A disruption can limit the maximum dimensions of vehicles, increase travel time or decrease capacity. It can also halt all freight transport on one or more of the associated modalities.

4.5.2. Tunnel

Another way to cross other infrastructure is with the use of a tunnel. A tunnel is an artificial underground passage, through which infrastructure can pass under e.g. constructions, hills or other infrastructure. A tunnel is shown in Figure 4.15. Distinguishing very short tunnels from bridges can be ambiguous, due to similarities in the structure. In the Netherlands only roads and railways pass through tunnels, no waterway tunnels exist in the Netherlands. Due to safety regulations, some cargo (i.e. hazardous goods) is not allowed through tunnels. A tunnel imposes a height limitation on vehicles in the tunnel, while infrastructure passing over a tunnel is often unhindered⁴.

A tunnel can also be disrupted in several ways, e.g. leaking (ground)water, an accident or a broken down vehicle. Safety concerns play an important role in a tunnel, as a tunnel creates an enclosed space. Due to safety considerations, a tunnel is often closed completely when a disruption occurs. Otherwise the number of vehicles allowed to pass through a tunnel can be limited, decreasing capacity and increasing travel time.

4.5.3. Railway Crossing

The last method to cross other infrastructure is with the use of a railway crossing (see Figure 4.16). At a railway crossing a road and railway cross each other at the same level. Unlike the other interdependence elements, a railway crossing is thus not grade-separated. The amount of traffic may require flashing lights and crossing gates to warn traffic on the road of an approaching train. For high amounts of traffic, usually a bridge or tunnel is used instead of a railway crossing. As vehicles cross each other at the same level, railway crossings pose a safety risk. Which is another reason to replace a railway crossing with either a bridge or tunnel.

A railway crossing can be disrupted due to several reasons, e.g. an accident between vehicles or a malfunction of the crossing gates. As with the other interdependent elements, a disruption of a railway crossing can affect one or both modalities. The capacity can decrease, a delay can increase the travel time or freight transport can come to a halt for one or both modalities.

³A high water level decreases the maximum height of barges able to move under a bridge

⁴A waterway over a tunnel can have a draught limitation

4.6. Available Data

There are several databases publicly available detailing the infrastructure of each modality in the Netherlands. In this section, the databases that were used for the model are presented. The information available in the databases, the advantages and disadvantages are discussed. The NWB (*Nationaal Wegenbestand*) is a geographic database of all public roads, waterways and railways in the Netherlands. The NWB is made by Rijkswaterstaat and is split per modality: waterway [71], road [72] and railway [70].

Waterway

In the NWB the waterway sections and intersections in the Netherlands are defined with a unique identification (ID). For the waterway sections additional data is available, like the name, type (waterway or port) and kilometre marking. The advantage of NWB is a very clear definition of sections and intersections, making a transformation to a graph with nodes and links possible. But the disadvantage is the lack of information on the CEMT-class and waterway objects (e.g. bridges, locks, weirs).

The Dutch Waterway Information database (VIN, Dutch: *Vaarweg Informatie Nederland*) is also made by Rijkswaterstaat and can be seen as an extension on the NWB [73]⁵. In VIN properties like draught, CEMT-class and management authority are defined for the waterway sections. Also the locations of objects on the waterway (e.g. bridges and locks) are defined in VIN. The advantage of VIN is the wide range of data available about the waterways. But the disadvantage is that waterway intersections are not clearly defined in the database.

Road

All public roads with either a road number or street name can be found in the NWB. Each road section and intersection has a unique ID. For each road section some additional data is available, such as the responsible road authority, direction for one-way road sections and kilometre marking. Similar to the waterway part of the NWB, road sections and intersections are clearly defined. But again additional data like road objects, speed or number of lanes is not available.

For the roads managed by Rijkswaterstaat, additional data is available in the database *Weggegevens* [74]. In this database properties like maximum speed, number of lanes and structures (e.g. bridges or tunnels) are defined for the road sections. The advantage of all this data is partly mitigated, as it is only available for roads managed by Rijkswaterstaat. Similar to the VIN database for the waterway, *Weggegevens* is an extension on NWB and consequently road sections and intersection are not clearly defined.

Railway

The railway part of the NWB consists of rail sections (each with a unique ID) and rail intersections. For the rail sections some limited additional data is available, e.g. the name of a rail section. As rail sections are represented in the database and not individual railway tracks, the number of railway tracks is unavailable in the database. The data available for the railways is the most limited, as there is no additional database available for the railways (unlike for the waterway and the road).

4.7. Concluding Remarks

The aim of this chapter is to give an overview of the synchromodal transport infrastructure and consequently to answer the first research sub-question, which reads as follows:

1. What are the different elements of the synchromodal transport infrastructure and how do these elements affect synchromodal transport on the different modalities?

An overview of the different infrastructural elements of the synchromodal transport network is shown in Tables 4.1 to 4.3. Combinations of quay, (un)loading area and freight station are also considered an element, namely the container terminal. All these elements can affect synchromodal transport in different ways, which

⁵During this research VIN is discontinued, the same functionality is offered by VNDS

is described in each element's subsection. Although some similarities can be found between elements of different modalities, the effects for synchromodal transport are often different.

Now that the first research sub-question is answered and the different infrastructural elements of the synchromodal transport network are described, the second research sub-question can be answered. For the previously described elements it will be evaluated in the next chapter if and how they should be taken into account in the graph model.

5

Synchromodal Transport Network

In this chapter, the graph model that is used in the robustness analysis is presented. Consequently, this chapter answers the second research sub-question, which reads as follows:

2. How do the infrastructural elements and the other properties of the synchromodal transport system need to be taken into account in a network model to give a relevant representation of the synchromodal transport system?

It is important to determine the purpose of the graph model. Only then the relevance of the infrastructure elements can be evaluated and the validity of the graph model can be determined. The graph model is to be used in a robustness analysis, from which the results must reflect the robustness of the synchromodal transport network. The graph model is limited to the predefined scope (see Section 1.3), this means among other things that the graph model needs to be macroscopic. Two functions are identified for the graph model. The first function regards the inclusion of those infrastructure elements of which a disruption affects the macroscopic network operation. The second function is that the traffic flows in the model should reflect the traffic flows of a real synchromodal network. With such a graph model the effect of disruptions on the ability to meet the cargo demands in the network can be evaluated, i.e. the robustness of the synchromodal network can be analysed.

First the graph topology is presented in Section 5.1. The graph topology is concerned with what the nodes and links represent. The modelling of the interdependence between different network layers is described in Section 5.2. In Section 5.3, the link attributes which are used in the synchromodal transport graph are presented. Next, the allocation of traffic in the graph is described in Section 5.4. The validity of the resulting synchromodal transport graph for the robustness analysis is discussed in Section 5.5. Subsequently, a representative example of a synchromodal network is presented in Section 5.6. This example network will be used in the next chapter to evaluate the simulations of disruptions. Finally, the chapter is recapped and some concluding remarks are given in Section 5.7.

5.1. Graph Topology

The basis of the graph model is what the nodes and links represent of the synchromodal infrastructure. The synchromodal infrastructure is described in Chapter 4 and the graph topologies of (synchromodal) freight transport networks from earlier research are presented in Subsection 3.1.1. The graph topology presented in this section should accurately represent the synchromodal infrastructure, partly using graph topologies from earlier research.

The synchromodal freight network is represented by a directed graph $G = (\mathcal{N}, \mathcal{L})$, where the set \mathcal{N} consists of N nodes and the set \mathcal{L} consists of L directed links. A directed link has a direction associated with it, only allowing movement in that direction. The need for a directed graph to represent a freight transport network is recognised in earlier research [3, 45]. For each directed link, another link going in the opposite direction is added. This is called a symmetric directed graph. An asymmetric directed graph would reflect the syn-

chromodal infrastructure better, as at intersections not always all other sections are accessible from a certain section (see for example Figure 4.7 on Page 28). In the available databases the data necessary for such a graph is unavailable for all modes of transport and therefor a symmetric directed graph is used.

The graph G is defined as a supergraph which consists of multiple directed subgraphs. The three modalities each have a subgraph representing the infrastructure of that modality:

$$G^m = (\mathcal{N}^m, \mathcal{L}^m) \quad m \in \{IWW, Road, Rail\}^1 \quad (5.1)$$

Similarly, the terminals providing the interconnection between modalities and the origins and destinations (OD) representing the cargo demand are represented by the subgraph G^T and G^{OD} respectively. With the infrastructure split into several subgraphs, the robustness of different parts of the sychromodal network can be analysed. The resulting supergraph can be defined as $G = (\mathcal{N}, \mathcal{L})$, with:

$$\mathcal{N} = \mathcal{N}^{IWW} \cup \mathcal{N}^{Road} \cup \mathcal{N}^{Rail} \cup \mathcal{N}^T \cup \mathcal{N}^{OD} \quad (5.2)$$

$$\mathcal{L} = \mathcal{L}^{IWW} \cup \mathcal{L}^{Road} \cup \mathcal{L}^{Rail} \cup \mathcal{L}^T \cup \mathcal{L}^{OD} \quad (5.3)$$

5.1.1. Inland Waterway

The (inland) waterway infrastructure is represented by the directed subgraph $G^{IWW} = (\mathcal{N}^{IWW}, \mathcal{L}^{IWW})$. The elements of the waterway infrastructure are described in Section 4.1. To recap, the elements of the waterway infrastructure are: waterway section, waterway intersection, bridge, tunnel, water-retaining structure, lock and quay.

Not all waterways are relevant for sychromodal freight transport, as the size of barges used for the transport of containers is larger than the maximal dimensions of barges allowed on some waterways. The maximal dimensions of barges able to navigate a waterway is defined as the CEMT-class [57]. An overview of the different CEMT-classes is given in Appendix D. The smallest barges used for the transport of containers belong to CEMT-class III [7]. This agrees with the container terminals in the Netherlands, which are connected to waterways with CEMT-class III or higher [14, 60, 81]. Therefor, only waterway infrastructure with CEMT-class III or higher is included in the waterway subgraph.

When a waterway does not connect a container terminal or another waterway to the network, the waterway is an irrelevant dead end for container transport. These waterways are not part of the waterway subgraph. This is analogue to only including the nodes in the subgraph that are part of at least one simple path² between the origins and destinations.

In earlier research, only sections, intersections and container quays are considered [13, 45, 88, 115]. In this research, the bridges, tunnels, water-retaining structures and locks are also considered. These elements are considered because they are relevant for the robustness analysis. Of the infrastructure elements identified in Section 4.1, quays not part of a container terminal are not considered. As a macroscopic model is made, these quays are not relevant. Microscopic aspects such as adequate resting periods and the refuelling of barges are also not considered.

Waterway sections are represented by links. The links connect all other elements of the waterway, which are represented by nodes. The water-retaining structures can be split into weirs and flood barriers (see Subsection 4.1.3). There is always a lock build parallel to the weir and barges either navigate the lock (when the weir is closed) or navigate the weir (when it is opened). Although this time-dependent characteristic is relevant for sychromodal transport, it is not modelled in the waterway subgraph. Due to its effect on freight transport this characteristic is interesting for future research. In this research only the locks that are parallel to the weir are added to the graph and it is assumed that the weir is always closed. Flood barriers can be closed based on the water level, but this time-dependent characteristic is also not modelled (modelled as always open). Only quays that are part of a container terminal are considered. Furthermore, when a container terminals has multiple quays, these are simplified into a single node.

¹IWW = inland waterway, in this research sometimes simply referred to as waterway

²A simple path has no repeating nodes.

The resulting set of nodes \mathcal{N}^{IWW} and set of links \mathcal{L}^{IWW} of the waterway subgraph consists of the following disjoint subsets:

$$\mathcal{N}^{IWW} = \mathcal{N}_{intersection}^{IWW} \cup \mathcal{N}_{bridge}^{IWW} \cup \mathcal{N}_{tunnel}^{IWW} \cup \mathcal{N}_{flood\ barrier}^{IWW} \cup \mathcal{N}_{lock}^{IWW} \cup \mathcal{N}_{quay}^{IWW} \quad (5.4)$$

$$\mathcal{L}^{IWW} = \mathcal{L}_{section}^{IWW} \quad (5.5)$$

5.1.2. Road

The directed subgraph $G^{Road} = (\mathcal{N}^{Road}, \mathcal{L}^{Road})$ represents the road infrastructure. The elements of the road infrastructure are described in Section 4.2, these are: section, intersection, bridge, tunnel, railway crossing and (un)loading area.

The road infrastructure can be split according to the road authorities responsible for the maintenance of the road. The national roads are managed by Rijkswaterstaat, the provincial roads are managed by the provinces and the remaining public roads are managed by municipalities and regional water authorities [72]. Unlike barges on the waterway, trucks transporting containers can use almost any road. Only the smaller residential roads (mainly managed by municipalities) cannot be navigated by trucks. Only the national roads are explicitly considered in the graph model, due to the available data for the roads [72, 74] and the cargo demand [75]. Similar to earlier research [115], it is assumed only the initial and final part of the journey are done using roads of a smaller category. These parts of the journey are implicitly considered in the subgraph G^{OD} for the origins and destinations.

Only sections, intersections, and container (un)loading areas of the road infrastructure are considered in earlier research [3, 13, 45, 88, 115]. The bridges, tunnels and railway crossings are considered as well in this research. As the initial and last part of the journey are not explicitly considered in the road subgraph, the (un)loading areas for containers are not represented in the road subgraph, but these are represented in the terminal and origin/destination subgraphs (see Subsections 5.1.4 and 5.1.5). The points where the terminal and origin/destination subgraphs connect to the road subgraph are represented by nodes. Similar to the waterway network, when a road does not connect a container terminal, origin/destination point or another road to the network, this road is an irrelevant dead end for container transport. These roads are therefor not part of the road subgraph.

Road sections are represented by links, these links connect all other elements of the road infrastructure, which are represented by nodes. The resulting set of nodes \mathcal{N}^{Road} and set of links \mathcal{L}^{Road} of the road subgraph consists of the following disjoint subsets:

$$\mathcal{N}^{Road} = \mathcal{N}_{intersection}^{Road} \cup \mathcal{N}_{bridge}^{Road} \cup \mathcal{N}_{tunnel}^{Road} \cup \mathcal{N}_{railway\ crossing}^{Road} \cup \mathcal{N}_{TIOD\ connection}^{Road} \quad (5.6)$$

$$\mathcal{L}^{Road} = \mathcal{L}_{section}^{Road} \quad (5.7)$$

5.1.3. Railway

The rail infrastructure is represented by the directed subgraph $G^{Rail} = (\mathcal{N}^{Rail}, \mathcal{L}^{Rail})$. The infrastructure elements of the rail infrastructure are: section, intersection, bridge, tunnel, railway crossing and freight station. These are described in more detail in Section 4.3.

Trains navigating the rail infrastructure are bound to a timetable. This timetable is necessary for the safety, because the capacity of the railways is limited and the rail infrastructure is shared with passenger transport. The number of cargo trains that can use a certain railway per direction per hour is defined as the number of cargo-paths (Dutch: *goederenpaden*) [65]. When a railway has zero cargo-paths, it can still be used occasionally by cargo trains (e.g. a few trains per day). Railways that have zero cargo-paths and that are not structurally used by cargo trains (less than one train per direction per day), are not represented in the rail subgraph.

In earlier research, only sections, intersections and container freight stations are considered [3, 13, 45, 88, 115]. In this research, bridges, tunnels and railway crossings are considered as well. A railway is an irrelevant dead end for container transport when a railway does not connect a container terminal or another railway to the network. These railways are not part of the rail subgraph. Rail sections are represented by links. These

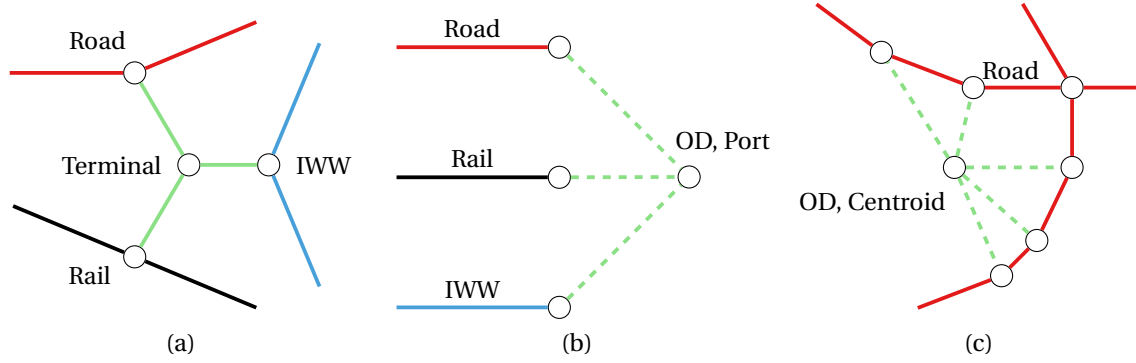


Figure 5.1: The schematic methods to (a) represent container terminals in the graph model, (b) represent origins and destinations (corridor variant) in the graph model and (c) represent origins and destinations (regions variant) in the graph model.

links connect the other elements of the rail infrastructure, which are all represented by nodes. Only freight stations that are part of a container terminal are considered. The resulting set of nodes \mathcal{N}^{Rail} and set of links \mathcal{L}^{Rail} of the rail subgraph consists of the following disjoint subsets:

$$\mathcal{N}^{Rail} = \mathcal{N}_{intersection}^{Rail} \cup \mathcal{N}_{bridge}^{Rail} \cup \mathcal{N}_{tunnel}^{Rail} \cup \mathcal{N}_{railway\ crossing}^{Rail} \cup \mathcal{N}_{freight\ station}^{Rail} \quad (5.8)$$

$$\mathcal{L}^{Rail} = \mathcal{L}_{section}^{Rail} \quad (5.9)$$

5.1.4. Interconnection (Terminals)

The container terminals are represented by the directed subgraph $G^T = (\mathcal{N}^T, \mathcal{L}^T)$. In Section 4.4, a distinction is made between container ports and inland container terminals. In the graph model both of these are represented as container terminals.

There are several methods to represent terminals in a graph model (see Figure 3.1). In this research the method shown in Figure 5.1(a) is used. The terminal is represented by a single node, which is connected to the relevant infrastructure with links [115]. This method best reflects the operations of a terminal from a robustness point of view: the entire terminal can be disrupted, then the node should be removed. Or a single modality connection can be disrupted (i.e. the quay, freight station or the (un)loading area), in this case a link should be removed. A more complete model for the terminal, where an additional node represents the container storage capacity of a terminal, is used in earlier research [45]. The storage of individual containers is a microscopic aspect of sychromodal transport and such a node is therefore not added to the model.

The links connect the terminal nodes to the subgraphs of the different modalities. This means that of the two nodes that are connected by the link, one is part of the terminal subgraph and the other is part of the subgraph of one of the modalities. The resulting set of nodes \mathcal{N}^T and set of links \mathcal{L}^T of the terminal subgraph consists of the following disjoint subsets:

$$\mathcal{N}^T = \mathcal{N}_{terminal}^T \quad (5.10)$$

$$\mathcal{L}^T = \mathcal{L}_{transshipment\ IWW}^T \cup \mathcal{L}_{transshipment\ road}^T \cup \mathcal{L}_{transshipment\ rail}^T \quad (5.11)$$

5.1.5. Origins and Destinations

The directed subgraph $G^{OD} = (\mathcal{N}^{OD}, \mathcal{L}^{OD})$ represents the origins and destinations of the containers being transported. As is mentioned in Section 1.5, both corridors and a country divided into regions are researched. The origins and destinations of a corridor are modelled differently than those of the regions variant.

In a corridor the transport of containers between both ends of the corridor is researched. For the corridors considered in this research, the ends of the corridor are (inland) container ports (i.e. Port of Rotterdam, Port of Antwerp and Port of Duisburg). These container ports are represented by a node. To avoid a container port being represented twice in the supergraph, these are not represented in the terminal subgraph. The nodes

are connected to the subgraphs of the different modalities with access/egress links, as direct access at the origin and destination is assumed (see Figure 5.1(b)). The resulting set of nodes \mathcal{N}^{OD} and set of links \mathcal{L}^{OD} of the subgraph consists of the following disjoint subsets for a corridor:

$$\mathcal{N}^{OD} = \mathcal{N}_{Port}^{OD} \quad (5.12)$$

$$\mathcal{L}^{OD} = \mathcal{L}_{Access/egress}^{OD} \quad (5.13)$$

For the regions variant all containers transported on the infrastructure of a country are researched. To model the origins and destinations for the regions variant, centroids³ of regions are used [88, 115]. The country is split into regions, where the centroid of each region represents the container demand of the origins and destinations in that region. The containers transported between origins and destinations in the same region are not considered. These centroids are added as nodes to the graph. It can only be assumed that all origins and destinations in a region have a connection to the road infrastructure [22, 115]. In earlier research a single connection has been used to connect a centroid to the road network [115], but for a robustness analysis this creates a single point of failure not necessarily present in the region. Thus the centroid is connected to all access points available in the road subgraph of the region (see Figure 5.1(c)). As the terminals are connected to the nearest access point in the road subgraph, terminals in a region are indirectly connected to the centroid via a node from $\mathcal{N}_{T/OD}^{Road\ connection}$. The links represent the use of smaller (i.e. non-national) roads to reach a national road from the centroid. The resulting set of nodes \mathcal{N}^{OD} and set of links \mathcal{L}^{OD} of the subgraph consists of the following disjoint subsets for the regions variant:

$$\mathcal{N}^{OD} = \mathcal{N}_{Centroid}^{OD} \quad (5.14)$$

$$\mathcal{L}^{OD} = \mathcal{L}_{Access/egress}^{OD} \quad (5.15)$$

The number of containers or the amount of containers in tonnes that are transported between the origins and destinations can be found in the demand matrix \mathbf{D} of the subgraph (see Equation (5.16)). This matrix has size 2×2 for the corridor variant and size $n \times n$ for the regions variant where n is the number of regions. The diagonal elements of the demand matrix are all equal to zero for both corridors and countries, as containers transported between origins and destinations in the same region are not considered. The other elements reflect the amount of cargo transported on an average business day (assuming 253 business days per year).

$$\mathbf{D}_{\mathcal{N}^{OD} \times \mathcal{N}^{OD}} (\mathcal{R}_{\geq 0}), \quad \text{with } d_{ii} = 0 \quad (5.16)$$

5.2. Interdependence

Between the subgraphs of the modalities interdependencies exist, which is different from the interconnection (i.e. container terminals) between the subgraphs. Interconnections facilitate the transshipment of containers between different modes of transport. Interdependencies are infrastructure elements whose functioning influences multiple modes of transport, e.g. the disruption of a bridge can affect two modalities. Interdependencies do not facilitate any transshipment of containers. Considering interdependence in robustness analysis is important, as multiple complex networks are often coupled together [12]. To the best of this author's knowledge, this interdependence between modalities has not previously been considered in research on (synchronodal) freight transport networks. The method of representing interdependence in a graph model used in earlier research [34, 35, 38, 98] (see Subsections 3.1.2 and 3.2.2), is also used in this research.

Three types of infrastructure elements can create an interdependence: bridges, tunnels and railway crossings. When such an element is represented in more than one subgraph, these nodes are connected with an interdependency link. These links are bidirectional [34], as when either node is disrupted, the other node can be disrupted as well. Furthermore, no feedback⁴ [35] is allowed for these interdependency links. The set of interdependency nodes (nodes that are connected with an interdependency link) is a subset of the union of nodes representing the three types of infrastructure elements (see Equation (5.17)). When a rail bridge crosses a road that is not part of the subgraph G^{Road} , the bridge node is not an interdependency node.

$$\mathcal{N}_{Interdependency} \in \mathcal{N}_{bridge}^m \cup \mathcal{N}_{tunnel}^m \cup \mathcal{N}_{railway\ crossing}^m \quad \forall m \in \{IWW, Road, Rail\} \quad (5.17)$$

³The centroid of a polygon is located at the centre of mass of that polygon.

⁴When feedback is allowed, disruptions of a node in subgraph G_1 caused by the disruptions of a node in subgraph G_2 can in turn cause a disruptions of another node in subgraph G_2 .

The interdependency links are categorised based on how likely it is that a disruption affects the other modality. Three categories are distinguished with decreasing likelihood of a disruption affecting the other modality. The first category consists of structures that have movable parts, this is the case for movable bridges and railway crossings. The second category consists of structures that are fixed and are embedded in the infrastructure of both modalities, these are the fixed bridges. And the last category consists of structures that are fixed and are only embedded in the infrastructure of one modality, this is the case for tunnels.

5.3. Link Attributes

The links in the graph model have several attributes or weights. These attributes describe various properties of the links. In the graph only links have weights, thus when a node has relevant properties these are added to the connected links. The link attributes are used to assign the (container) freight traffic to the graph network (see Section 5.4).

The second goal of the graph model is that the traffic flows in the model should reflect the traffic flows in a synchronomodal network. The link attributes used in the graph model are primarily based on those used in earlier research [115] and in *Basgoed* [75], a freight transport model used at Rijkswaterstaat. A generalised cost for the uncapacitated freight transport is presented in this section. In an uncapacitated graph there is no congestion, while in a capacitated graph there is congestion when the capacity of an infrastructure element is reached.

5.3.1. Generalised Cost for Uncapacitated Freight Transport

The generalised cost is a single value based on several attributes of the links. The generalised cost C_l is used as the weight $w(i \rightarrow j)$ of the link l between nodes i and j . The generalised cost used in this research is based on earlier research [44, 75, 115]. The generalised cost is different for the links of the different subgraphs. It depends on the length of a link, the time spend on a link and the time spend at the end node of the directed link. For the three modalities (waterway, road and railway) the generalised cost of transporting one unit of cargo over a link is defined as:

$$C_l(d_l) = \kappa_m \cdot d_l + \tau_m \cdot \left(\frac{d_l}{v_{avg,m}} + t_{lock} \right), \quad \forall l \in \{ \mathcal{L}^{IWW}, \mathcal{L}^{Road}, \mathcal{L}^{Rail} \} \quad (5.18)$$

where κ_m is the unit cost per unit of distance for the mode m ; d_l is the length of the link l ; τ_m is the unit cost per unit of time for the mode m ; $v_{avg,m}$ is the average speed of mode m ; t_{lock} is a time parameter equal to the delay incurred by the node in which the directed link ends. Only the time delay incurred by the locks is added as a time constant. As bridges only have to open for ships exceeding the height of the bridge, this property is not added to the macroscopic model. Two average speeds are defined for the roads, one for motorways (mtwy) and one for non-motorways. On non-motorways the average speed is lower (see Figure B.4 for a map with motorways and non-motorways). For the generalised cost it is assumed that vehicles are fully loaded, which means the economies of scale apply to all amounts of cargo. It should be noted that this results in an underestimation of the cost per tonne for small amounts of cargo.

For the links in the origin and destination subgraph, the generalised cost is different for the corridor variant than it is for the region variant. For a corridor the generalised cost of the links is equal to zero: $C_l = 0 \forall l \in \mathcal{L}_{Access/egress}^{OD}$. In a corridor direct access is assumed, so the links do not represent transport of cargo but only connect a node of the origin and destination subgraph to the subgraphs of the modalities.

For the regions variant the links in the origin and destination subgraph represent the transport of cargo on the roads of a lower category than national roads. The as the crow flies distance⁵ is multiplied by 1.5 to approximate the actual distance of the link. This value is based on comparing the difference between the as the crow flies distances and the distance of actual routes for a few links (using OpenStreetMap [62]). The generalised cost is similar to that of a road link, only the average speed is lower:

$$C_l(d_l) = \kappa_{Road} \cdot 1.5 \cdot d_l + \tau_{Road} \cdot \left(\frac{1.5 \cdot d_l}{v_{avg,OD}} \right), \quad \forall l \in \{ \mathcal{L}_{Access/egress}^{OD} \} \quad (5.19)$$

⁵The as the crow flies distance is the length of the straight line connecting two points.

Parameter		Symbol	Value	Unit
Unit cost per unit of time for	waterway	τ_{IWW}	0.13	€/tonne/h
	road	τ_{Road}	3.98	€/tonne/h
	railway	τ_{Rail}	1.00	€/tonne/h
Unit cost per unit of distance for	waterway	κ_{IWW}	0.004	€/tonne/km
	road	κ_{Road}	0.038	€/tonne/km
	railway	κ_{Rail}	0.004	€/tonne/km
Average speed for	waterway	$v_{avg,IWW}$	15	km/h
	road	$v_{avg,Road}$	60	km/h
	road (mtwy)	$v_{avg,Road,mtwy}$	75	km/h
	railway	$v_{avg,Rail}$	35	km/h
	OD	$v_{avg,OD}$	30	km/h
Average time needed for navigating a lock		t_{lock}	0.2	h
Transshipment cost		a	26.285	
		b	0.146	

Table 5.1: The values used in this research for the parameters of the generalised cost function [22, 33, 44, 75, 114, 115].

The transshipment of cargo uses two links in the graph, thus the transshipment cost needs to be split between these links. Due to economies of scale, the cost of transshipment is based on the annual number of containers transported f_{avg} through each container terminal. The relationship between the scale of a container terminal and the transshipment cost is shown to be a group of convex curves [4]. The monotonic decreasing function derived from these curves in earlier research [114] is used to determine the generalised cost for the transshipment. Similar to the links $\mathcal{L}_{Access/egress}^{OD}$ for the regions variant, the links connecting the terminals to the road infrastructure also represent the transport on roads of a lower category than national roads. Two generalised costs are thus defined for the transshipment links:

$$C_l(f_{avg}) = a \cdot f_{avg}^{-b}, \quad \forall l \in \left\{ \mathcal{L}_{transshipment\ IWW}^T, \mathcal{L}_{transshipment\ rail}^T \right\} \quad (5.20)$$

$$C_l(f_{avg}, d_l) = a \cdot f_{avg}^{-b} + \kappa_{Road} \cdot 1.5 \cdot d_l + \tau_{Road} \cdot \left(\frac{1.5 \cdot d_l}{v_{avg,OD}} \right), \quad \forall l \in \left\{ \mathcal{L}_{transshipment\ road}^T \right\} \quad (5.21)$$

The values used for the parameters of the generalised cost are shown in Table 5.1. Several sources [22, 33, 44, 75, 114, 115] are used to determine these values. The sensitivity of the results for changes in these values is researched in Subsection 6.2.4. The distance of a link d_l is the only variable of the generalised cost. Because in the uncapacitated graph the time spend on a link only depends on the distance of a link and the average speed parameter.

5.4. Traffic Assignment

It is necessary to assign traffic to the graph to analyse the effects of a disruption on the transport of containers. As this is a macroscopic model, the traffic is seen as flows and not as individual vehicles. The computational time of the traffic assignment algorithm needs to be limited for several reasons. The algorithm will need to run many times for a single robustness simulation, the available hardware is limited and the geographic area is large. Earlier research has shown that complex models cannot be easily scaled to large geographic areas [50]. In this section two traffic assignment algorithms are proposed, each of increasing computational complexity. The validity of the different algorithms is evaluated in Section 5.5.

5.4.1. Any-Path

For this first algorithm, the traffic is actually not assigned to the graph. Instead it is checked if a path exists between each origin-destination pair. This is checked using a bidirectional breadth-first search algo-

rithm. When a path exists, it is assumed that the transport of containers can take place between an origin-destination pair. Paths are only allowed to use the links $\mathcal{L}_{Access/egress}^{OD}$ at the start and end of the path. Thus the path cannot pass another centroid. This algorithm does not use the generalised cost presented in the previous section and can consequently say nothing about the cost of the available paths. The main advantage of this algorithm is that it is fast, as the time complexity of a breadth-first search is $\mathcal{O}(N + L)^6$ [18]. The main disadvantage is that paths cannot be evaluated on their transport cost.

5.4.2. Shortest Path All-Or-Nothing

In this algorithm the traffic is assigned to the shortest path between each origin-destination pair. This is called all-or-nothing assignment [3, 36, 45, 82]. Similar to the any-path algorithm, paths can only use two links from the set $\mathcal{L}_{Access/egress}^{OD}$, one at the start and one at the end of the path. The shortest path with the lowest generalised cost is determined using Dijkstra's algorithm, which has a time complexity of $\mathcal{O}((N + L) \log N)$ [18]. The advantage of this algorithm is that the increased generalised cost caused by a disruption can be analysed. A disadvantage is that the algorithm has a larger time complexity.

Different variants of Dijkstra's algorithm are used in the traffic assignment algorithm. Using a single source Dijkstra algorithm, the Dijkstra algorithm only needs to run once for each origin as the shortest path to all destinations are determined in one run. Using a bidirectional Dijkstra algorithm is faster than a single source Dijkstra algorithm, but the bidirectional Dijkstra algorithm needs to run for each origin/destination pair. Either one or the other variant is faster, depending on the average number of links between origins and destinations, the number of regions and the method of link removal. Although using the time complexity of a bidirectional shortest path algorithm $\mathcal{O}(2 \cdot b^{d/2})^7$ compared to that of a normal shortest path algorithm $\mathcal{O}(b^d)$ can give an indication of the fastest algorithm, in this research empirical methods are used.

5.5. Discussion of Graph Model

This section aims to evaluate the validity of the synchronomodal graph model proposed for the robustness analysis in Chapter 6. A model is an abstraction of reality and as G. E. P. Box observed: "*all models are wrong but some are useful*" [11]. It is important to investigate whether results from the model, although wrong, are still useful for the reality the model represents. For the graph model two functions are identified. First, when the disruption of an infrastructure element affects the macroscopic operation of the network, this infrastructure element should be included in the graph model. And second, the traffic flows in the model should reflect the traffic flows of a real synchronomodal network. In this section, the validity of the graph model is evaluated using these functions. An overview of the assumptions and considerations that are made for the model is given in Appendix A.

5.5.1. Infrastructure Elements

In Chapter 4 the synchronomodal transport infrastructure is examined and an overview of the infrastructure elements is given. As the infrastructure forms a network, it is decided to represent this network as a geographic (directed) graph network. It is assumed that this is an accurate type of model, based on the use of this type of model in earlier research [3, 9, 13, 82, 84, 115]. In the graph model almost all infrastructure elements presented in Chapter 4 are represented in the graph model using nodes and links. It is assumed that databases representing the infrastructure (see Section 4.6) are faultless. Although microscopic models are more accurate, the validity has been a point of discussion as complex models often suffer from a lack of transparency [83]. Because all the details of the graph model are specified in this chapter, the macroscopic graph model is transparent. This gives readers the opportunity to fully consider the usefulness of the results.

It is also relevant to consider how the infrastructure elements are represented in the graph model. As an illustrative example the locks in the graph model will be discussed here. A lock is represented in the graph model as a single node, while in reality a lock can consist of multiple chambers (see Subsection 4.1.4). If one chamber fails, a lock with two parallel chambers is more robust than a lock with a single chamber. Both locks are represented in the model as a single node which can fail. This means the robustness of a lock is

⁶ \mathcal{O} is the big O notation.

⁷ b is the branching factor and d is the distance between origin and destination.

underestimated in the graph model. As other infrastructure elements are also represented by single nodes, the robustness of these elements is always underestimated. In this sense the graph model offers a worst-case representation of the infrastructure elements. The question arises though if all modalities are affected equally by this worst-case representation. In this research it is assumed it does effect all modalities equally, but it could be a point of interest for future research (see Section 9.2).

When researching the sychromodal transport infrastructure in a country, the country is divided into regions. The centroids of these regions are used as origin and destination for all cargo flows originating and terminating in that region (see Subsection 5.1.5). This introduces an error to the results as in reality cargo flows can originate and terminate at different locations in the region. It is assumed the centroid is not only the centre of mass of the polygon, but also the centre of mass of the traffic demand. Depending on the path, this can result in either an underestimation or overestimation of the generalised cost. The centroids of the regions are connected to all access points available in the road subgraph of the region. This results in the assumption that each access point has a independent connection to the centroid, which is not necessarily the case. The non-national road network is thus assumed to be ideal. This is an overestimation of the robustness of the non-national road network. These problems could be solved when exact points of origin and destination are defined for all cargo flows and the complete road network is represented in the graph, but due to limitations of the available databases this is not done in this graph model.

5.5.2. Traffic Assignment

For the assignment of traffic the generalised cost can be used, the validity of this generalised cost is discussed first. The generalised cost is based on that used in other models [75, 115] and also the parameters are based on earlier research [22, 33, 44, 75, 114, 115]. It is assumed that the generalised cost proposed in Section 5.3 sufficiently corresponds to earlier work, so that the validity can be expected. In Subsection 6.2.4, the sensitivity to changes in the generalised cost of the robustness analysis results is researched. For future research, an extensive analysis of the validity of the generalised cost is recommended.

Multiple algorithms are proposed in Section 5.4 to assign traffic to the graph model. A complex set of factors influence the actual paths taken by vehicles [88]. In the graph model, the traffic should be assigned in such a way that the flows reflect the flows of the real sychromodal network. Due to the simulations that will be done, the allowed time complexity of the traffic assignment algorithm is limited. Similar as with the generalised cost, this research relies on earlier work for the assignment of traffic [3, 36, 45, 75, 82, 115].

For the least computational time intensive algorithm, it is only checked if the origin-destination pairs are connected to each other (any-path). As generalised cost is not considered, a long path using multiple modalities is equally valid as a short path using a single modality. When a failure of an element causes a lot of traffic to reroute to a longer route, this is not reflected in the results using this algorithm. The advantage of using this algorithm is that the results do not rely on the validity of the generalised cost and resulting traffic flows. The results of this algorithm remain valid when the generalised cost used in this research proves to be incorrect. A disadvantage of this algorithm is that the degradation before disconnection cannot be analysed.

For the shortest path all-or-nothing algorithm, the generalised cost of the paths is considered. Using this algorithm, the degradation of the sychromodal network before disconnection can be analysed. Although not all vehicles will make use of shortest path [88], it is assumed that most vehicles will. It is assumed that the results of this algorithm are meaningful, as this algorithm has been often used in earlier work [3, 36, 45, 82]. As the capacity of the infrastructure is not considered for this algorithm, it is possible that an unrealistic amount of cargo is transported on an infrastructure element. It must be noted that the increase of the generalised cost caused by the disruption of an element should not be seen as the real monetary cost of that disruption. These costs are likely not the same due to the inaccuracies of the graph model. The increase of the generalised cost should only be used to compare the effect of the disruption to the disruption of another element.

5.6. Representative Example of a Sychromodal Network

The goal of this research is to analyse the robustness of the Dutch sychromodal freight transport network. As this network is quite large, it is proposed in Section 1.5 to first use a smaller representative sychromodal network to work out how the robustness can be analysed using simulations of disruptions. The representative

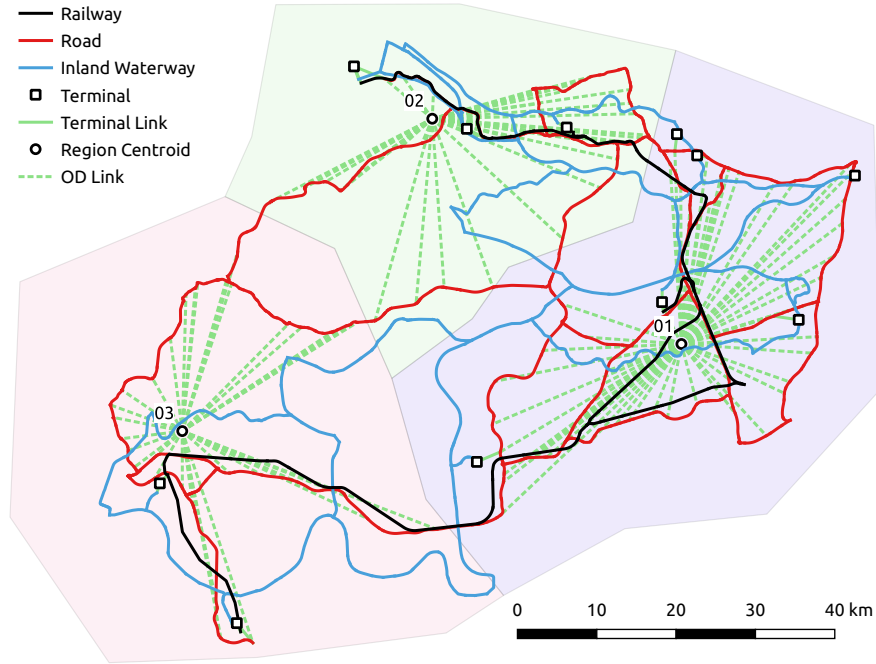


Figure 5.2: A map of the representative example of a synchronodal network (regions variant).

Configuration	Nodes	Links	Length	In-Degree Distribution					Connectivity	
				1	2	3	4	5+	Node	Link
Regions (complete)	912	2140	1288 km	0	725	174	10	3	5	5
Corridor (complete)	805	1676	1288 km	0	740	64	1	0	3	3
Corridor (IWW)	108	232	505 km	2	88	18	0	0	1	1
Corridor (Road)	505	1028	549 km	2	483	20	0	0	1	1
Corridor (Rail)	153	306	209 km	2	149	2	0	0	1	1

Table 5.2: Some statistics for several configurations of the representative example of a synchronodal network. For the length only the length of one of two opposing links is counted. When there are multiple origin and destination pairs in the graph (regions variant), the connectivity of the pair with the lowest values is shown.

network is presented in this section and will be used in Chapter 6. The network is based on the south-west of the Netherlands. The same databases [70–74] are used, as are used for the case studies in Chapter 7.

An overview of the representative synchronodal network is shown in Figure 5.2. For additional images of the representative network, see Appendix B. The network consists of three regions, labelled 01, 02 and 03. The three regions are interconnected with the infrastructure of the three modalities waterway, road and railway. All the infrastructure elements of the graph model presented in this chapter are included in the representative synchronodal network. For this research no data is available on the infrastructure structures (e.g. bridges, tunnels) of the railways. These structures are added to the graph model based on satellite imagery. Apart from the three regions, a corridor is also defined on the example graph. In the most northern and southern region, either ends of the corridor are defined (C01 and C02 respectively). The corridor variant is shown in Figure B.1.

Some general statistics for the graph model of the representative synchronodal network are presented in Table 5.2. Several configurations of the graph model are used: the regions variant with all modalities (complete), the corridor variant with all modalities and the corridor variant for each individual modality. For the length statistic only the length of one of two opposing links is counted. The regions variant has 11 terminals, 6 of which connect the waterway to the road and 5 of which are trimodal (i.e. connect all three modalities). The

corridor variant has 2 trimodal terminals less, as these are container ports used as the start and end of the corridor.

5.7. Concluding Remarks

In this chapter the graph model is presented that is used in the robustness analysis. The aim of this chapter is to answer the second research sub-question, which reads as follows:

2. How do the infrastructural elements and the other properties of the synchromodal transport system need to be taken into account in a network model to give a relevant representation of the synchromodal transport system?

Unlike the freight transport graphs used in earlier research, infrastructure elements like locks, bridges and tunnels are represented in the proposed synchromodal graph model. For the link weights and the traffic assignment, methods from earlier work are used. When the infrastructure of different modalities cross each other, interdependence links are defined between the different modalities. To the best of this author's knowledge, no earlier research considers the interconnection and interdependence simultaneously in the synchromodal network.

With the first two research sub-questions answered, the third research sub-question can be answered. The robustness of the described graph model will be analysed in Chapter 6. To this end an example synchromodal graph is presented, for which the effects of disruptions will be simulated for the next chapter.

6

Robustness Analysis Method for the Sychromodal Transport Network

In this chapter, the robustness analysis methodology used in this research is presented. This chapter aims to answer the third and last research sub-question, which reads as follows:

3. How can the robustness of the sychromodal network model be analysed and how well does it apply to the robustness of the sychromodal transport infrastructure?

The representative example of a sychromodal network presented in Section 5.6 is used to answer the research sub-question. First, several methods to simulate disruptions and how to quantify the robustness using these simulations are discussed in Section 6.1. The results likely depend on the graph model and the type of simulation that is used. In Section 6.2, the effects on the results of several choices in this graph model and in the robustness analysis are discussed. The targeted removal strategy is briefly discussed in Section 6.3. Finally, the chapter is briefly summarised and concluding remarks are given in Section 6.4.

6.1. Robustness Analysis using Simulations of Disruptions

In this research, the robustness of the sychromodal freight transport network is analysed by simulating disruptions on the macroscopic graph model presented in Chapter 5. The robustness is defined as follows (see Section 3.2):

The robustness of a network is a measure of the network's ability to keep functioning when elements of the network are disrupted [2, 10, 37, 41, 97].

The function of a sychromodal freight transport network can be described as facilitating the cargo demands in the network. In this section the simulations of disruptions will be described in detail. Three stages are distinguished for the simulation. First, it is determined which graph elements can be disrupted and how these are disrupted. Next, a removal strategy is chosen defining in what order graph elements are disrupted. And lastly, the effect of the disruptions on the functioning of the sychromodal network is analysed.

6.1.1. Disruptions

The infrastructure elements of the sychromodal network and their possible disruptions are described in Chapter 4. A disruption can have different effects on the transport of containers. The infrastructure element can completely fail, cutting off all transport on that infrastructure element. It is also possible that a disruption causes a delay for transport on that infrastructure element, causing an increase of the generalised cost. Similarly, a disruption can cause the capacity of the infrastructure element to decrease. Partial failures like increased cost and decreased capacity are not considered, but the complete failures of infrastructure elements are studied (see the scope in Section 1.3). For the graph model this means that one or more graph elements

(a node or link) are removed from the graph when a disruption occurs. A removal is one of the elementary changes possible on a graph¹. A challenge is a set of one or more elementary changes. A disruption in the real world is represented by a challenge in the model.

A subset of the graph elements in the sychromodal graph $G = (\mathcal{N}, \mathcal{L})$ can be selected which can be removed from the graph. For the sychromodal graph model presented in Chapter 5, both nodes and links represent infrastructure elements that can be disrupted. For example a bridge (represented by a node) can be disrupted or a rail track (represented by a link) can be disrupted. When a node is removed, the links connected to that node are removed as well. It can be decided to not remove certain elements. For example the nodes and links in the origin and destination subgraph can be assumed to be always functioning. For each simulation a set of elements is defined that can be removed in the simulation, where:

$$\{\text{Graph Elements}\}_{to\ be\ removed} \subseteq \{\mathcal{N} \cup \mathcal{L}\} \quad (6.1)$$

Some nodes are connected to nodes of other modalities with interdependence links, see Section 5.2. Three categories are defined with different likelihoods of a disruption spreading to another modality. When a node which is connected to another node with an interdependence link is removed from the network, the other node is removed as well. This spreading can be done for all, none or a selection of the three categories. When multiple nodes are removed, it is still counted as a single challenge.

For each link between two nodes in the graph model, there is an opposing link between the same two nodes. In Chapter 4 it is explained that only for roads with a division between opposing lanes of traffic, a disruption can affect a single direction of traffic. For roads without a division and for the other modalities a disruption affects both directions of traffic. This phenomenon of a disruption affecting a single direction of traffic is not added to the simulations in this research. One of the two opposing links is added to the set of graph elements that can be removed. When a link is removed as part of a challenge, the opposing link is removed as well.

Opposing links are removed simultaneously due to the available data. Several graph elements are represented by a single node, while in reality the opposing directions of traffic are separated (e.g. two one-way tunnels or two one-way bridges often used on motorways). These elements should be represented by two nodes when opposing links can be disrupted individually, to preserve consistency. But then not all links in the graph would have opposing links, the graph would be asymmetric. In Section 5.1, it is discussed that such a graph cannot be made due to the available data.

6.1.2. Removal Strategies

The next stage for the simulation is removing graph elements in a certain sequence. The removal strategy specifies in what order the challenges occur. Disruptions can have different causes. Some are caused by failures of infrastructure elements or by failures of the vehicles on the infrastructure, these disruptions are to some extent random. Others are caused by planned maintenance or could be caused by a terrorist attack, these disruptions have a more deterministic nature. In this research, two removal strategies are used for the sychromodal network: random removal and targeted attacks. In this subsection these removal strategies will be described in more detail.

For the random removal strategy, at each time step a graph element is randomly chosen from the set of graph elements that can be removed [1, 108]. For each simulation, the sequence of challenges can be different. A Monte Carlo simulation is used to obtain accurate numerical results. When interdependence links are considered, all nodes connected to the chosen graph element with interdependence links are removed as well. This process is repeated until no transport is possible between any region pair (or on the corridor). The graph element can be selected using different probability distributions. The element can be selected using a uniform distribution so that the failure probability is equal for each element. Links can also be chosen using the length of the links as a probability distribution, so that longer links have a higher chance of a disruption occurring. The random removal strategy is further discussed in Subsection 6.2.1.

In a targeted attack, the goal is to degrade the functioning of the sychromodal network as fast as possible [1, 38, 108]. Different strategies can be used to select which elements should be removed first. For example the

¹Elementary changes are: an addition of a node, a removal of a node, an addition of a link, a removal of a link or a change of a link weight [97].

nodes with the highest degree could be removed first. Or the node with the highest betweenness centrality² could be removed first. Some targeted attack strategies are researched in Section 6.3.

6.1.3. Robustness Analysis

A performance metric is necessary to examine the effects of challenges in the graph model. This performance metric should measure the functioning of the synchromodal network. Different performance metrics can be used, depending on the traffic assignment algorithm used. The different algorithms are described in Section 5.4. Using any of the assignment algorithms, it can be examined if the origins and destinations are connected to each other. The disconnection of origins and destinations is a performance metric describing the basic functioning of the synchromodal network. When for one network more challenges can take place before the corridor becomes disconnected than for another network, the first network is more robust. This metric does not show the gradual degradation of the network. A challenge might not disconnect a region, but it could increase the cost of transport significantly. Unlike the disconnection metric, the current cost of transport does show this gradual degradation. This performance metric does require the use of the shortest path all-or-nothing traffic assignment algorithm which takes cost into account. The cost performance metric is further discussed in Subsection 6.2.3.

The results for different networks and for different regions pairs are compared to each other. For the random removals, the results are a set of samples of a certain performance metric. When the simulation is run a sufficiently high number of times, this can be seen as an approximation of the probability density function (PDF) for the performance metric at a specific number of challenges. To accurately compare the results for the random simulations, Welch's t -test [111] is used for the null hypothesis that the results have identical sample means. The significance level for the test is chosen as $\alpha = 0.01$. If a difference between means is discussed in this research, it can be assumed that the null hypothesis has been rejected. The statistic t in Welch's t -test is defined as:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (6.2)$$

Apart from the sample mean, the complete distributions of samples can also be analysed visually. Furthermore, it can be determined what the probability is that a randomly selected sample of one region pair is higher than a randomly selected sample of another region pair.

To plot the results for the random simulation, different variables can be used for the x -axis. The number of graph elements from $\{Graph\ Elements\}_{to\ be\ removed}$ that have been removed can be used. In earlier research [1, 108], the fraction of graph elements that have been removed is used. An advantage of this variable is that graphs with different number of elements in $\{Graph\ Elements\}_{to\ be\ removed}$ can be compared, as it is normalised. The variable indicates how efficient the topology of the graph is with regards to the robustness.

A single disruption can cause the removal of multiple graph elements, due to interdependence and the removal of links when a node is removed. The next variable takes this into account as it indicates the number of challenges that have occurred. Using this variable the value judgement of the efficiency of the topology is decoupled from the simulation results. Another variable is the number of challenges per 100 km of infrastructure, again evaluating the efficiency of the topology with regards to the robustness. For example a network A with 300 km of infrastructure requires 15 challenges on average to be disconnected and a network B with 400 km kilometres of infrastructure also requires 15 challenges on average to be disconnected. When considering the number of challenges per 100 km of infrastructure, it becomes apparent network A is more robust, as more challenges have to occur per kilometre of infrastructure before the network is disconnected.

6.2. Various Aspects of Robustness Analysis

Many aspects of the graph model presented in the previous chapter and of the simulations described in Section 6.1 likely affect the results of the robustness analysis. Some aspects of the graph model with regards to the robustness analysis results are discussed in Section 5.5. For example that both locks with a single chamber

²Betweenness centrality of a node is a measure specifying the number of shortest paths that pass through the node.

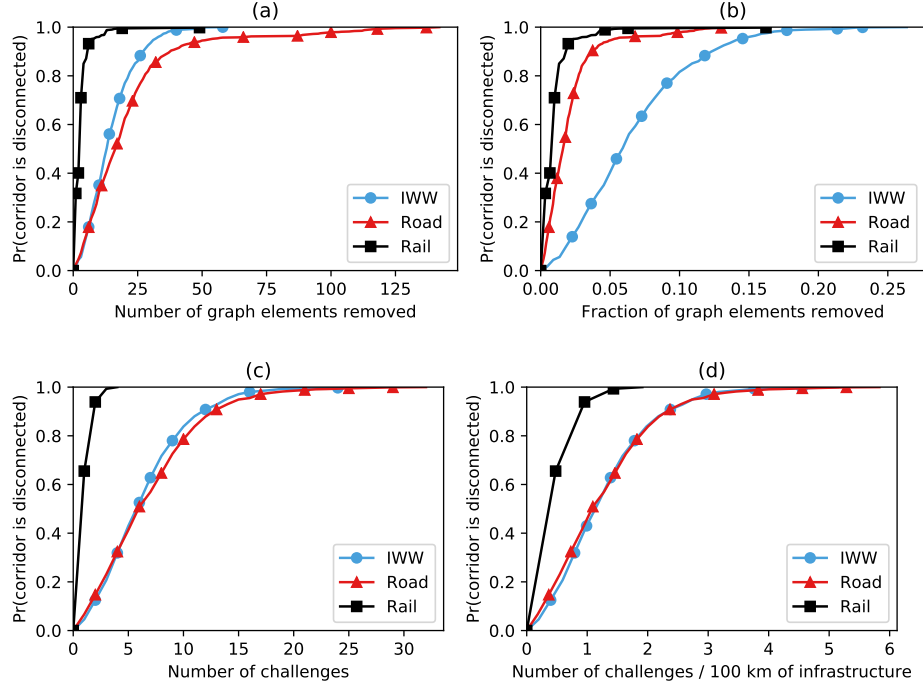


Figure 6.1: Probability that corridor is disconnected for (a) number of graph elements removed, (b) fraction of graph elements removed, (c) number of challenges and (d) number of challenges per 100 km infrastructure. Removing graph elements using a uniform probability of failure. The modality IWW has 505 km of infrastructure and 220 elements can be removed, the modality road has 549 km of infrastructure and 1015 elements can be removed, the modality rail has 209 km of infrastructure and 302 elements can be removed. The simulation of each modality is run 1,000 times.

and locks with multiple parallel chambers are represented by a single node, which underestimates the robustness of some locks. In this section the effects of several aspects of both the graph model and the simulations are researched. The example network presented in Section 5.6 is used for this research. The random removal strategy is used in this section, the targeted removal strategy is only briefly discussed in Section 6.3.

6.2.1. Random Removal Strategy

Simulating random removals of graph elements does not always produce the results expected for the synchronodal transport graph. This will be demonstrated using the following simulations. For these simulations, the corridor variant of the example network is used. Three graphs are used, each consisting of one of the modality subgraphs and the origin and destination subgraph. The results of the simulations of these three graphs are compared to each other. In these simulations the following graph elements can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{\text{IWW}, \text{Road}, \text{Rail}\} \quad (6.3)$$

Not all these elements are present in each graph, when elements are not present they are not added to the set of graph elements that can be removed. Interdependence is not used in this simulation, as unimodal transport is analysed. The random removal strategy with an uniform distribution is used to select the elements that are removed. The simulation of disruptions is run 1,000 times per modality.

The results of these simulations are shown in Figure 6.1. The results shown in Figure 6.1(b) differ significantly from the other subfigures. From Figure 6.1(b), it could be concluded that the waterway graph is significantly more robust than the graph of the other two modalities. Furthermore, it could be concluded that the road graph is only slightly more robust than the railway graph. These conclusions do not correspond with the expectations when visually analysing the networks shown in Figure B.3. This is caused by the fact that the number of nodes per kilometre of infrastructure is far from homogeneous for the different modalities. The road graph has 0.92 nodes per kilometre, the railway graph has 0.50 nodes per kilometre, while the waterway graph only has 0.21 nodes per kilometre for the example synchronodal graph. The addition of infrastruc-



Figure 6.2: Two simple synchmodal transport networks transporting containers between node 1 and node 2. Network (b) has more infrastructure elements (nodes 3 and 4) than network (a). For network (a) 2 challenges have to occur or 100% of the infrastructure elements have to be removed to disconnect the network. For network (b) either 2, 3 or 4 challenges need to occur or either 33%, 50% or 67% of the infrastructure elements have to be removed to disconnect the network.

ture elements (without creating new alternative paths), will result in the conclusion that the robustness has decreased.

For the x -axis the number of challenges can also be used, which is shown in Figure 6.1(c,d). From these results it could be concluded that the road graph is the most robust, the inland waterway graph is just slightly less robust and the railway graph is the least robust. When considering the number of challenges per 100 km of infrastructure, the road graph and waterway graph have almost identical probabilities of disconnection. Although this corresponds better with the expectation, when visually analysing the networks, the validity of these conclusions is still debatable. When a large amount of locks and water retaining structures would be build for the inland waterways, more challenges would be required before disconnection occurs. The addition of infrastructure elements (without creating new alternative paths) results in the conclusion that the robustness has increased. As the addition of infrastructure elements (without creating new alternative paths) does not increase the ability of the network to keep functioning when elements of the network are disrupted (i.e. the robustness), this conclusion is not correct.

To illustrate the different effects of the addition of infrastructure elements (without creating new alternative paths) on the fraction of graph elements removed and on the number of challenges per 100 km of infrastructure, the following example is used. In Figure 6.2, two networks are shown transporting containers between node 1 and node 2. Nodes 1 and 2 cannot be removed, similar to the nodes and links of the origin and destination subgraph. For Figure 6.2(a), two links need to be removed to disconnect the network (2 challenges or 100% of the infrastructure elements). For Figure 6.2(b), the removal of multiple combinations of graph elements can result in disconnection. In terms of challenges either 2, 3 or 4 challenges are required and in terms of percentage either 33%, 50% or 67% of the infrastructure elements have to be removed to disconnect the network. The addition of graph elements thus results in a higher number of challenges required and a lower fraction of graph elements to be removed for disconnection.

For the previous simulations, the assumption is that all graph elements have uniform probability of failure. It should be noted that although the road and railway graphs have many infrastructure objects per kilometre, these are often small fixed bridges. While the few infrastructure objects on the waterway are locks, water retaining structures and (movable) bridges. Furthermore, for the regions variant the road graph has many more nodes, as the origins and destinations are connected to all access points of the roads. The assumption that objects have uniform probability of failure thus seems to be inappropriate. This problem can be solved by assigning accurate probabilities to all infrastructure elements. This would resemble a reliability study, which is outside the scope of this research.

The problem described here affects the corridor case studies to a lesser extend. The number of nodes per kilometre of infrastructure is more homogeneous for the corridor case studies, due to limitations of the databases. These limitations are described in more detail in Subsection 7.1.1. In the example synchmodal graph (corridor variant) without all infrastructure elements (similar to the corridor case studies), the road graph has 0.12 nodes per kilometre, the railway graph has 0.15 nodes per kilometre and the waterway graph has 0.13 nodes per kilometre. Nonetheless, when using the uniform probability of failure, the disadvantages of the method should be kept in mind. The combination of the fraction of graph elements removed and the number of challenges per 100 km of infrastructure should be used. Because when infrastructure elements are added, the probability of disconnection increases for the fraction of graph elements removed and decreases for the number of challenges per 100 km of infrastructure.

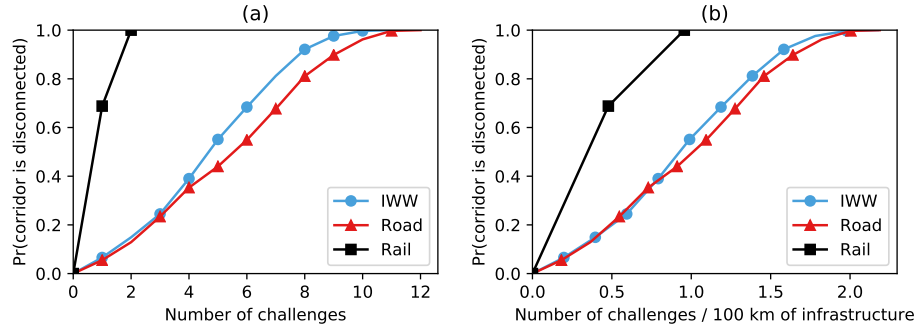


Figure 6.3: Probability that corridor is disconnected for (a) number of challenges and (b) number of challenges per 100 km infrastructure. Removing all graph elements not contributing to the sychromodal network after each challenge. The modality IWW has 505 km of infrastructure and 220 elements can be removed, the modality road has 549 km of infrastructure and 1015 elements can be removed, the modality rail has 209 km of infrastructure and 302 elements can be removed. The simulation of each modality is run 1,000 times.

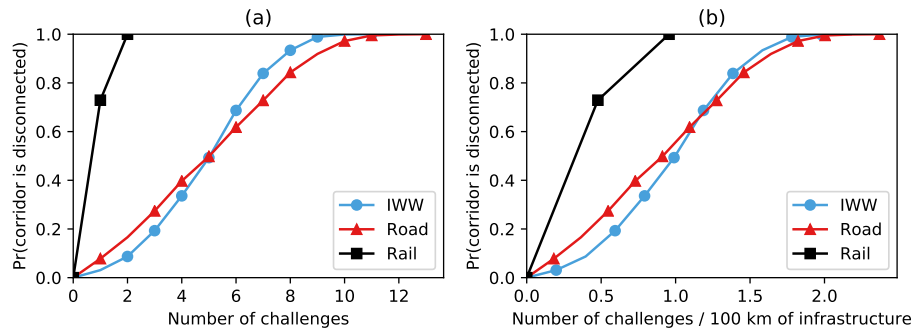


Figure 6.4: Probability that corridor is disconnected for (a) number of challenges and (b) number of challenges per 100 km infrastructure. Removing links based on length and removing all graph elements not contributing to the sychromodal network after each challenge. The modality IWW has 505 km of infrastructure and 114 elements can be removed, the modality road has 549 km of infrastructure and 512 elements can be removed, the modality rail has 151 km of infrastructure and 302 elements can be removed. The simulation of each modality is run 1,000 times.

Two solutions are proposed for the dependence of the results on the number of graph elements. The first solution is to remove all graph elements not contributing to the sychromodal network (e.g. dead ends) after each challenge. Due to the additional graph elements removed after each challenge, the results for the number and the fraction of graph elements removed are no longer relevant. The results of this method are shown in Figure 6.3. The probabilities of disconnection barely change for this method when graph elements are homogeneously added to the graph. But when graph elements are added to certain links, the results can change. This is because the probability that any element between two intersections is selected, is equal to the number of elements between two intersections. This method still suffers from the problem that the assumption that objects have uniform probability of failure, is inappropriate.

The second solution is to use an uniform probability of failure per kilometre of infrastructure, instead of an uniform probability of failure per graph element. This means only links can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{L}^m \quad m \in \{\text{IWW}, \text{Road}, \text{Rail}\} \quad (6.4)$$

The link is chosen using the length d_l of the link as a probability distribution. The probability of a link l from the set $\{\text{Graph Elements}\}_{\text{to be removed}}$ being removed is equal to:

$$\Pr(l \text{ removed}) = \frac{d_l}{\sum_{\text{link} \in \{\text{Graph Elements}\}_{\text{to be removed}}} s_{\text{link}}} \quad (6.5)$$

Furthermore, after each removal all links not contributing to the functioning of the sychromodal network (i.e. dead ends) are removed to avoid any influence of the number of graph elements. The results for the number and the fraction of graph elements removed are again not relevant, due to the additional graph elements

removed after each challenge. The results of these simulations are shown in Figure 6.4. As is shown in Subsection 6.2.2, these results are not dependent on the number of nodes per kilometre. This method has some disadvantages. First, interdependence cannot be considered as it is represented by nodes and only links can be removed. Second, terminal links cannot be removed as they do not have a physical length. And third, many infrastructure elements are represented by nodes, but nodes cannot be removed using this method.

Concluding Remarks

The second solution proposed (removing links based on length) offers a solution to the dependence of the results on the number of graph elements. This method will be referenced to as method V. Unfortunately, this method introduces new problems (e.g. not being able to remove nodes). The uniform probability of failure method is used in most cases in the rest of this research. This method is referenced to as method U. The link based probability of failure method is sometimes used to check conclusions. It is important to keep the disadvantages of both method U and method V in mind when evaluating the results.

6.2.2. Missing Infrastructure Elements

Not all infrastructure elements of the graph model are present in the available databases (see Section 4.6) or can easily be used from the available databases. This means that many infrastructure elements cannot be added to the graph models for the case studies. Most bridges, tunnels, flood barriers and railway crossings are not added for the case studies. Using GIS (Geographic Information System) techniques and manual work, the infrastructure elements that create interdependencies are added for the case studies. This is described in more detail in Subsection 7.1.1. Locks are added for the case studies, as these have an effect on the generalised cost (an increased travel time). The graph model used in the case studies thus differs from that proposed in the previous chapter. This graph model with missing infrastructure elements is referenced to as \bar{G} , while the graph model proposed in the previous chapter is referenced to as G . Some general statistics of the representative example network (\bar{G} variant) are shown in Table B.1.

Several simulations are done to analyse the differences between G and \bar{G} . Both the regions and the corridor variant of the example network are used. For the regions variant, all modalities and the terminal subgraph are included. For the corridor variant, again single modalities are analysed (three graphs, each with only one modality subgraph and the origin and destination subgraph). Interdependence is not used in these simulations. Per graph 1,000 simulations are run. Both method U (uniform probability of failure) and method V (link based probability of failure) are used for the random removal simulation. The following sets of graph elements can be removed for respectively the regions variant and the corridor variant using method U:

$$\{\text{Graph Elements}\}_{\text{to be removed, regions}} = \mathcal{N}^T \cup \mathcal{L}^T \cup \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.6)$$

$$\{\text{Graph Elements}\}_{\text{to be removed, corridor}} = \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.7)$$

For the corridor variant no terminals can be removed as unimodal transport is considered. For method V the following sets of graph elements can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed, regions}} = \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.8)$$

$$\{\text{Graph Elements}\}_{\text{to be removed, corridor}} = \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.9)$$

First, G and \bar{G} are compared using method U. The results are shown in Figure 6.5. For the fraction of graph elements (Figure 6.5(a-c)), the missing infrastructure elements (\bar{G}) cause the probability of disconnection to become lower. While for the number of challenges / 100 km of infrastructure (Figure 6.5(d-f)), the missing infrastructure elements cause the probability of disconnection to become higher. This confirms the argumentation in the previous subsection (see Figure 6.2). Especially in Figure 6.5(f), it can be seen that changing the number of infrastructure elements can have considerable effects on the results.

The results of using method V are shown in Figure 6.6. As described in the previous subsection, the number of nodes (without creating new alternative paths) has no influence on the results. When a network without an even distribution of infrastructure elements is analysed, this method could thus be useful. The fact that nodes cannot be removed continues to be a large disadvantage for this method.

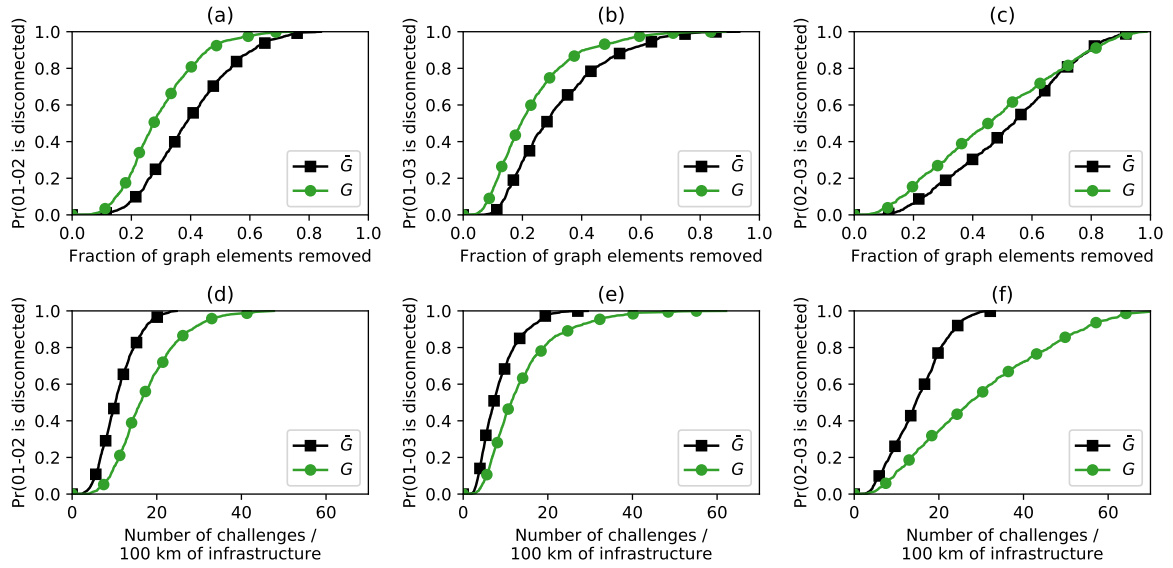


Figure 6.5: Probabilities that region pairs become disconnected for G and \tilde{G} . Using method U for removing graph elements. Both graphs have 1288 km of infrastructure. For G 1851 graph elements can be removed and for \tilde{G} 661 graph elements can be removed. For both graphs 1,000 simulations are run.

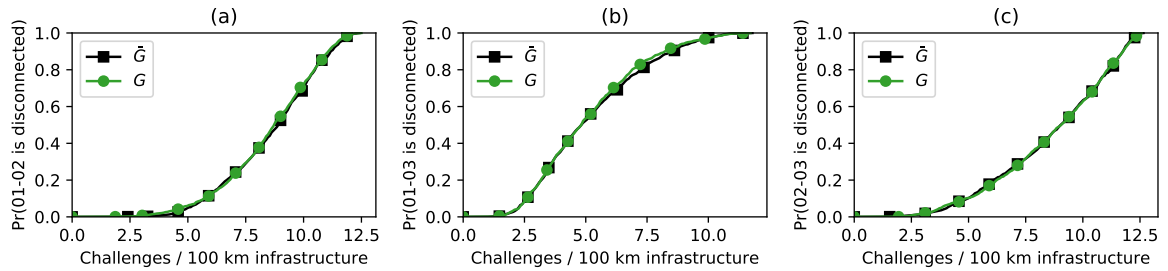


Figure 6.6: Probabilities that region pairs become disconnected for G and \tilde{G} . Using method V for removing graph elements. Both graphs have 1288 km of infrastructure. For G 915 graph elements can be removed and for \tilde{G} 320 graph elements can be removed. For both graphs 1,000 simulations are run.

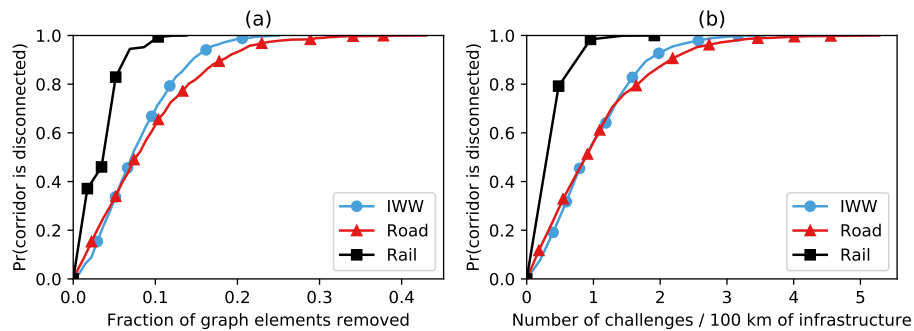


Figure 6.7: Probability that corridor is disconnected for (a) fraction of graph elements removed and (b) number of challenges per 100 km infrastructure. Using method U for removing graph elements. The modality IWW has 505 km of infrastructure and 136 elements can be removed, the modality road has 549 km of infrastructure and 135 elements can be removed, the modality rail has 209 km of infrastructure and 58 elements can be removed. Per modality 1,000 simulations are run.

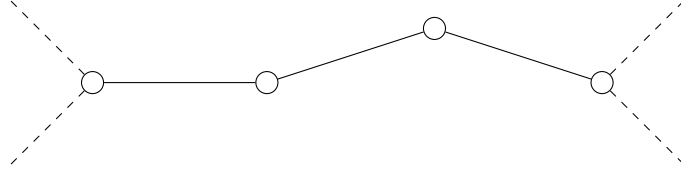


Figure 6.8: The removal of one of the two centre nodes and the removal of any of the non-dashed links all have the same effect on the transport on this excerpt of a synchronomodal network.

In the previous subsection, using either the fraction of graph elements removed or the number of challenges / 100 km of infrastructure lead to different conclusions (see Figure 6.1). This is caused by the fact that the number of nodes per kilometre of infrastructure is far from homogeneous for the different modalities. In Figure 6.7, the results are shown for \bar{G} . For this graph the number of nodes per kilometre are more homogeneous. The road graph has 0.12 nodes per kilometre, the railway graph has 0.15 nodes per kilometre and the waterway graph has 0.13 nodes per kilometre. Nonetheless caution is advised when using this method, as an uneven distribution of nodes in the network will have an effect on the results.

For the targeted attack removal strategy, the missing infrastructure elements have controllable effects on the results. Adding more infrastructure elements does not change the results directly, as their removal has the same effect as removing the original link (see Figure 6.8). It should be noted that the elements of a group are incomplete when not all infrastructure elements are present in the graph. Thus when the conclusion states that a certain link is important for the functioning of the network, all the missing infrastructure elements on that link are important as well.

6.2.3. Cost Performance Metric

In the previous subsections the disconnection of region pairs and corridors is used as a performance metric. In Subsection 6.1.3, another performance metric is proposed: the cost of transport. This performance metric uses the generalised cost of transporting containers presented in Section 5.3. The sensitivity of the cost performance metric for changes in the parameters used for the generalised cost is discussed in Subsection 6.2.4. In this subsection, it is discussed how results using the cost performance metric should be presented and how the cost performance metric compares to the disconnection metric.

The regions variant of the example network is used, without all infrastructure elements. All the subgraphs (i.e. three modalities, terminals and origins and destinations) are included. Two simulations are run for this subsection. When the results do not lead to different conclusions, results are only shown for the second simulation. For the first simulation, method U is used. The following set of graph elements can be removed using this method:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{N}^T \cup \mathcal{L}^T \cup \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.10)$$

For method V, the following set of graph elements can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.11)$$

Interdependence is not used in these simulations. Both simulations are run 1,000 times. The results of these simulations using the disconnection metric are shown in Figure 6.9. According to the first simulation (uniform probability of failure, Figure 6.9(a,b)), the region pair 02-03 is the most robust (as probability of disconnection is lowest), region pair 01-02 is less robust and region pair 01-03 is the least robust. According to the second simulation (length of links as a probability of failure, Figure 6.9(c)), the region pairs 01-02 and 02-03 are the most robust and the region pair 01-03 is the least robust. Thus the two methods can lead to different conclusions.

For the cost performance metric the total system cost or the cost per region pair can be used. For the system cost the costs for each region pair can be summed, either as cost per tonne or as the cost of transporting the cargo demand. The increase in cost per region pair for 4 runs of the random simulation is shown in Figure 6.10. Once a region pair becomes disconnected in a simulation run, the cost performance metric no

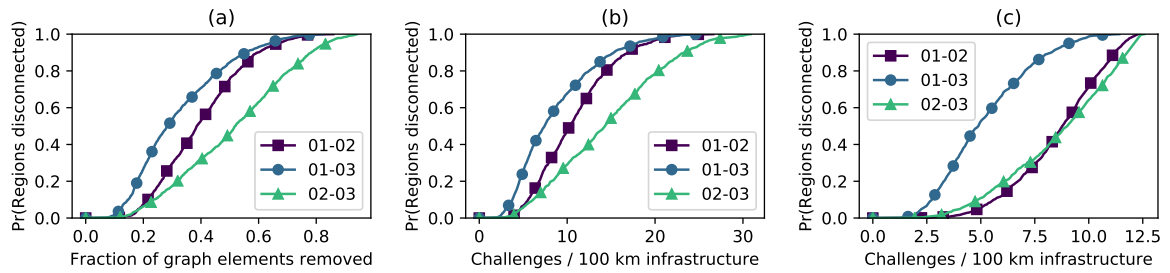


Figure 6.9: The probability that the three region pairs become disconnected, (a,b) using method U for removing graph elements and (c) using method V for removing graph elements. The graph has 1288 km of infrastructure. (a,b) 661 graph elements can be removed and (c) 320 graph elements can be removed. The simulation is run a thousand times.

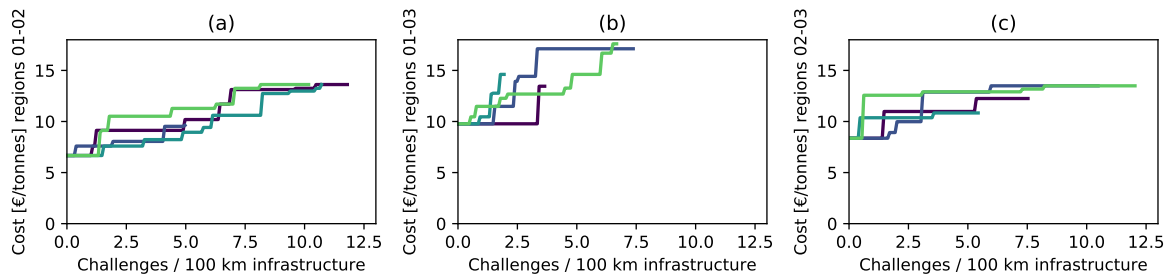


Figure 6.10: The increase in cost for the number of challenges per 100 km infrastructure per region pair for 4 runs of the random simulation. The graph has 1288 km of infrastructure.

longer has a value. For each run the cost performance metric is strictly increasing, as is expected from using the shortest path all-or-nothing algorithm. The increase in cost for all runs is shown as a density function in Figure 6.11. These graphs can be normalised using the initial cost when no challenges have occurred. For the density function it seems that for the worst case (highest cost) the cost can decrease when more challenges happen. This is caused by the discontinuity of the cost performance metric once disconnection occurs. This discontinuity also influences the graphs in less noticeable ways. When interpreting the results, this limitation should be taken into consideration. This can be done by either only evaluating the cost performance metric for the numbers of challenges per 100 km infrastructure when no disconnections occur or by resolving the discontinuity.

Normalised Inverse Cost

Two methods are investigated, which try to resolve the discontinuity of the cost performance metric for the random simulations. For the first method a cost of not transporting cargo is defined. In this research the cost for not transporting cargo is defined as ∞ . The limit of the inverse is used to fit the results in a graph.

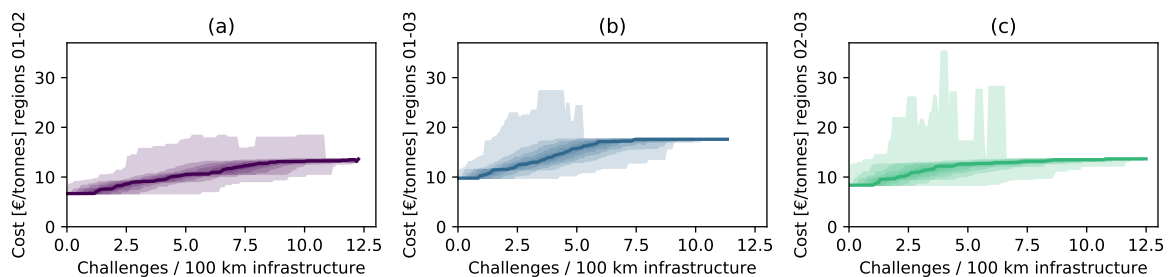


Figure 6.11: The increase in cost for the number of challenges per 100 km infrastructure per region pair for 1,000 runs of the simulation, with a total of 1288 km of infrastructure. The thick line represents the median, while the light to darker shaded areas represent 100%, 80%, 60%, 40%, 20% of the samples respectively. A 1,000 simulations are run.

Region pair	ε_{avg}	ε_{min}	S
01-02	6.13	1.54	3.10
01-03	4.08	0.90	2.97
02-03	6.42	1.15	4.26

Table 6.1: Comparison of the normalised inverse cost density functions for different region pairs. Using the energies ε_{min} and ε_{avg} and the sensitivity S .

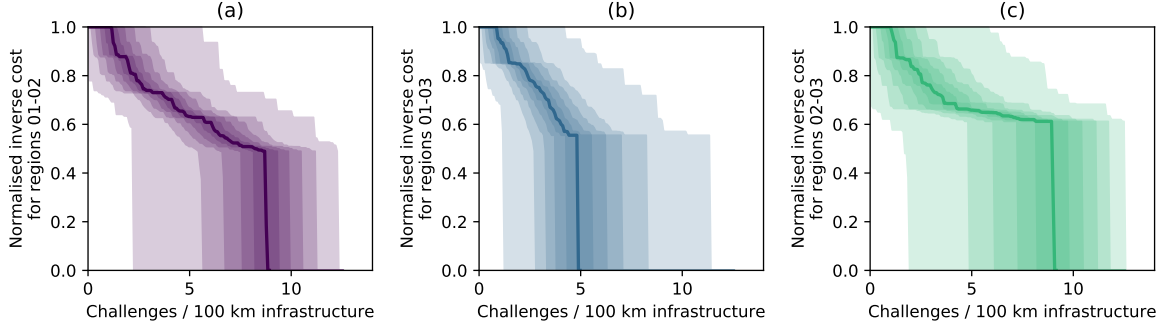


Figure 6.12: Comparison of the normalised inverse cost at number of challenges per 100 km infrastructure for each region pair for 1,000 runs of the random simulation, with a total of 1280 km of infrastructure. The thick line represents the median, while the light to darker shaded areas represent 100%, 80%, 60%, 40%, 20% of the samples respectively.

Furthermore, the cost is normalised with the initial cost $C_{initial}$ (when no challenges have occurred) to compare different region pairs. Equation (6.12) is used to calculate the normalised inverse cost $C_{normalised, inverse}$, inverse from a cost C . The cost C changes as more challenges occur, as can be seen in Figure 6.11. The normalised inverse cost is equal to 1 when no disruptions have occurred and equal to 0 when the region pair is disconnected.

$$C_{normalised, inverse}(C) = \begin{cases} 0, & \text{if } C = \infty \\ C_{initial} \cdot \frac{1}{C}, & \text{otherwise} \end{cases} \quad (6.12)$$

In Figure 6.12, the results for the same simulation (as described at the start of Subsection 6.2.3) is shown using the normalised inverse cost. A similarity between Figure 6.9(c) and the lower part of the graphs in Figure 6.12 can be observed. This is caused by the fact that when a region pair is disconnected the normalised inverse cost is equal to zero. The graphs share a similarity with the robustness envelopes of the R -value shown in Figure 3.3 on Page 20. Using the metrics for the robustness envelopes described in Subsection 3.2.1, the graphs can be analysed. In Table 6.1 the values for the minimum energy ε_{min} (higher is better), average energy ε_{avg} (higher is better) and the sensitivity S (lower is better) are shown.

The values in Table 6.1 are now compared to the results obtained using the disconnection performance metric shown in Figure 6.9(c). The average energy ε_{avg} is higher for the region pairs 01-02 and 02-03 than it is for the region pair 01-03. This corresponds with lower probability of disconnection for the region pairs 01-02 and 02-03. The minimum energy ε_{min} is highest for the region pair 01-02. This corresponds with the low probability of disconnection of this region pair for low number of challenges per 100 km of infrastructure shown in Figure 6.9(c). The sensitivity S is lower for region pairs 01-02 and 01-03 than it is for region pair 02-03. This corresponds with the less steep curve of region pair 02-03 in Figure 6.9(c).

From this comparison it can be seen that this measure is heavily influenced by the disconnections of region pairs. It can therefore be used as a performance metric which incorporates both the disconnection and the cost into one measure. Furthermore, the energies ε_{min} and ε_{avg} and the sensitivity S reflect some of the main characteristics of the probability of disconnection curves in Figure 6.9(c).

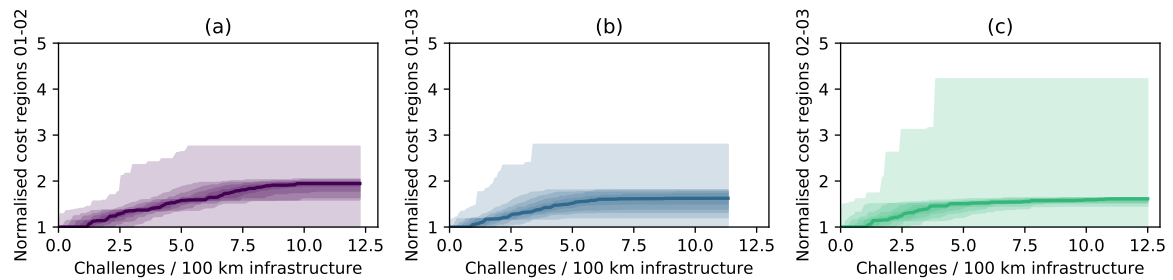


Figure 6.13: Comparison of the normalised padded cost at number of challenges per 100 km infrastructure for each region pair for 1,000 runs of the random simulation, with a total of 1320 km of infrastructure. The thick line represents the median, while the light to darker shaded areas represent 100%, 80%, 60%, 40%, 20% of the samples respectively.

Padded Normalised Cost

For the second method, once a disconnection occurs in a run, the last cost of transport is padded to the result until the maximum number of challenges per 100 km infrastructure is reached. This results in the graphs shown in Figure 6.13. These graphs are still quite similar to those in Figure 6.11. Although the discontinuity seems to be resolved, the validity of padding the last cost of transport is questionable. This method does provide a new insight, not dependent on this validity. For the last (most right) value on the x -axis, the samples show the possible costs when disconnection occurs.

For the region pair 01-02 the normalised cost increases more before disconnection than it does for region pair 02-03, although these region pairs have similar probabilities of disconnection (see Figure 6.9(c)). The region pair 02-03 has a much higher worst-case normalised cost than the other region pairs. A rerun of the simulation confirmed this is not a coincidence. The region pair 02-03 has the lowest variance, the normalised cost before disconnection is very often around 1.5. Based on the normalised cost before disconnection, region pair 02-03 is chosen as most robust. This method thus offers additional information compared to the disconnection performance metric.

Concluding Remarks

From this research on the cost performance metric, several conclusions can be drawn. First, the discontinuity of the cost performance metric when disconnection occurs produces problems for the random simulation of disruptions. Three methods can produce valuable results. The first method sets the cost to ∞ when disconnection occurs and uses the normalised inverse cost, creating a measure that combines both the disconnection and cost performance metric. The second method uses the cost of transport just before disconnection occurs to investigate the robustness. For the third method only the cost performance metric for the numbers of challenges per 100 km infrastructure when no disconnections occur is evaluated. This method is not useful when disconnection can occur after a single challenge. For the random simulation, the cost performance metric should be regarded as an supplementary performance metric to evaluate the robustness.

6.2.4. Generalised Cost Sensitivity

A generalised cost for the transport of cargo is described in Section 5.3. This generalised cost depends on several parameters, which are presented in Table 5.1. The values of the parameters are determined using earlier research, but in earlier research the parameters are seldom the same. It is possible that the parameters used in this research do not match with reality. The sensitivity of the robustness analysis results with regards to these parameters needs to be analysed. This analysis is done using the simulation of random disruptions, as this removal strategy is also used for the case studies.

As the number of input parameters is quite large (see Table 5.1), several scenarios are defined in which the specific input parameters change. Each scenario is analysed for both a small deviation (5%) of the parameters and a large deviation (20%) of the parameters. The scenarios are presented in Table 6.2. The regions variant of the example network is used for the simulations. \bar{G} is used, as the simulation time is significantly longer

Scenario	Parameter changes
benchmark	No changes
a	Increase τ^{Road} and κ^{Road} , decrease v^{OD} , v^{Road} and $v^{Road,mtwy}$
b	Decrease τ^{Road} and κ^{Road} , increase v^{OD} , v^{Road} and $v^{Road,mtwy}$
c	Increase τ^{IWW} and κ^{IWW} , decrease v^{IWW}
d	Decrease τ^{IWW} and κ^{IWW} , increase v^{IWW}
e	Increase τ^{Rail} and κ^{Rail} , decrease v^{Rail}
f	Decrease τ^{Rail} and κ^{Rail} , increase v^{Rail}
g	Increase transshipment cost
h	Decrease transshipment cost

Table 6.2: The scenarios proposed to analyse the cost parameter sensitivity. For each scenario, a small deviation (5%) and a large deviation (20%) of the parameters is researched. The parameters are defined in Table 5.1. Each simulation is run a 1,000 times. The other variables are equal to the values presented in Table 5.1.

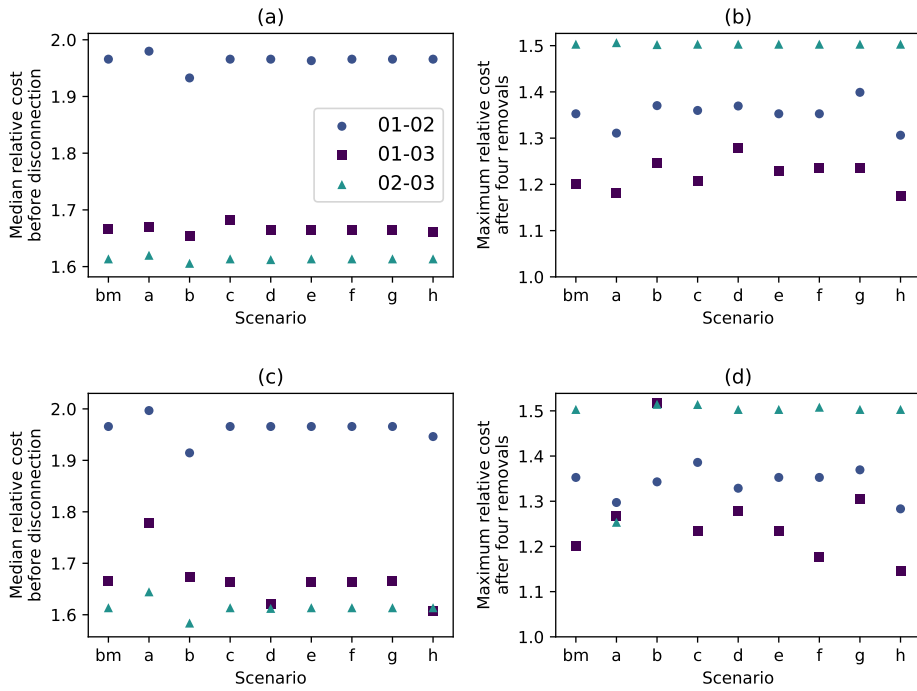


Figure 6.14: Comparison of cost performance metric results (median and maximum) per region pair for different values for the generalised cost parameters. The median relative cost before disconnection (a,c) and the maximum relative cost after four removals (b,d) are used. The effects of small changes (5%) are shown in (a,b) and the effects of large changes (20%) are shown in (c,d). 1,000 simulations are run per scenario.

for G than it is for \tilde{G} . The following elements can be removed:

$$\{\text{Graph Elements}\}_{to\ be\ removed} = \mathcal{L}^{IWW} \cup \mathcal{L}^{Road} \cup \mathcal{L}^{Rail} \quad (6.13)$$

Method U is used for removing graph elements. Interdependence is not used in these simulations. For each scenario, the simulation is run a 1,000 times. The second method (use cost before disconnection) and the third method (use cost before any disconnection) proposed in the previous subsection are used to analyse the results. The link connectivity between regions in the example network is equal to 5, this means at least 5 links need to be removed before disconnection can occur. The results of the cost performance metric after four removals are thus not influenced by the disconnection discontinuity.

The results of the sensitivity analysis for the cost performance metric when using random simulations are shown in Figure 6.14. For small deviations of the generalised cost parameters, the median relative cost just

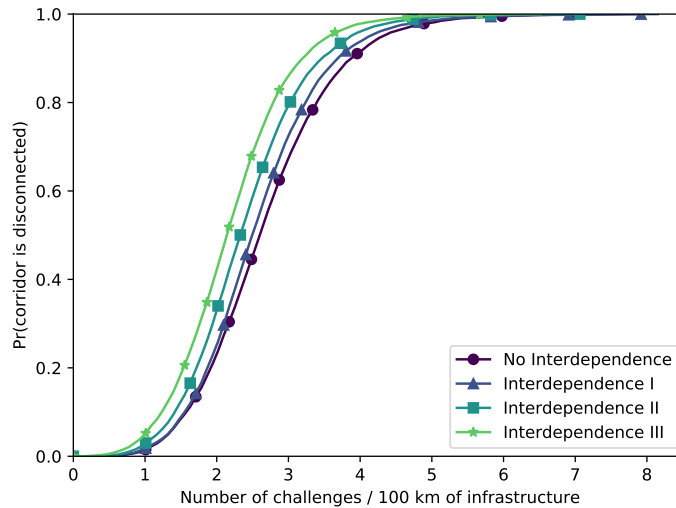


Figure 6.15: Probability that the example corridor (all three modalities and terminals) is disconnected for different degrees of interdependence. For interdependence I movable bridges are considered, for interdependence II all bridges are considered and for interdependence III all bridges and tunnels are considered. The graph has 1288 km of infrastructure. Each simulation is run 10,000 times.

before disconnection occurs does not change significantly. The maximum relative cost after four removals seems to be more sensitive to small deviations. When using this metric, the significance of small differences should be questioned. Both cost performance metrics are sensitive to large deviations of the generalised cost parameters. Although it can be observed that the median relative cost before disconnection is not sensitive to the deviations of several scenarios (see scenario c, e, f and g in Figure 6.14(c)). When the values of the parameters used in this research prove to be very inaccurate, the results of the cost performance metric will no longer be valid. But based on this sensitivity research the results remain valid for small deviations of the generalised cost parameters.

6.2.5. Effect of Interdependence

There is not only interconnection (i.e. container terminals) between the different modes of transport, there is also interdependence. Interdependencies are infrastructure elements whose functioning influences multiple modes of transport. For example, the disruption of a bridge can affect two modalities. In Section 5.2, it is described how the interdependence is represented in the graph model. In this subsection, the effect of the interdependence on the results of the robustness analysis is researched.

Three categories of interdependencies are distinguished in Section 5.2, with decreasing likelihood of a disruption affecting both modalities. Four simulations are run for the analysis in this subsection. The first simulation does not consider interdependence. The second simulation considers interdependencies of the first category (i.e. movable bridges). The third simulation considers interdependencies of both the first and second category (i.e. all bridges). The last simulation considers all interdependencies (i.e. all bridges and tunnels). The simulations that consider some form of interdependence are numbered I, II, III for increasing number of interdependence elements considered.

For these simulations, the corridor variant of the example network is used. All three modalities and the terminal subgraph are included. In these simulations the following graph elements can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{IWW, \text{Road}, \text{Rail}\} \quad (6.14)$$

The random removal strategy with method U is used to select the elements that are removed. Each simulation is run 10,000 times.

The results of the simulations are shown in Figure 6.15. The fraction of graph elements removed cannot be used, as the disruption of an interdependence object results in the removal of multiple nodes. In the Figure it can be seen that the probability of disconnection increases when more interdependence categories are

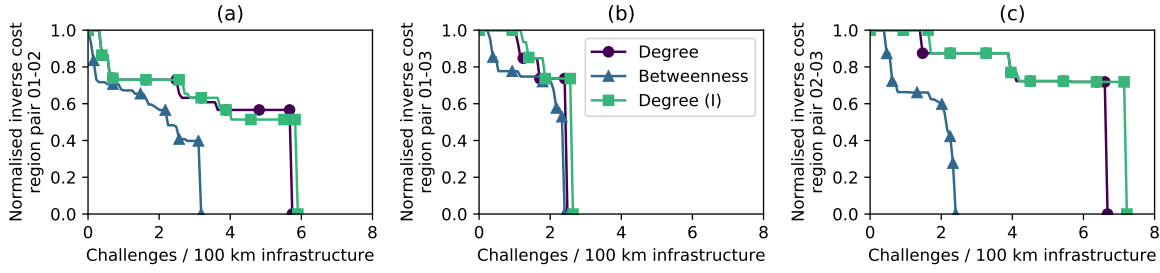


Figure 6.16: The normalised inverse cost for the three region pairs of the example network, under three different targeted attack removal strategies.

considered. Thus interdependence reduces the robustness of the synchromodal network. This is a probable result, as considering interdependence increases the possible impact of a challenge.

For the case studies not all interdependence categories will be considered. The third category consists of structures that are fixed and are only embedded in the infrastructure of one modality (i.e. tunnels). The probability of a disruption affecting both modalities for this third category is therefore very low. Therefore, movable and fixed bridges (interdependence II) are considered for the interdependence in the case studies.

6.3. Targeted Attack Removal Strategies

For the targeted removal strategies, the goal is to degrade the functioning of the synchromodal network as fast as possible [1, 38, 108]. Three attack strategies are considered in this research. Only nodes are removed in these simulations, as removing one of the two nodes connected by the link always has either the same effect or a worse effect. The following elements can be removed for the simulations in this section:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{N}^T \cup \mathcal{N}^m \quad m \in \{\text{IWW, Road, Rail}\} \quad (6.15)$$

The normalised inverse cost is used to show the gradual degradation of the network, this performance metric is described in Subsection 6.2.3. The first targeted attack strategy removes the node with the highest degree for each challenge. When multiple nodes have the same degree, a random node is chosen. The second targeted attack strategy removes the node with the highest betweenness³ for each challenge. And finally, the third targeted attack strategy adds the number of interdependence links connected to the nodes to the degree, and then removes the node with the highest degree for each challenge. For all simulations, the interdependence of bridges is considered. As stated in the previous section, tunnels are not considered.

The results of the targeted attack simulations for the three region pairs in the example network are shown in Figure 6.16. The region pair 01-03 requires the least challenges to be disconnected, while the other two region pairs require a similar amount of challenges. This corresponds with the results for the random removal strategy, shown in Figure 6.12. For the region pairs 01-02 and 02-03 the second targeted attack strategy (betweenness) results in the quickest disconnection, while for the region pairs 01-03 the differences between the targeted attack strategies is minimal.

The results of the targeted attack simulations for the corridor variant of the example network are shown in Figure 6.17(a). The two corridors of the case studies (see Chapter 7) are used as well in this section, so that the results of multiple corridors can be compared. The results for the Rotterdam-Antwerp corridor and the Rotterdam-Duisburg corridor are shown in Figure 6.17(b,c). The Rotterdam-Antwerp corridor requires more challenges to be disconnected than the Rotterdam-Duisburg corridor, this corresponds with the discussion of the results of the case studies (see Subsection 8.2.1). The second targeted attack strategy (betweenness) results in the quickest disconnection for all three corridors. The third targeted attack strategy (degree (I)) disconnects the corridor more quickly than the first targeted attack strategy (degree) for the example network (corridor variant) and for the Rotterdam-Antwerp corridor, while there is no significant difference between these targeted attack strategies for the Rotterdam-Duisburg corridor.

³The node betweenness is a measure specifying the number of shortest paths that pass through the node.

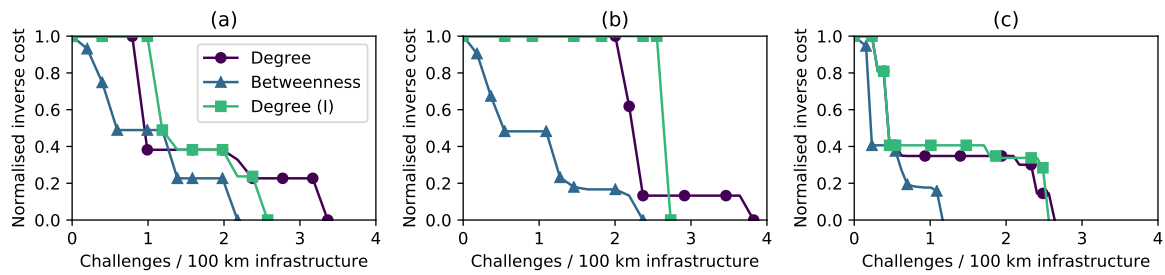


Figure 6.17: The normalised inverse cost for (a) the example network (corridor variant), (b) the Rotterdam-Antwerp corridor and (c) the Rotterdam-Duisburg corridor, under three different targeted attack removal strategies.

The betweenness targeted attack strategy generally leads to the quickest disconnection. A reason for this result is that the degree distribution of a sychromodal network more closely resembles a random network than a scale-free network. The degree targeted attack strategy has similar effects as a random removal strategy on a random network [1]. Furthermore, the performance metric measures the shortest path between the origins and destinations, while the betweenness targeted attack strategy directly attacks these shortest paths. It would be expected that the third targeted attack strategy (degree (I)) leads to a quicker disconnection than the first targeted attack strategy (degree), as interdependence nodes are targeted more. This is only the case for the example network (corridor variant) and the Rotterdam-Antwerp corridor. This result could be interesting for future research.

The targeted attack removal strategy is only briefly studied in this research. It is a useful removal strategy to consider next to the random removal strategy, as the worst case scenario becomes more apparent. Better targeted removal strategies could be devised, as the removal strategies presented here are not optimal (remove least amount of nodes necessary, i.e. the node connectivity). Therefor the targeted attack removal strategy offers a great opportunity for future research.

6.4. Concluding Remarks

The robustness analysis methodology used in this research is presented in this chapter. The aim of this chapter is to answer the second research sub-question, which reads as follows:

3. How can the robustness of the sychromodal network model be analysed and how well does it apply to the robustness of the sychromodal transport infrastructure?

The robustness is analysed by simulating disruptions and investigating the effects on the sychromodal network. Infrastructure elements are selected randomly to be disrupted, until no transport of containers is possible in the network. To investigate the effects, two performance metrics are used: the disconnection performance metric (measures whether origins and destinations are connected) and the cost performance metric (measures the generalised cost of transporting containers).

Both nodes and links represent infrastructure elements in the graph model. When removing both nodes and links in the simulation with a uniform probability of failure (method U) while the amount of nodes per kilometre is not homogeneous, the results can lead to wrong conclusions. This can be solved by only removing links based on their length and removing all graph elements not contributing to the sychromodal network after each challenge (method V). As only links are removed in method V, among other things interdependence cannot be considered when using this method. For the case studies the method U is used in most cases, keeping the disadvantage in mind. Method V is used to check conclusions.

The cost performance metric suffers from a discontinuity when the origin and destination become disconnected. Three methods are proposed to obtain valuable results. The first method sets the cost to ∞ when disconnection occurs and subsequently uses the normalised inverse cost to analyse the results. The second method investigates the last cost of transport before disconnection. For the third method, the cost performance metric is only evaluated for the numbers of challenges when no disconnections can occur. From a sensitivity analysis it is clear that the cost performance metric is not very sensitive to small changes in the

parameters used for the generalised cost.

When more categories of interdependence are considered, the probability of disconnection increases. Considering the interdependence in the synchromodal network reduces the robustness of the network. The probability of a disruption of a tunnel affecting both modalities is very low. Therefore, movable and fixed bridges (interdependence II) are considered as interdependence for the case studies.

The targeted attack removal strategy is briefly discussed. Initial results indicate that removing nodes with the highest betweenness first, degrades the synchromodal network more quickly than removing nodes with the highest degree first. The targeted attack removal strategy is a useful removal strategy to consider next to the random removal strategy, as the worst case scenario becomes more apparent. This is an opportunity for future research.

The results of the robustness analysis methodology proposed in this chapter do not correspond perfectly with the real world. Real world phenomena, their representation in the model and simulation, and the effects on the results are listed in Appendix A. Now that the three research sub-questions are answered, the main research question of this research can be answered using the case studies presented in the next chapter.

7

Case Studies

The case studies of the two corridors and of the whole Netherlands are presented in this chapter. These three case studies are chosen so that the domestic freight transport (whole Netherlands) and most international freight transport (two corridors) are researched. This chapter aims to describe the synchromodal networks of the case studies and to describe the simulations of disruptions that are done. In Chapter 8, the results of the case studies are presented and subsequently discussed. As described in Chapter 1, three case studies are done in this research. Although the corridors are part of the Netherlands, the amount of cargo transported and the direct access at both ends of the corridors justify a more detailed look at these corridors. The graph model described in Chapter 5 and the methodology for the robustness analysis presented in Chapter 6 are used for the case studies.

The chapter is structured as follows. First the synchromodal network used in the case studies is described in Section 7.1. In this section the graphs that are used in the simulations are presented, the cargo demand is described and some general metrics of these graphs are presented. In Section 7.2, the simulations of disruptions that are done are described. The results of the simulations presented in Section 7.2 are shown in Chapter 8.

7.1. Synchromodal Network

The structure of this section is as follows. First, the making of the graph model using the available databases is described in Subsection 7.1.1. Some aspects of the graph model deviate from that presented in Chapter 5. Next the cargo demand in the Netherlands is discussed in Subsection 7.1.2. The graphs of the two corridors that are analysed are presented in Subsection 7.1.3. And finally, the graph of the Netherlands is presented in Subsection 7.1.4.

7.1.1. Transport Network Model

The graph model for the synchromodal network is presented in Chapter 5. This subsection does not aim to repeat that chapter, but instead describes how the graph model is made from the available databases and highlights the deviations from the graph model in Chapter 5.

In Section 4.6, the available databases detailing the infrastructure are presented. In the NWB databases [70–72] the sections and intersections of the three modalities are defined. These databases form the basis for the nodes and links in the synchromodal graph. As described in Chapter 5, not all infrastructure sections are added to the synchromodal graph. Using the VIN [73] database, only waterways with CEMT-class III or higher are added to the graph. Only the national roads are added to the graph model, using information available in the NWB database. Two exceptions to this rule are the Western Scheldt Tunnel to connect region NL341 to the network (see Figure 7.2) and a small section of road to connect two national roads in Zwolle. For the railways, all railways not structurally used for freight transport are not added to the graph model. To determine if a railway is structurally used, an overview of the cargo-paths in the Netherlands [77] is used. Multiple sources

[14, 60, 81] are used to add the container terminals to the graph. These terminals form the interconnection between modalities, i.e. the locations where cargo can change modality.

Not all infrastructure elements required for the graph model are present in the available databases. Unlike for the road (Weggeg [74]) and for the waterway (VIN [73]), there is no additional database for the railway describing the other infrastructure elements. To avoid discrepancies between the different modalities, the infrastructure elements are not solely added for the road and inland waterways. But only two types of infrastructure element are added: locks and structures creating interdependences between modalities. Locks are added, as these infrastructure elements impose a delay on all barges navigating an inland waterway and therefore effect the generalised cost (see Section 5.3). The locks are added to the graph using the VIN database.

The interdependence structures are added to the graph using GIS (Geographic Information System) techniques and manual work. As the sections of the different modalities cross each other at the interdependence structures, the intersection of these sections can be used to define the interdependence nodes on both modalities. Furthermore, using satellite imagery and the databases VIN and Weggeg the interdependence nodes are categorised according to the categories specified in Section 5.2. The categories indicate how likely it is that a disruption of the infrastructure element affects both modalities.

Two variants of the origins and destinations subgraph are described in Subsection 5.1.5. In the regions variant several regions are defined and the traffic demand of each region is represented by a single node (centroid). In the corridor variant two ends of a corridor are defined that are both represented by a single node. The two variants are two methods to study the robustness of a single synchromodal transport network. In the regions variant all cargo transported between the regions in the network is analysed, while in a corridor the analysis is focused on one origin destination pair between which a relatively large amount of cargo is transported. Furthermore, both ends of the corridor have direct access to all three modalities. The two variants are used in conjunction with each other in this research, as both variants complement each other.

Parts of the corridors are located outside the Netherlands, both in Belgium and in Germany. In the used databases, only the infrastructure of the Netherlands is defined. The infrastructure outside the Netherlands is added by hand to the graph model for the corridors, using OpenStreetMap [62]. As the road management governance in Belgium and Germany is different from the Netherlands, instead of the national roads, the motorways are added to the graph model.

7.1.2. Cargo Demand

A model for the transport of cargo in the Netherlands is used by Rijkswaterstaat, called BasGoed [75]. The parameters used in this model are used to determine the generalised cost parameters in Section 5.3. In the model, the amount of containers (in tonnes) transported from, towards and in the Netherlands is specified. This is done using the NUTS (French: *Nomenclature des Unités Territoriales Statistiques*) classification of Europe, for which the economic territories of the European Union are divided into smaller regions for statistical analysis purposes [16]. Three levels of subdivision are defined, BasGoed uses the smallest regions in the Netherlands: NUTS-3. The NUTS-3 regions in the Netherlands are shown in Figure 7.2. A list with the region codes and region names is provided in Appendix E. The first two letters of the NUTS-3 region code indicates

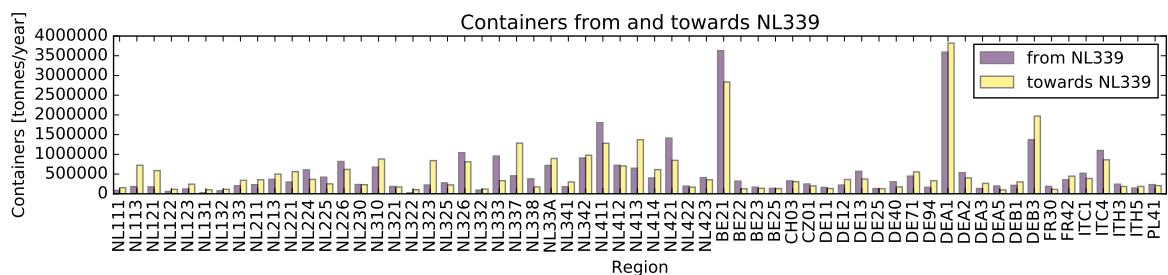


Figure 7.1: The amount of containers (in tonnes per year) transported from and towards NL339 per year (for regions with at least 250,000 tonnes transported from or towards NL339). BE = Belgium, CH = Switzerland, CZ = Czech Republic, DE = Germany, FR = France, IT = Italy, PL = Poland. [75]

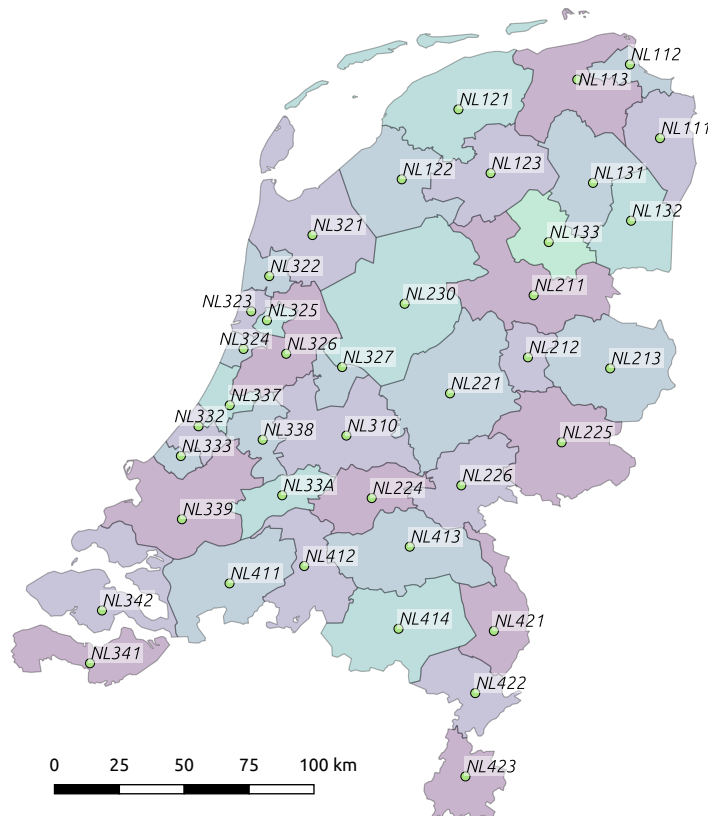


Figure 7.2: Map of the NUTS-3 regions in the Netherlands [16].

the country where the region is located. The last three symbols (usually numbers) indicate the specific region and the level of subdivision, 3 symbols for NUTS-3 regions, 2 symbols for NUTS-2 regions and 1 symbol for NUTS-1 regions.

In Subsection 2.3.1, it is shown that a majority of all cargo transported in the Netherlands is international transport. Almost half of the amount of containers (in tonnes) transported in the Netherlands has an international origin or destination, according to BasGoed. It is thus important to consider international transport in this research. Most (international) cargo is transported from or towards region NL339, in which the Port of Rotterdam is located. The amount of containers transported from and towards NL339 per region is plotted in Figure 7.1, for regions with at least 250,000 tonnes transported from or towards NL339. Two regions stick out in this figure: BE21 and DEA1. In these regions Antwerp and Duisburg are located respectively, which confirms the importance of the Rotterdam-Duisburg and Rotterdam-Antwerp corridor. The demand matrix for the regions variant is shown in Figure 7.3. In this figure the cargo transported inside a single region is also shown, but this cargo is not considered in this research (see Subsection 5.1.5). The cargo demand is bidirectional and usually not the same amount in both directions.

7.1.3. Corridors

Two corridors are researched, the Rotterdam-Antwerp corridor and the Rotterdam-Duisburg corridor. In the corridors the origins and destinations are directly connected to the infrastructure (direct access). Not all the infrastructure of the Netherlands is added to the corridor graphs. Only infrastructure located at less than 50 km from the direct line between both ends of the corridor is added to the graph. Routes outside this area often take a disproportionate amount of time or are located outside the Netherlands, they are therefore not considered. Some exceptions are made when a viable alternative route is otherwise not represented in the graph.

This results in the two synchronodal networks shown in Figures 7.4 and 7.5. Additionally, more detailed

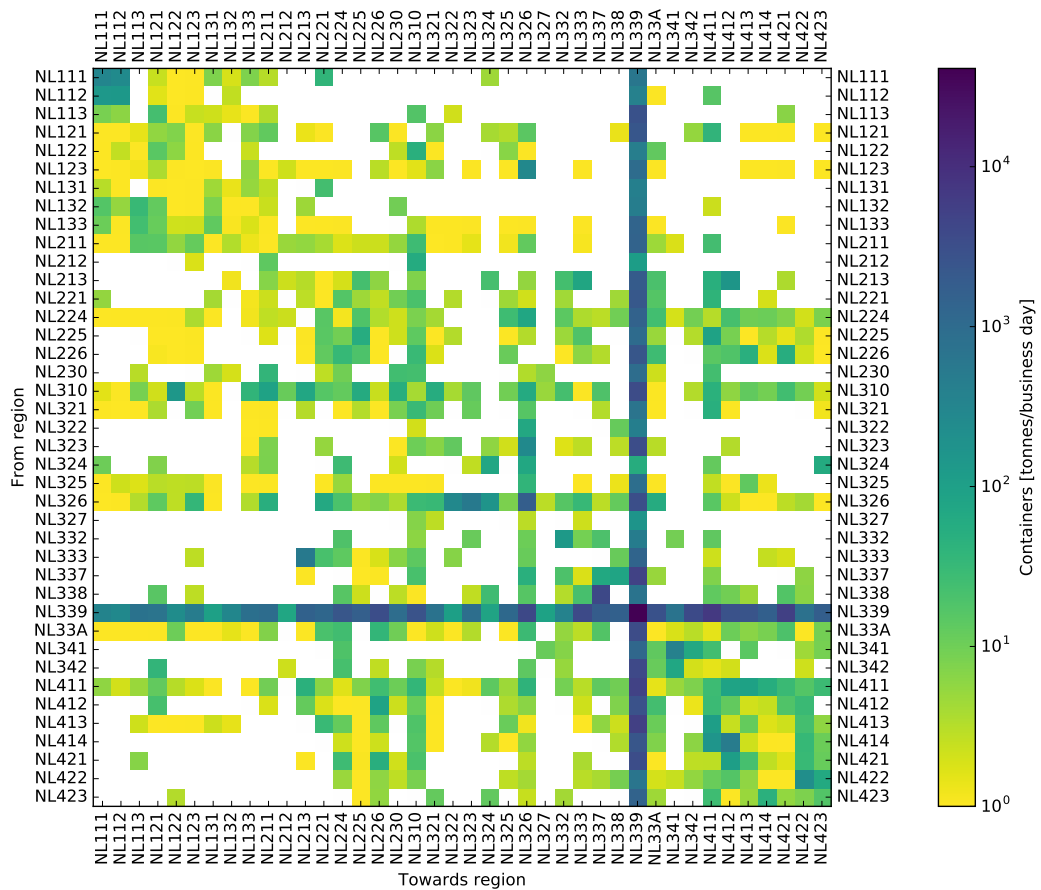


Figure 7.3: The amount of containers (in tonnes per business day) transported from and towards all regions in the Netherlands (domestic transport only). There are 758 region pairs (including duplicates, e.g. $a \rightarrow b$ and $b \rightarrow a$) for which containers are transported, 463 region pairs are unique (no duplicates) [75].

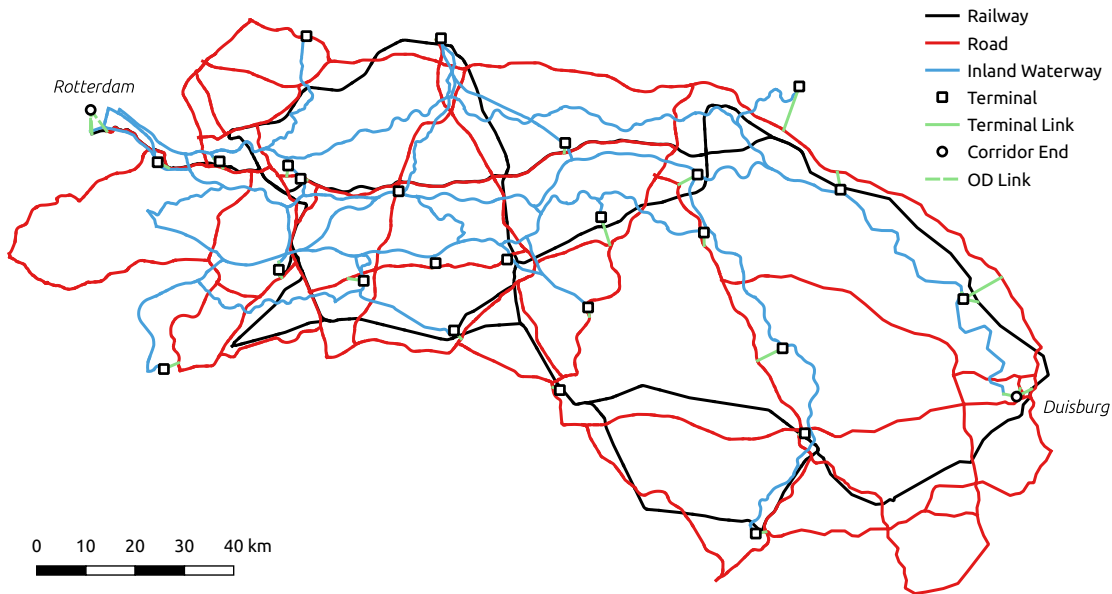


Figure 7.4: Map of the sychromodal network of the Rotterdam-Duisburg corridor.

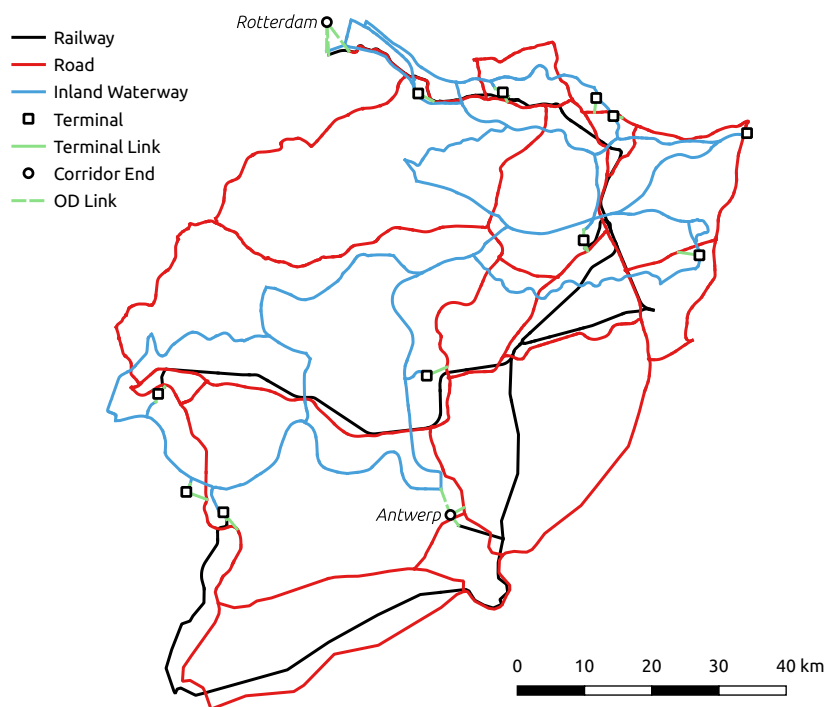


Figure 7.5: Map of the sychromodal network of the Rotterdam-Antwerp corridor.

images of these networks are shown in Appendices B.2 and B.3 (for example showing the interdependence nodes). In Appendix B, some general statistics for the graphs of the two corridors are also presented. There are 11 terminals in the Rotterdam-Antwerp corridor, 7 are waterway terminals and 4 are trimodal (i.e. connect all three modalities). In the Rotterdam-Duisburg corridor there are 25 terminals, 17 are waterway terminals, 1 is a rail terminal and 7 are trimodal.

Number	Abbreviation	Configuration
Wa	G^{OD}, G^{IWW}	
Ro	G^{OD}, G^{Road}	
Ra	G^{OD}, G^{Rail}	
WaRo	$G^{OD}, G^{IWW}, G^{Road}$	
WaRa	$G^{OD}, G^{IWW}, G^{Rail}$	
RoRa	$G^{OD}, G^{Road}, G^{Rail}$	
WaRoT	$G^{OD}, G^{IWW}, G^{Road}, G^T$	
WaRaT	$G^{OD}, G^{IWW}, G^{Rail}, G^T$	
RoRaT	$G^{OD}, G^{Road}, G^{Rail}, G^T$	
WaRoRa	$G^{OD}, G^{IWW}, G^{Road}, G^{Rail}$	
WaRoRaT	$G^{OD}, G^{IWW}, G^{Road}, G^{Rail}, G^T$	

Table 7.1: The eleven possible configurations of the synchronomodal graph model and their abbreviations that can be researched for the corridor variant.

Synchronomodal Graph Configurations

To put the results of the robustness analysis for the synchronomodal network into perspective, the results can be compared to the results for parts of the synchronomodal network. Parts of the synchronomodal network can be analysed by removing one or more of the subgraphs or parts of the subgraphs presented in the previous chapter. This can also be used to study the effects of adding a modality for the robustness of the network. The origins and destinations subgraph G^{OD} cannot be removed, as no cargo could then be transported in the network.

In total there are eleven configurations of the synchronomodal graph model that can be researched for the corridor variant: the three modalities individually, the three combinations of two modalities together, the three combinations of two modalities together with terminals, the three modalities combined and the three modalities together with the terminals. An overview of these configurations and the abbreviations used for these configurations in this research are shown in Table 7.1. Wa is the abbreviation for the waterway, Ro is the abbreviation for the road and Ra is the abbreviation for the railway.

7.1.4. The Netherlands

The third case study uses the region variant to analyse the synchronomodal network of the Netherlands. For this case study 40 regions are defined in the Netherlands. The regions and the amount of containers (in tonnes) transported between the regions are shown in Figure 7.3. An overview of the network used is shown in Figure 7.6. Additional images of the network are shown in Appendix B.4 (for example showing the interdependence nodes). Some statistics are also presented in Appendix B. There are 44 container terminals in the Netherlands, 29 are waterway terminals, 2 are rail terminals and 13 are trimodal terminals.

For the Netherlands, the robustness between 463 unique region pairs is analysed. Such a high number of region pairs requires a simplification of the results, so that the results can still be interpreted. Therefore the sample means of the results are used, e.g. the mean fraction of graph elements required to disconnect the origin and destination. Welch's t-test [111] is used to test if two sample means are significantly different.

Synchronomodal Graph Configurations

Parts of the synchronomodal network of the Netherlands can be researched, similar to the two corridors. For the regions variant of the origin and destination subgraph, the road subgraph G^{road} cannot be removed as this is the modality the origins and destinations are connected to. The terminal subgraph G^T cannot be removed when either the waterway subgraph G^{IWW} or rail subgraph G^{rail} are present, as there is no direct access for the regions variant. This results in four possible configurations of the synchronomodal graph model that can be researched: the complete synchronomodal graph, the graph without the modality rail, the graph without

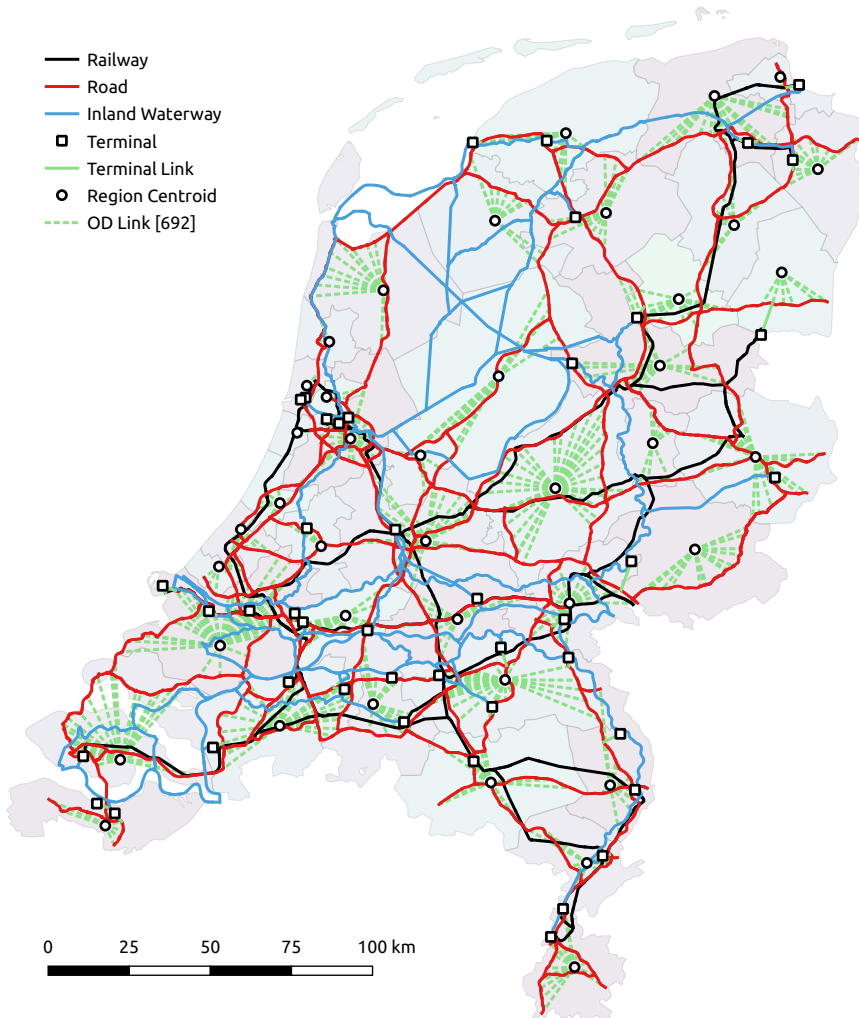


Figure 7.6: Map of the synchromodal network of the Netherlands (regions variant).

Abbreviation	Configuration
Ro	G^{OD}, G^{Road}
WaRoT	$G^{OD}, G^{IWW}, G^{Road}, G^T$
RoRaT	$G^{OD}, G^{Road}, G^{Rail}, G^T$
WaRoRaT	$G^{OD}, G^{IWW}, G^{Road}, G^{Rail}, G^T$

Table 7.2: The four possible configurations of the synchromodal graph model and their abbreviations that can be researched for the Netherlands (regions variant).

the modality waterway and the graph without the modalities rail and waterway. These configurations and their corresponding abbreviations are shown in Table 7.2. Wa is the abbreviation for the waterway, Ro is the abbreviation for the road and Ra is the abbreviation for the railway.

7.2. Simulations

The simulation methodology presented in Chapter 6 is applied to the three case studies done in this research. In this section, all the simulations of the case studies are described. There are three case studies with in total 26 configurations (2 corridors with 11 configuration each and 1 regions variant with 4 configurations). For each configuration the simulations are run. The shortest path all-or-nothing traffic assignment algorithm is used for each simulation. Therefor both the disconnection performance metric and the cost performance metric can be used to analyse the effects of disruptions.

7.2.1. Random Disruptions - Method U

The random removal strategy, extensively discussed in the previous chapter, is used to evaluate the robustness of the synchromodal networks of the case studies. The following elements can be removed in the random removal simulations using method U (uniform probability of failure):

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{N}^T \cup \mathcal{L}^T \cup \mathcal{N}^m \cup \mathcal{L}^m \quad m \in \{IWW, Road, Rail\} \quad (7.1)$$

Not all these elements are present in each configuration, when elements are not present they are not added to the set of graph elements that can be removed. When removing a graph element, it is selected using a uniform distribution. Interdependence is considered for all configurations with at least two modalities. The movable bridges and fixed bridges are used as interdependence points (interdependence II). Tunnels are not considered as an interdependence point, as the probability of a disruption of a tunnel affecting both modalities is very low (see Subsection 6.2.5). For each configuration of the case studies, the simulation is run a 1,000 times.

7.2.2. Random Disruptions - Method V

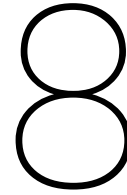
For this simulation, the following graph elements can be removed:

$$\{\text{Graph Elements}\}_{\text{to be removed}} = \mathcal{L}^m \quad m \in \{IWW, Road, Rail\} \quad (7.2)$$

Method V is used for removing graph elements. The link is chosen using the length d_l of the link as a probability distribution. The probability of a link l from the set $\{\text{Graph Elements}\}_{\text{to be removed}}$ being removed is equal to:

$$\Pr(l \text{ removed}) = \frac{d_l}{\sum_{\text{link} \in \{\text{Graph Elements}\}_{\text{to be removed}}} d_{\text{link}}} \quad (7.3)$$

Furthermore, after each removal all links not contributing to the functioning of the synchromodal network (i.e. dead ends) are removed to avoid any influence of the number of graph elements. Interdependence is not used in this simulation. For each configuration of the case studies, the simulation is run a 1,000 times. For this many runs, the results do not change significantly between simulations. The results of this simulation are used to check conclusions of the simulations using method U.



Results and Discussion of the Case Studies

In this Chapter the results of the three case studies are presented. The three case studies are: the Rotterdam-Antwerp corridor, the Rotterdam-Duisburg corridor and the Netherlands (regions variant). The case studies are described in detail in Chapter 7. The Chapter is structured as follows. First the results are presented in Section 8.1. These results are presented per case study. Subsequently, these results are discussed in Section 8.2. This discussion is split into three parts: the corridors, the Netherlands and the validity of the results.

8.1. Results

8.1.1. The Rotterdam-Antwerp Corridor

In Figures 8.1 and 8.2, the results using the disconnection performance metric are shown for the random removal of graph elements using method U (uniform probability of failure). The different configurations (Table 7.1) are ordered by the number of modalities, whether terminals are present and subsequently by the mean values of the results in Figure 8.1. The order of the configurations in Figure 8.2 is chosen to be the same as the order in Figure 8.1, to make a straightforward comparison possible. According to Welch's t -test [111], not all the means are significantly different. For the fraction of graph elements removed, the following configurations do not have a significantly different mean: Ro and WaRaT; WaRo and RoRaT. For the number of challenges per 100 km of infrastructure when disconnected, the following configurations do not have a significantly different mean: Ro, WaRa and RoRa; WaRo, WaRaT, RoRaT and WaRoRa; WaRoT and WaRoRaT. See Table 7.1 for the meaning of these abbreviations of the configurations.

In Figure 8.3, the results using the disconnection performance metric are shown for the random removal of graph elements using method V (length of link based probability of failure). The order of the configurations in Figures 8.4 and 8.5 is chosen to be the same as the order in Figure 8.1. The following configurations do not have a significantly different mean: Ro, Rora; WaRo, WaRoRa.

The results using the cost performance metric for all random disruptions simulations are shown in Appendix C. The Figures C.1 to C.6 show the results using the cost performance metric for both method U and method V.

8.1.2. The Rotterdam-Duisburg Corridor

The results of the disconnection performance metric are shown for the random removal of graph elements using method U (uniform probability of failure) in Figures 8.4 and 8.5. The order of the configurations in Figures 8.4 and 8.5 is chosen to be the same as the order in Figure 8.1, to make a straightforward comparison possible. For the fraction of graph elements removed, the following configurations do not have a significantly different mean: Ro, WaRa; RoRa, WaRo. The following configurations do not have a significantly different mean for the number of challenges per 100 km of infrastructure: Wa, WaRa, WaRo, WaRoRa; Ro, RoRa; WaRo, RoRaT; WaRoT, WaRoRaT.

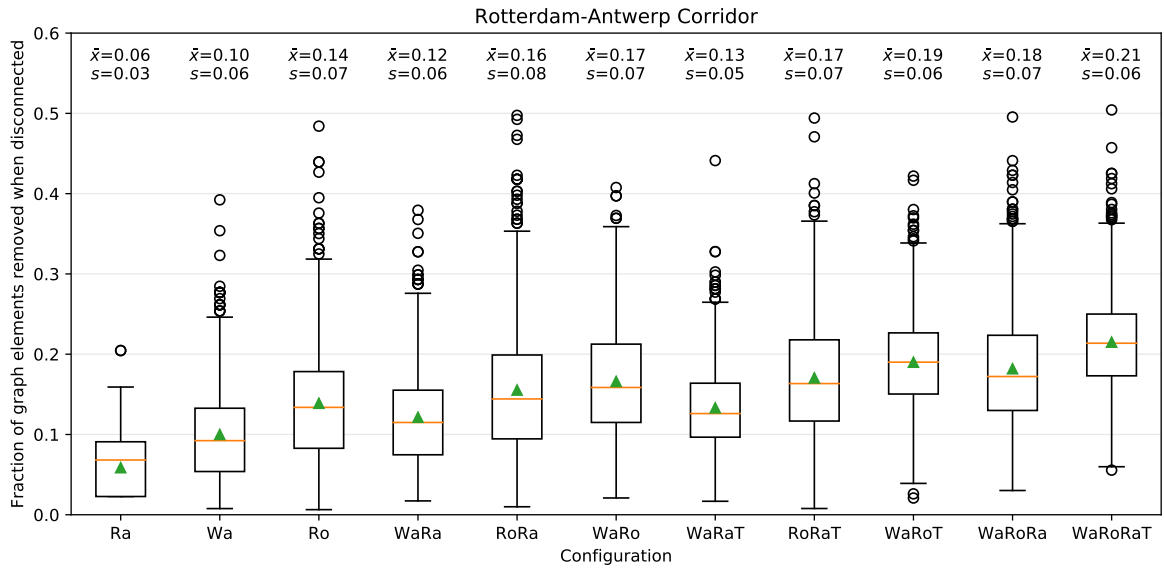


Figure 8.1: The fraction of graph elements removed at which disconnection occurs for the eleven configurations of the Rotterdam-Antwerp corridor. Using method U for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

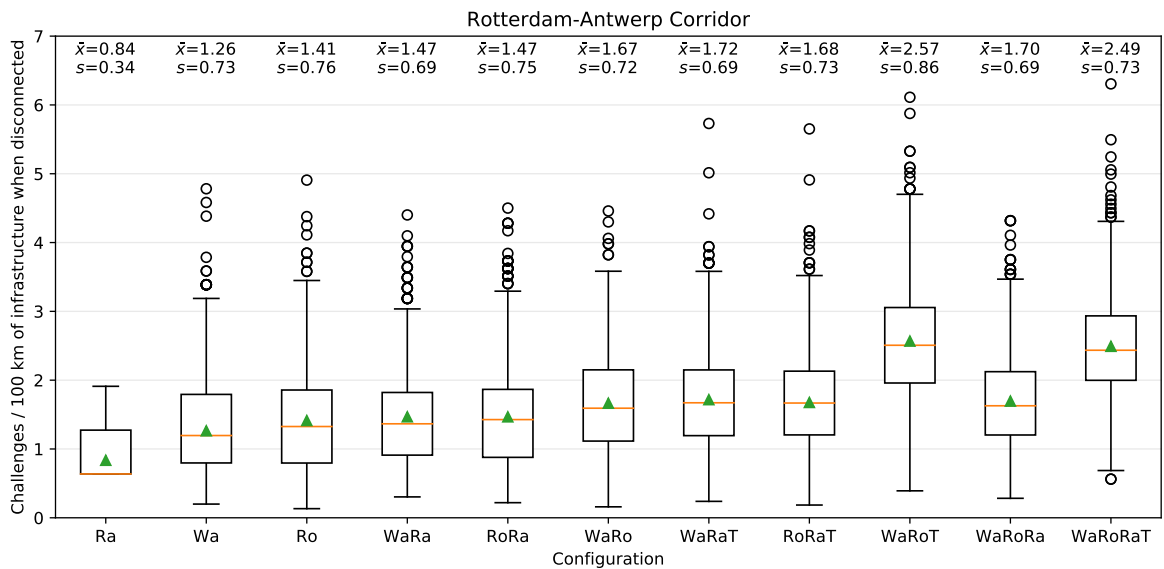


Figure 8.2: The number of challenges per 100 km of infrastructure at which disconnection occurs for the eleven configurations of the Rotterdam-Antwerp corridor. Using method U for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

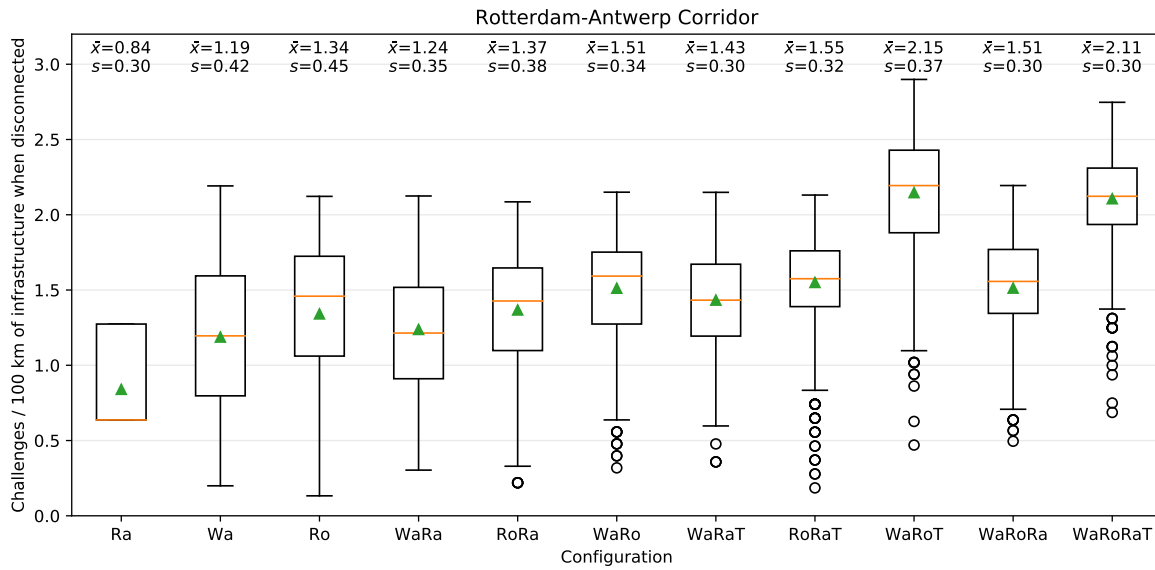


Figure 8.3: The number of challenges per 100 km of infrastructure at which disconnection occurs for the eleven configurations of the Rotterdam-Antwerp corridor. Using method V for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

In Figure 8.6, the results using the disconnection performance metric are shown for the random removal of graph elements using method V (length of link based probability of failure). The order of the configurations in Figure 8.6 is chosen to be the same as the order in Figure 8.1. The following configurations do not have a significantly different mean: Ro, Rora; WaRo, WaRoRa.

The results using the cost performance metric for all random disruptions simulations are shown in Appendix C. The Figures C.7 to C.12 show the results using the cost performance metric for both method U and method V.

8.1.3. The Netherlands

The results of the disconnection performance metric for the configuration WaRoRaT are shown for the random removal of graph elements using method U (uniform probability of failure) in Figures 8.7 to 8.12. Only the results using the mean number challenges per 100 km of infrastructure are shown. Because the mean fraction of graph elements removed for each region pair correlates heavily with the mean number of challenges per 100 km of infrastructure for each region pair ($\rho = 0.9995$), the mean fraction of graph elements is not shown. First, the mean number of challenges per 100 km of infrastructure at which disconnection occurs for each of the active (containers transported) region pairs in the Netherlands is shown in Figure 8.7. Next, some correlation plots are shown in Figures 8.9 to 8.11. Finally, the results are visualised in a new way in Figure 8.12. Showing the probability that more than n region pairs are disconnected.

In Figures 8.13 to 8.15, the results of the four configurations are shown. The probability that more than n region pairs are disconnected is shown for the configurations Ro, RoRaT, WaRoT and WaRoRaT. Using the fraction of graph elements removed (Figure 8.13), the number of challenges (Figure 8.14) and the number of challenges per 100 km of infrastructure (Figure 8.15).

A figure showing the results of the cost performance metric for the configuration WaRoRaT for the random removal of graph elements using method U is shown in Figure C.13. This figure shows the weighed average (using amount of cargo transported) of the normalised inverse cost for all region pairs. The results of the disconnection performance metric for the configuration WaRoRaT are shown for the random removal of graph elements using method V (length of link based probability of failure) in Appendix C. The results in the Figures C.14 to C.17 are not discussed in this thesis, as the results of method V correlate with those of method U. The mean number of challenges per 100 km of infrastructure for method U has a correlation coefficient $\rho = 0.919$ with the mean number of challenges per 100 km of infrastructure for method V.

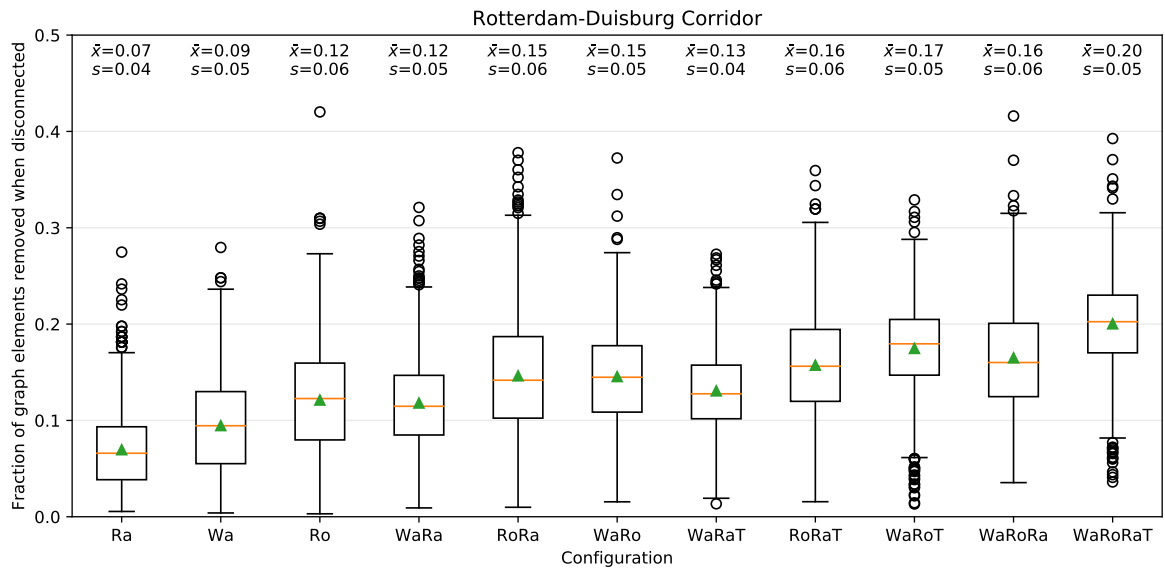


Figure 8.4: The number of challenges at which disconnection occurs for the eleven configurations of the Rotterdam-Duisburg corridor. Using method U for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

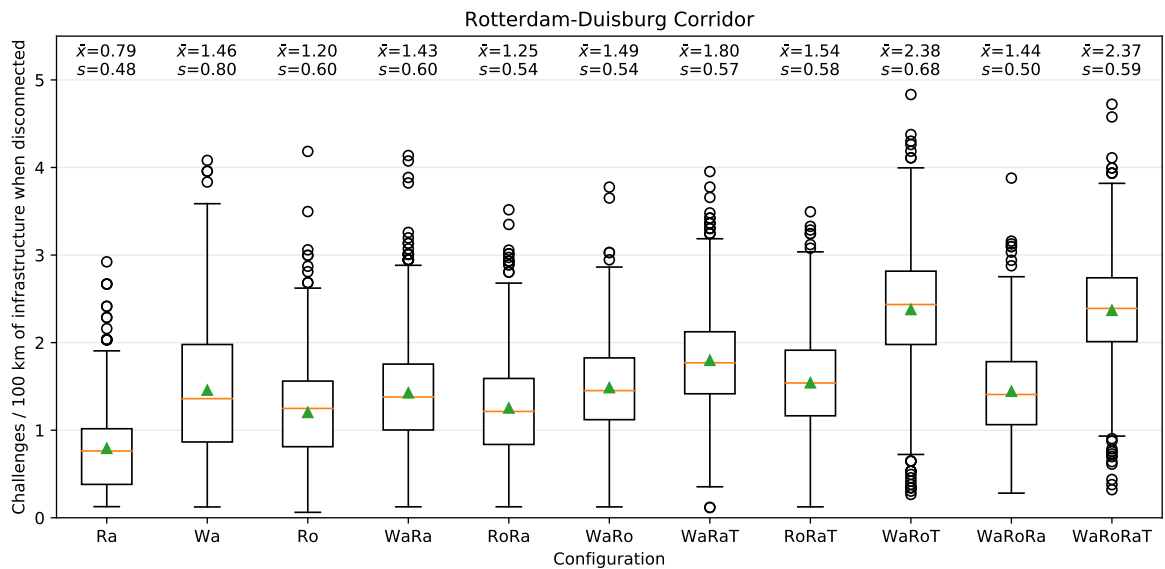


Figure 8.5: The number of challenges per 100 km of infrastructure at which disconnection occurs for the eleven configurations of the Rotterdam-Duisburg corridor. Using method U for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

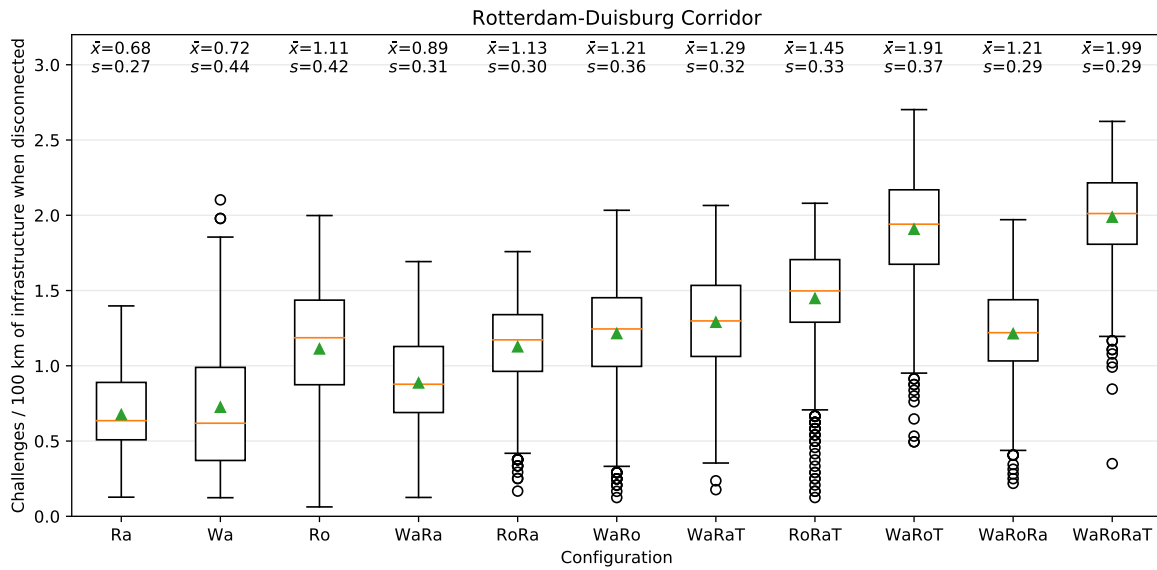


Figure 8.6: The number of challenges per 100 km of infrastructure at which disconnection occurs for the eleven configurations of the Rotterdam-Duisburg corridor. Using method V for removing graph elements. For each configuration the simulation is run a 1,000 times. The green triangle represents the mean of the samples and the orange line represents the median of the samples.

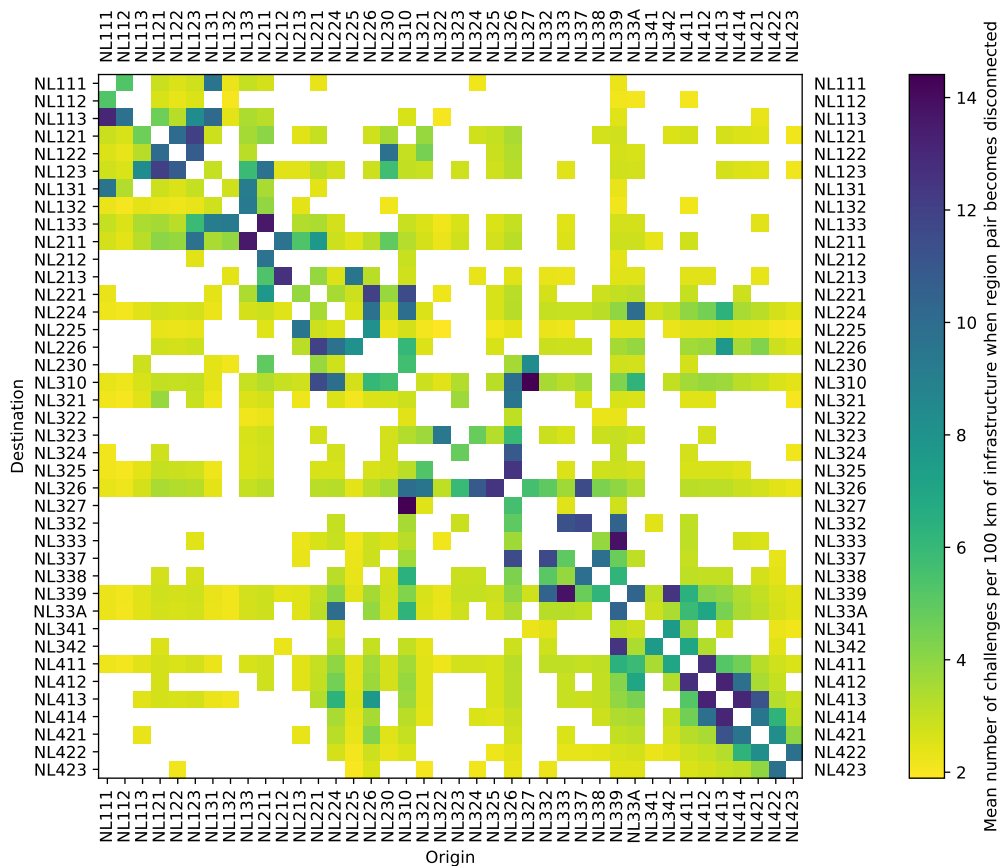


Figure 8.7: The mean number of challenges per 100 km of infrastructure at which disconnection occurs for each of the active (with containers transported) region pairs in the Netherlands (configuration WaRoRaT), using method U. The simulation is run a 1,000 times for a graph consisting of 6652 km of infrastructure.

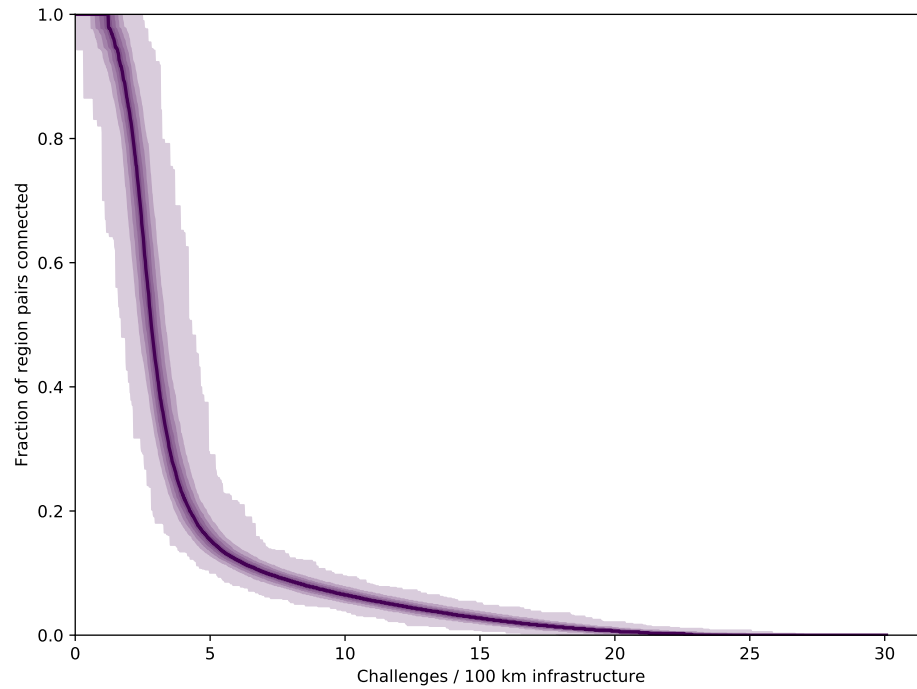


Figure 8.8: The fraction of region pairs connected in the Netherlands for the number of challenges per 100 km of infrastructure (configuration WaRoRaT), using method U. The simulation is run a 1,000 times for a graph consisting of 6652 km of infrastructure and 758 region pairs. The thick line represents the median, while the light to darker shaded areas represent 100%, 80%, 60%, 40%, 20% of the samples respectively.

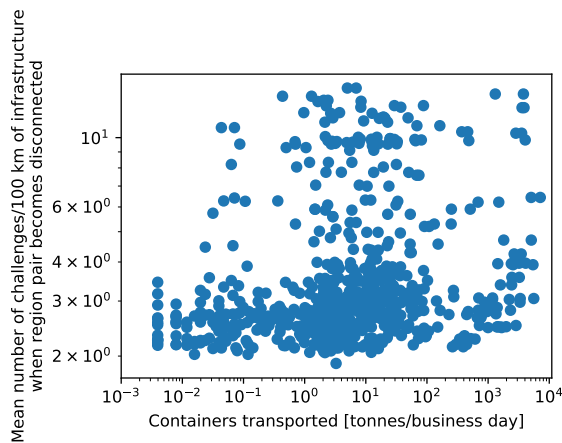


Figure 8.9: Correlation plot of the amount of containers (in tonnes/business day, logarithmic) transported between each active region pair versus the mean number of challenges per 100 km of infrastructure (logarithmic) at which disconnection occurs, using method U. The simulation is run a 1,000 times for the configuration WaRoRaT, correlation coefficient $\rho = 0.219$ (logarithmic).

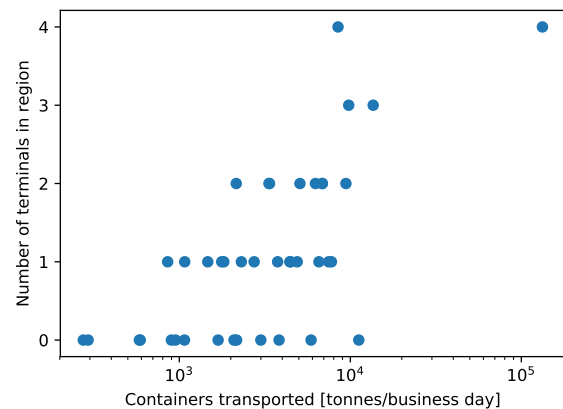


Figure 8.10: Correlation plot of the amount of containers (in tonnes/business day, logarithmic) transported between each active region pair versus the number of terminals in a region. The amount of containers is the total amount transported from and towards the region. The correlation coefficient $\rho = 0.507$.

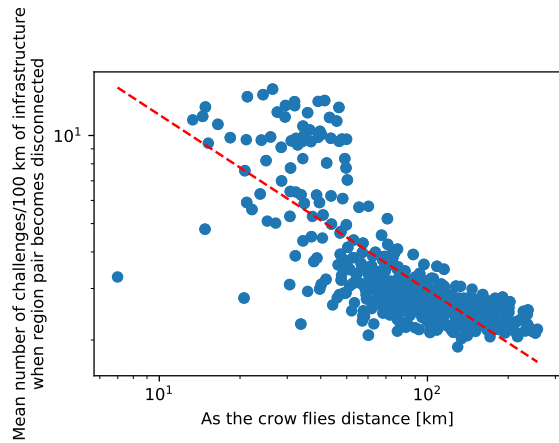


Figure 8.11: Correlation plot of the as the crow flies distance (logarithmic) between two each active region pair's centroids versus the mean number of challenges per 100 km of infrastructure (logarithmic) at which disconnection occurs, using method U. The simulation is run a 1,000 times for the configuration WaRoRaT, correlation coefficient $\rho = -0.770$ (logarithmic).

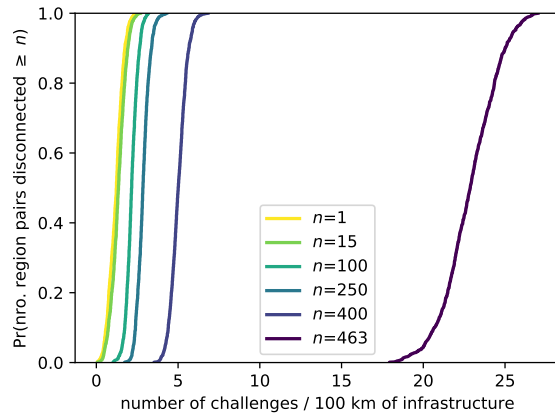


Figure 8.12: The probability that at least n number of region pairs are disconnected for the number of challenges per 100 km of infrastructure for the Netherlands (WaRoRaT), using method U. As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times for a graph consisting of 6782 km of infrastructure.

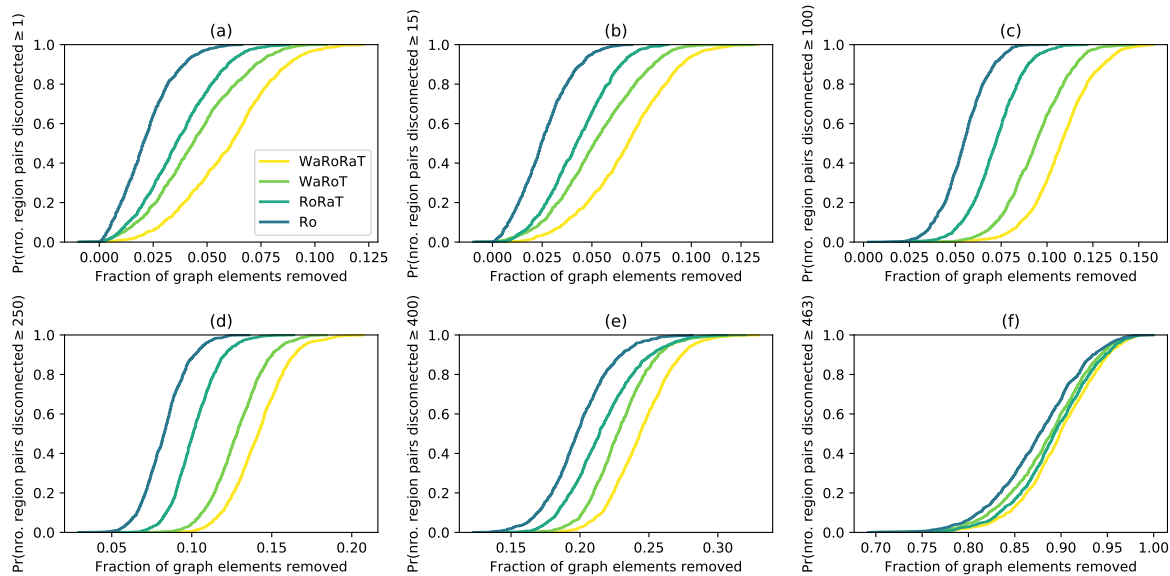


Figure 8.13: The probability that at least n number of region pairs are disconnected for the fraction of graph elements removed for the four configurations of the Netherlands graph (WaRoRaT, WaRoT, RoRaT, Ro). As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times. (a) at least 1 region pair, (b) at least 15 region pairs, (c) at least 100 region pairs, (d) at least 250 region pairs, (e) at least 400 region pairs and (f) 463 (which are all) region pairs.

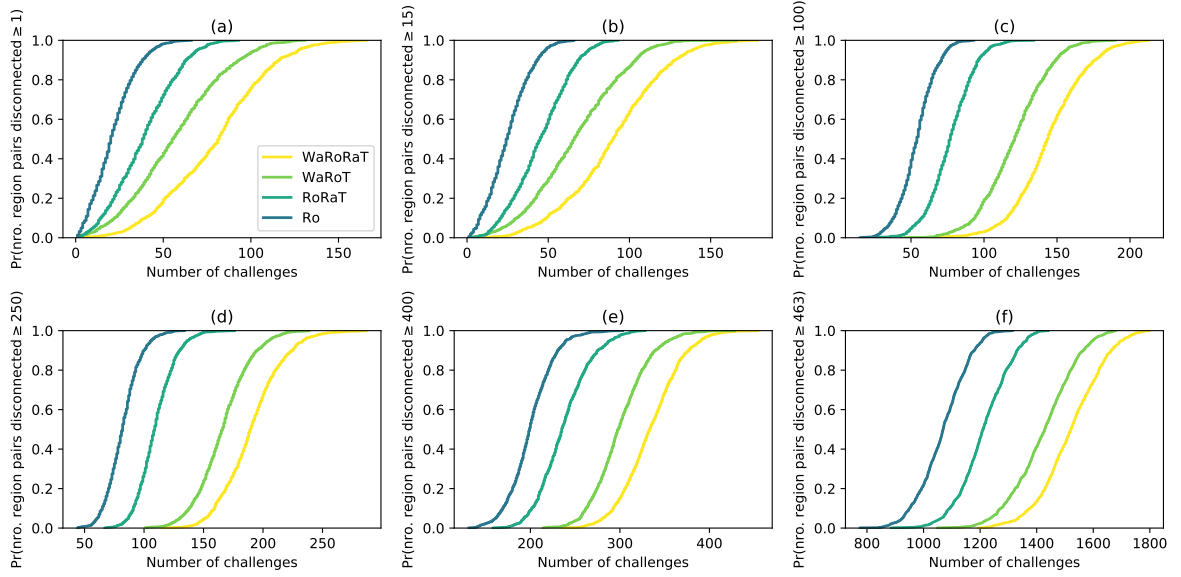


Figure 8.14: The probability that at least n number of region pairs are disconnected for the number of challenges for the four configurations of the Netherlands graph (WaRoRaT, WaRoT, RoRaT, Ro). As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times. (a) at least 1 region pair, (b) at least 15 region pairs, (c) at least 100 region pairs, (d) at least 250 region pairs, (e) at least 400 region pairs and (f) 463 (which are all) region pairs.

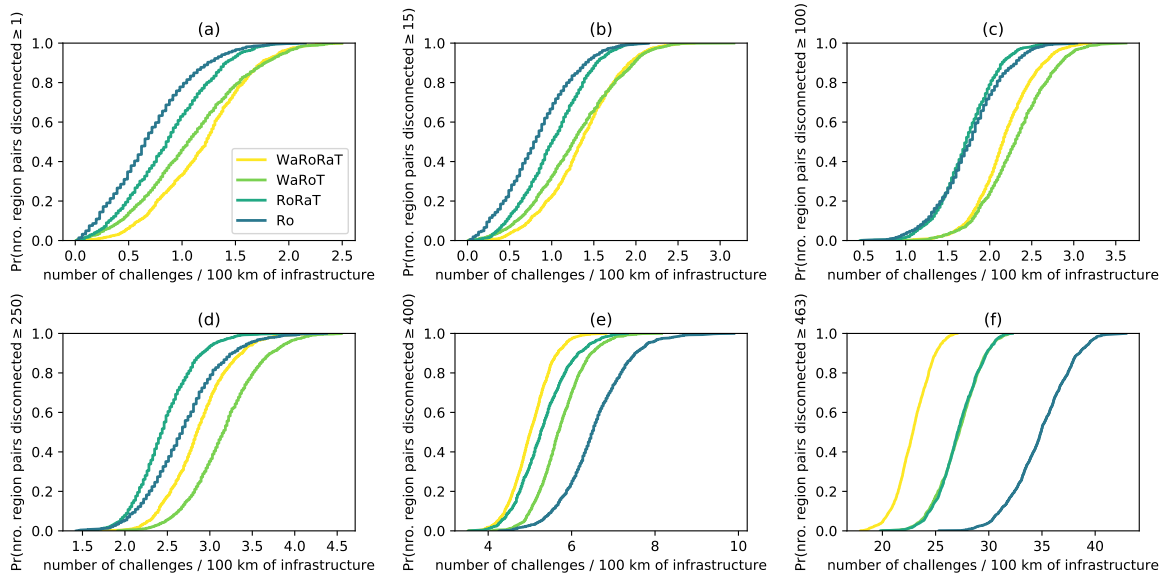


Figure 8.15: The probability that at least n number of region pairs are disconnected for the number of challenges per 100 km of infrastructure for the four configurations of the Netherlands graph (WaRoRaT, WaRoT, RoRaT, Ro). As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times for graphs consisting of 6782 km (WaRoRaT), 5377 km (WaRoT), 4599 km (RoRaT) and 3193 km (Ro) of infrastructure. (a) at least 1 region pair, (b) at least 15 region pairs, (c) at least 100 region pairs, (d) at least 250 region pairs, (e) at least 400 region pairs and (f) 463 (which are all) region pairs.

8.2. Discussion

The results shown in the previous section are discussed in this section. First, both corridors are discussed. The results of both corridors can be compared, as the same graph model is used. First the disconnection performance metric is discussed, after which the cost performance metric is briefly discussed. The Netherlands (regions variant) is discussed separately. The graph model for the regions variant is different from the corridor variant, preventing a straightforward comparison of the results.

8.2.1. The Corridors - Disconnection Performance Metric

The results can be seen in Figures 8.1 to 8.6. When considering individual modalities, almost all the results show that the road is the most robust modality, the inland waterway is less robust and the railway is the least robust modality. An exception is the result for the uniform probability of failure using the number of challenges per 100 km of infrastructure for the Rotterdam-Duisburg corridor (Figure 8.5). This result shows the inland waterway graph being more robust than the road graph. The contradicting results of Figures 8.4 and 8.5 suggests that the number of nodes per kilometre is not sufficiently homogeneous (see Subsection 6.2.1). When comparing the number of nodes per kilometre (see Tables B.2 and B.3), it is indeed less homogeneous for the Rotterdam-Duisburg corridor than it is for the Rotterdam-Antwerp corridor. Therefore caution is advised for evaluating the Rotterdam-Duisburg results of the random disruptions with uniform probability of failure.

These differences between the modalities have an effect on the other configurations. For example when comparing the configurations WaRoT and WaRoRaT for both corridors. In Figures 8.1, 8.4 and 8.6 the configuration WaRoRaT is slightly more robust, in Figures 8.2 and 8.5 the configurations do not differ significantly and in Figure 8.3 the configuration WaRoRaT is even less robust than the configuration WaRoT. When considering these results, it cannot be concluded that the rail modality has an added value for the robustness of the synchmodal freight transport network. One important remark should be taken into account when interpreting this conclusion, which is that only the disconnection is considered. The possible cost benefit and capacity benefit of having the rail modality is not considered.

Interconnection and Interdependence

From the results the large benefit of terminals for the robustness becomes clear. For all the results, each configuration with terminals has a higher robustness than the corresponding configuration without terminals (e.g. configuration WaRoT is more robust than configuration WaRo). The terminals, which form the interconnection in the graph model, create many more alternative paths in the network. This has a very positive effect on the robustness.

In Subsection 6.2.5, it is shown that interdependence has a negative effect on the robustness. Figures 8.1 and 8.2 are used to analyse whether this negative effect mitigates the positive effect of new modalities (i.e. new alternative paths). The Rotterdam-Duisburg corridor is not used for this analysis, as the number of nodes per kilometre is not sufficiently homogeneous. For the fraction of graph elements removed when disconnected, the positive effect of adding a modality is stronger than the negative effect of the added interdependence. For the number of challenges per 100 km of infrastructure this is not always the case. The configurations Ro and RoRa and the configurations WaRo and WaRoRa do not have significantly different means. When considering the worst case (lowest number of challenges per 100 km of infrastructure when disconnected), an increase can be observed for these configurations as well. Therefore, the benefits of adding a modality outweigh the harms according to these results. When considering both the interconnection and interdependence (e.g. configurations Ro and RoRaT), it is clear that option to change modality during transit outweigh the disadvantages of the interdependence.

Two Corridors Compared

To compare the two corridors, Figures 8.3 and 8.6 are used. For each configuration the Rotterdam-Antwerp corridor has a higher robustness than the Rotterdam-Duisburg corridor. It should be noted that the number of challenges per 100 km of infrastructure is used and that the Rotterdam-Duisburg corridor has significantly

more infrastructure than the Rotterdam-Antwerp corridor. When considering the absolute number of challenges when disconnected, the Rotterdam-Duisburg corridor scores better than the Rotterdam-Antwerp corridor. The Rotterdam-Duisburg corridor not only has significantly more infrastructure, the as the crow flies distance¹ between the corridor ends (197 km) is also larger compared to the Rotterdam-Antwerp corridor (76 km). When taking this distance into account, it could be concluded that the corridor Rotterdam-Duisburg is more robust. It could be interesting to research this further, this is discussed in Section 9.2.

8.2.2. The Corridors - Cost Performance Metric

The results for the corridors using the cost performance metric are shown in Appendix C. The method using the cost performance metric for the numbers of challenges per 100 km infrastructure when no disconnections occur is not used. For the corridor, disconnection can occur after 1, 2 or 3 challenges (depending on the number of modalities in the configuration). The results using the cost performance metric are not thoroughly discussed in this thesis. However, some quick observations are written here and are briefly discussed.

For the disconnection performance metric, it is discussed that the terminals have a large positive effect on the robustness. When considering the cost performance metric (normalised cost when disconnected), it becomes clear that this positive effect has a price. When no challenges have occurred, the shortest path never crosses a terminal due to the high cost. But when challenges have occurred, terminals are often used. This shows in the normalised cost when disconnected (see Figures C.3, C.6, C.9 and C.12) for configurations with terminals, which is generally higher than the normalised cost when disconnected for configurations without terminals.

It cannot be concluded whether the rail modality has an added value for the robustness of the synchromodal freight transport network, based on the disconnection performance metric. But when considering the cost performance metric, it becomes clear that the rail modality does have an added value by providing a relatively cheap alternative. To illustrate this the configurations WaRo and WaRoRa are compared in Figures C.3, C.6, C.9 and C.12. For the average normalised cost when disconnected, the configuration WaRoRa outperforms the configuration WaRo in each simulation.

8.2.3. The Netherlands

The disconnection performance metric results of method U using the number of challenges per 100 km of infrastructure can be seen in Figures 8.7 to 8.12, 8.14 and 8.15. The mean number of challenges per 100 km of infrastructure when each active (containers transported) region pair becomes disconnected is shown in Figure 8.7. Many region pairs have a comparable robustness compared to the corridors, with means of around 2.5 challenges per 100 km of infrastructure. A considerable amount of the region pairs has a significantly higher robustness according to the disconnection performance metric.

Figure 8.7 is not straightforward to read or compare to possible future case studies. Therefore, another visualisation is shown in Figure 8.8. The fraction of region pairs that are connected for the number of challenges per 100 km of infrastructure is shown. This result can be compared to that for the normalised inverse cost in Figure 6.13. Due to the similarities, the same metrics (the energies ϵ_{min} and ϵ_{avg} and the sensitivity S) could be used to describe this figure. The density plot in Figure 8.7 is quite similar to that in Figure C.13, which shows the cost performance metric. The large influence of the disconnections of region pairs on the normalised inverse cost (described in Subsection 6.2.3), can be seen in these two figures.

Correlations

The results are compared to both the amount of containers transported (Figure 8.9) and the as the crow flies distance Figure 8.11 between each region pair. There is no significant correlation between the amount of containers transported and the robustness. A positive correlation would have been plausible, as the amount of terminals in a region is (weakly) correlated with the amount of containers being transported from and towards that region (see Figure 8.10). Furthermore, region pairs with a large amount of containers being transported could have more alternative paths between them as otherwise capacity issues could arise. But according to the results from this simulation, this is not necessarily the case.

¹The as the crow flies distance is the length of the straight line connecting two points.

There is a significant negative correlation between the as the crow flies distance and the robustness (Figure 8.11). As the distance between two regions increase, the robustness is lower. When considering the connection of the centroids to the synchromodal network, this result does not seem unusual. For two adjacent regions the as the crow flies distance is very low and at least one or more (relatively short) road links need to be removed for the regions to become disconnected. The probability that these short road links are removed in the random simulation is small, causing a high robustness (i.e. mean number of challenges). For two non-adjacent regions the as the crow flies distance is higher and many infrastructure elements can cause a disconnection without the region(s) in between becoming disconnected (as paths can only use two links from the set $\mathcal{L}_{Access/egress}^{OD}$, one at the start and one at the end of the path). This causes the robustness to be lower for this region pair. For both the adjacent and non-adjacent region pair the minimum number of challenges could be the same. This behaviour should be taken into consideration for the random simulations and emphasises the need of different removal strategies to get a complete understanding of the robustness of the synchromodal network.

Although the corridors use a slightly different methodology (i.e. direct access), the results of the corridor Rotterdam-Antwerp and Rotterdam-Duisburg fit in Figure 8.11. The Rotterdam-Antwerp corridor has a as the crow flies distance of 76 km and a mean number of challenges per 100 km of infrastructure when the corridor becomes disconnected of 2.5. The Rotterdam-Duisburg corridor has a as the crow flies distance of 197 km and a mean number of challenges per 100 km of infrastructure when the corridor becomes disconnected of 2.3. The influence of the as the crow flies distance was also noted for the corridors in the previous subsection. As this could be interesting for future research, this is discussed in Section 9.2. There are a few outliers in Figure 8.11, towards the lower left of the graph. These are caused by region pairs that are close together but have a relatively lengthy shortest road path connecting them (e.g. region pair NL111-NL132 and region pair NL323-NL325).

At Least n Region Pairs Disconnected

In Figure 8.12, the probability that at least n number of region pairs are disconnected for the number of challenges per 100 km of infrastructure for the Netherlands is shown. From these results it can be seen (compare $n = 1$ and $n = 15$) that once the first region pair is disconnected, there is a large probability that more region pairs are disconnected. This result is caused by the fact that the disconnection of a region pair often means that one of the regions becomes disconnected from the rest of the synchromodal network. Consequently, all region pairs with that region become disconnected at the same time.

The same performance metric (probability that at least n number of region pairs are disconnected) is used to analyse the different graph configurations of the Netherlands in Figures 8.13 to 8.15. For the number of challenges (Figure 8.14), the results correspond with the expectations based on the results of the corridors. The configuration with all modalities is the most robust. The configuration with the combination waterway and road is less robust, but more robust than the combination rail and road. The single modality road is the least robust.

For the fraction of graph elements, an interesting result is shown in Figure 8.14(f) for the probability that all region pairs are disconnected. The probabilities of the different configurations almost overlap in this subfigure. To disconnect all region pairs in the synchromodal transport network, almost all graph elements have to be removed for all four configurations. This is likely caused by how the origins and destinations are connected to all access points of the national road infrastructure. To disconnect all the region pairs in any configuration, almost all graph elements in the road subgraph have to be removed. As graph elements are removed randomly, this means all the graph elements in the other subgraphs are likely to be removed as well.

Unexpected results can be seen for the number of challenges per 100 km of infrastructure in Figure 8.15. When n is larger, the order of the configurations (from least to most robust) is reversed. This is not a characteristic of the method U, as method V shows the same result (see Figure C.19). This might be caused by the following: As the regions are connected to all the access points of the modality road, almost the complete road graph has to fail to disconnect many or all region pairs. For the other modalities, the regions are connected to the terminals. The amount of challenges necessary to disconnect all the paths using the modalities waterway and rail is relatively low, while these modalities do add a substantial amount of infrastructure (in kilometres). This causes the robustness order to be reversed. It must be noted that larger n constitutes unlikely scenarios (e.g. a national disaster). Smaller n corresponds with more likely scenarios and thus the conclusion that

utilising more modalities increases the robustness remains reasonable.

8.2.4. Validity of Results

An overview of the model and method choices made and their effect on the results is shown in Appendix A. Many real world phenomena have been simplified or have not been considered in this research. Therefore the question arises what the validity of these results is. The amount of research on the robustness of multimodal transport systems is very limited. More research on this topic could help to better assess the validity of the results. This research should not be indisputably used as argumentation for policy decisions.

Some major trends in the results are likely still valid, while smaller differences between some configurations or region pairs should not be seen as significant. An example of a small difference are the light coloured region pairs in Figure 8.7. Some major trends are for example that the rail modality is least robust, the inland waterway modality is more robust and the road modality is the most robust. And that the interdependence decreases robustness and interconnection (terminals) increases robustness. These conclusions also agree with the expectations when viewing the networks.

9

Conclusion

Freight transport is an essential supply chain component and a vital component of the economy, as it ensures the efficient movement and timely availability of raw materials and finished goods [19, 82]. The thesis opened with this statement. Due to the importance of the freight transport network, the relevancy of research on its robustness is clear. The problem definition was stated as: *is the Dutch freight transport infrastructure a robust network suited for synchromodal transport?* There was a significant research gap on this topic at the start of this research. Although not offering a definitive answer to the problem definition, this research is an important step in filling the research gap. First the research questions are restated and subsequently answered in Section 9.1. During this research, many possibilities for future research were identified. These possibilities are discussed in Section 9.2. Finally, the thesis is finished with some concluding remarks in Section 9.3.

9.1. Conclusions

A main research question and three sub-questions were defined for this research. The three sub-questions are restated and answered first. Subsequently, the answer of this research for the main research question is presented.

1. What are the different elements of the synchromodal transport infrastructure and how do these elements affect synchromodal transport on the different modalities?

Chapter 4 answers this research sub-question. A clear overview of all the different elements of the synchromodal transport infrastructure did not exist at the start of this research. Such an overview is shown in Tables 4.1 to 4.3. All the elements presented in these tables can affect synchromodal transport in different ways. Although some similarities can be found between elements of different modalities, the effects for synchromodal transport are often different. Two special and important elements of the synchromodal transport infrastructure are identified: the *interconnections* and the *interdependencies* between different modes of transport. Interconnections facilitate the transshipment of containers between different modes of transport (e.g. a container terminal). Interdependencies are infrastructure elements whose functioning influence multiple modes of transport (e.g. the disruption of a bridge can affect two modalities).

2. How do the infrastructural elements and the other properties of the synchromodal transport system need to be taken into account in a network model to give a relevant representation of the synchromodal transport system?

After identifying the infrastructure elements, the question arises if and how they should be taken into account in the graph model. In Chapter 5, this second research sub-question is answered. An extensive graph model is proposed. Unlike the freight transport graphs used in earlier research, the locks, bridges, water-retaining structures, railway crossings and tunnels are represented in the proposed synchromodal graph model. For the link weights and the traffic assignment, methods from earlier work are used. Similar to earlier research, the interconnection (e.g. container terminals) is represented in the graph model. But different to earlier re-

search, the interdependencies are also represented in the graph model. When the infrastructure of different modalities cross each other, interdependence links are defined between the different modalities. To the best of this author's knowledge, no earlier research considers the interconnection and interdependence simultaneously in a synchromodal or multimodal network.

3. How can the robustness of the synchromodal network model be analysed and how well does it apply to the robustness of the synchromodal transport infrastructure?

The last research sub-question is answered in Chapter 6. The robustness is analysed by simulating disruptions and investigating the effects on the synchromodal network. Infrastructure elements are selected randomly to be disrupted, until no transport of containers is possible in the network. A targeted attack removal strategy is also briefly discussed, the added value of this removal strategy warrants additional research to be done. Both nodes and links represent infrastructure elements in the graph model. Two methods are proposed to select infrastructure elements randomly: an *uniform probability of failure* or a *length of link based probability of failure*. Both results have disadvantages and it is therefore advised to use both methods and compare the results, before coming to conclusions. To investigate the effects, two performance metrics are used: the *disconnection performance metric* (measures whether origins and destinations are connected) and the *cost performance metric* (measures the generalised cost of transporting containers).

The results of the robustness analysis methodology do not correspond perfectly with the real world. Real world phenomena, their representation in the model and simulation, and the effects on the results are listed in Appendix A. These limitations should be kept in mind when evaluating the results of the simulations.

How robust is the synchromodal transport infrastructure, comprising of the inland waterway, road, railway and container terminal infrastructure, for the transport of intermodal containers in the Netherlands?

Three case studies are described in Chapter 7: the *Rotterdam-Antwerp corridor*, the *Rotterdam-Duisburg corridor* and *the Netherlands*. With these three case studies national transport and most international transport can be analysed. For the case studies, not all infrastructure elements could be added due to limitations of the available data. Only locks and interdependencies are new compared to earlier research. The results for the three case studies are presented and discussed in Chapter 8. Keeping the limitations of the model and the method in mind, some conclusions can be derived from the results.

Two special and important elements of the synchromodal transport infrastructure are identified: the interconnections and the interdependencies between different modes of transport. The interconnections (i.e. container ports and inland container terminals) have a significant positive effect on the robustness. While the interdependencies have a smaller negative effect on the robustness. The option to change modality during transit outweighs the disadvantages of interdependencies. Generally, the road is the most robust modality, the inland waterways is less robust and the railway is the least robust modality. This does not mean that the rail modality is not important, as it provides a relatively cheap alternative and offers the capabilities to transport containers further into Europe than the inland waterways.

The synchromodal transport infrastructure, comprising of the inland waterway, road, railway and container terminal infrastructure, is more robust for the transport of intermodal containers in the Netherlands than other transport methods. Due to mode-free booking and the real-time and flexible switching among different modalities, synchromodal transport offers a robust transport method according to this research.

9.2. Future Research

During this research, many possibilities for future research were identified. As the research gap for analysing the robustness of a synchromodal transport network was very large at the start of this research, many things have not yet been researched. The importance of freight transport and the limited scientific research warrants additional research on this topic. The possibilities that were identified during the research are described in this section.

9.2.1. Graph Model

Not all viable modes of transport are considered in this research, as short-sea shipping is not included in the graph model. Short-sea shipping could be a relevant addition for the Rotterdam-Antwerp corridor. Implementing this mode of transport is not straightforward, as some infrastructure is shared by both short-sea shipping and the inland waterway modality. This could be solved by for example using more complex traffic allocation algorithms on a single waterway subgraph or by linking identical infrastructure elements in the short-sea subgraph and the inland waterway subgraph to be disrupted simultaneously.

Many complex infrastructure elements have a simplistic representation in the graph model of this research (e.g. a lock with multiple chambers represented by a single node). For most elements this is argued to be an underestimation of the robustness, but the question arises if each modality suffers equally from this underestimation. This should be researched when the graph model is used in future research. Alternatively, the graph model could also be expanded upon. For example a temporal graph could model the time-dependent characteristic of water retaining structures. Or each chamber of a lock could be modelled as an individual node. The water levels that depend on the seasons and influence the size of ships allowed on certain waterways could also be included in the model.

For the regions variant of the graph model, the centroids of the regions are connected to all access points available in the road subgraph of the region. This results in the assumption that each access point has an independent connection to the centroid, which is not necessarily the case. The non-national road network is thus assumed to be ideal. This is an overestimation of the robustness of the non-national road network. Apart from this limitation, the regions also affect the targeted attacks simulation. Suppose almost all cargo leaving a region uses a certain bridge in the real world. If there is an access point on the other side of the bridge, the results will not indicate this bridge as being important. In future research, the regions could be made smaller with more detailed data (e.g. zip codes). Although this would decrease the impact of using regions, only precise origin and destination addresses could fully solve this problem.

For the generalised cost other attributes of the links could also be used. For example the environmental impact of transporting containers [6, 115] or the availability of the infrastructure for the transport of hazardous goods. The traffic assignment algorithm could also be improved. In a corridor all traffic is assigned to a single modality (i.e. the shortest path), while in reality the traffic would be spread out more over multiple paths and modalities. To solve this the traffic could be assigned on the k shortest paths [88] or use that some cargo is time critical (instead of shortest path, use least time path).

Congestion and capacity are not considered in this research. Considering these aspects of freight transport could help with spreading the traffic over multiple paths. But more importantly, the model would not only indicate that no transport can occur when there is no connection. The model would also indicate when the capacity of the network is insufficient. A significant part of infrastructure investments is increasing the capacity of existing infrastructure, as new infrastructure is difficult to build in a densely population country like the Netherlands. During this research the problem arose of defining the capacity of an infrastructure element. The infrastructure is shared with passenger transport for the modalities road and rail, making the capacity dependent on the intensity of passenger transport. Furthermore, the containers are only one of the many cargo types transported for each modality. How can the capacity for one cargo type be determined? This question should be answered when congestion is considered in future research.

9.2.2. Robustness Analysis Method

Only complete disruptions are considered in this research. In reality, a wide range of effects can happen when something goes wrong. It could be interesting to analyse the effects of partial disruptions (e.g. only one direction disrupted or increased generalised cost). Both nodes and links represent infrastructure elements that can be disrupted. In more theoretical research on the robustness of network, often only nodes or only links are removed. When for more networks both nodes and links represent something from the real world, additional research is useful.

For the random disruption on graph elements, two methods are used in this research. Both these methods have significant flaws, one method is dependent on the homogeneous distribution of nodes in the network and the other method cannot consider disruptions of nodes. This warrants additional research to find a better

method. For example first choose a modality based on the length of the infrastructure and then choose an element in the subgraph with an uniform probability.

In this research the number of challenges per 100 km of infrastructure is used to visualise the results. It was shown that the resulting robustness correlates negatively with the as the crow flies distance between origin and destination. This can also be illustrated with the following example. Suppose there are two networks. Network A has one straight link of 100 km and network B has one straight link of 200 km connecting the origin and destination. According to the number of challenges per 100 km of infrastructure, network B would be more robust, while this is not intuitively correct. This could possibly be solved by not only normalising with the amount of infrastructure in a network, but also normalising with the as the crow flies distance between the origin and destination.

Cascading failures could also be researched for the synchromodal transport network. When a road bridge fails, the failure can cascade through the road network due to congestion. When a disruption leads to a lower water level on the waterway, this low water level will spread in the network until a lock or water retaining structure is reached (e.g. the incident with the weir at Grave on 29th of December, 2016).

The targeted attack removal strategy is only briefly considered during this research. The targeted attack removal strategy is a useful removal strategy to consider next to the random removal strategy, as the worst case scenario becomes more apparent. It would therefore be interesting to further research this removal strategy.

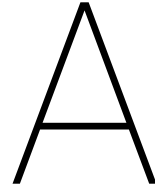
9.2.3. Miscellaneous

A reliability study could also be done for the synchromodal transport network. Using statistics of disruptions (e.g. traffic jams and bridge failures), the probability of failure could be approximated for the different infrastructure elements. The graph model proposed in this research could be used for a reliability study. The synchromodal transport network is not static, improvements are constantly made to the network. The method used in this research, could also be used to optimise the robustness of the Dutch synchromodal transport network. To this end, the critical components of the synchromodal transport network could also be identified. And finally, the robustness could also be analysed on a smaller geographical scale. For example how robust is the Port of Rotterdam and the surrounding infrastructure? How well can containers leave the Port of Rotterdam area when disruptions occur? Due to the importance of the Port of Rotterdam and the limited infrastructure to the Maasvlakte, this would be a relevant future research topic.

9.3. Concluding Remarks

The synchromodal transport network is a very complex system, it was a big challenge to research the robustness of this system with so little earlier research to build upon. The available time frame for this research did not allow more to be researched, although there are many possibilities for future research. This research likely does not give a definitive quantification of the robustness of the synchromodal transport network. But what it has achieved is an important step in the research on this topic. The analysis of the different elements in the synchromodal network with regards to the robustness offers an important framework for future research. Furthermore, the combination of interconnection and interdependence in the synchromodal network has been researched for the first time. Apart from the transport field, this research is also relevant for graph theory. Providing a new real world interdependent network to be researched.

It is this author's sincere hope that more research will be done on this interesting and important topic. Already new transport methods are being devised for the future. As the current way of transporting physical objects is unsustainable (economically, environmentally as well as socially), it is suggested to use the digital internet to develop a physical internet [51]. As the modalities will increasingly form a single transport network, the robustness of the interdependent freight transport network will only become more relevant.



Model and Method Choices and Their Effects on Results

In this Appendix, an overview is given of all the real world phenomena that have been considered in this research. For each phenomenon it is described if and how it is represented in the model and what the effects of this decision are on the results. It must be noted that these effects are mostly expected effects and are not fully researched. Additional research is required to confirm the effects presented here.

A.1. Scope

Real World Phenomenon	Representation in Model	Effect on Results
With short-sea shipping, containers are transported between ports in Europe.	Short-sea shipping is not represented as a mode of transport.	Underestimating the robustness between origins and destinations where short-sea shipping is a viable option.
Individual vehicles (e.g. trains and barges) are used to transport containers.	A macroscopic traffic model is used, aggregating individual vehicles into flows.	Less accurate results due to simplification, additional research is desirable to determine the effects.
Vehicles are not always fully loaded, therefore not fully utilising the economies of scale.	Costs of transport are per tonne of cargo, averaging the additional cost of vehicles not fully loaded.	When the modality rail or IWW is used between an origin and destination the actual cost of transport would be a lot higher when only a very small amount of cargo is transported. This influences the shortest path and the cost increase of some disruptions.
Vehicles that are on the way can be affected by disruptions. Disruptions causing vehicles to drive back a long distance to an alternative path have a larger effect than disruptions that cause vehicles to drive back a short distance.	This is not considered in the model, when a disruption occurs a new route is determined between the origin and the destination for all cargo.	In the results the disruption of infrastructure elements between two intersections have the same effect, while the effect can be different for vehicles that are underway.

Real World Phenomenon	Representation in Model	Effect on Results
Disruptions can have different effects, e.g. blocking all transport, decreasing the capacity or causing a delay.	Only disruptions leading to the complete unavailability of infrastructure elements for freight transport are simulated.	Results apply to worst case scenarios that do not occur frequently and not to small or partial disruptions.

A.2. Method

Real World Phenomenon	Representation in Model	Effect on Results
Containers are transported to both domestic and international destinations.	Domestic and international transport are researched in separate case studies.	Multiple results need to be combined to come to a complete conclusion.
Containers are transported between many unique addresses.	All origins and destinations in a region are aggregated into one point, resulting in one cargo demand for the region. For the Netherlands 40 regions are used.	Due to the use of a single point as origin/destination in a region, the generalised cost of a route in the model can be an underestimation or overestimation of the true generalised cost. Which causes inaccuracies in the results.
Trucks can use an extensive road network consisting of national roads and an underlying road network.	Only the national road infrastructure is explicitly considered in the model. The underlying road infrastructure is implicitly considered in the links of the subgraph G^{OD} , these links are only used at the start and end of a journey.	The robustness of the modality road is underestimated compared to other modalities as the underlying road infrastructure can offer alternative routes. The other modalities do not have such an underlying network. It should be pointed out that the underlying road network will quickly becomes congested when a national road is disrupted.

A.3. Synchromodal Transport Graph

Real World Phenomenon	Representation in Model	Effect on Results
The synchromodal infrastructure consists of roads, railways and waterways together with various structures (e.g. bridges and tunnels).	The synchromodal infrastructure is represented by a graph network, structures and intersections are represented by nodes and they are connected with links.	The graph network intuitively represents the synchromodal infrastructure. Based on the use of this type of model in earlier research [3, 9, 13, 82, 84, 115], it is assumed that this is an accurate type of model.
At intersections not always all other sections are accessible from a certain section, see for example Figure 4.7 on Page 28.	As a symmetric graph is used (each directed link has an opposing directed link), this is not represented in the graph.	Some paths in the graph model will not exist in the real world, the robustness could therefore be overestimated.

Real World Phenomenon	Representation in Model	Effect on Results
Based on the current water level, a weir can be either closed or open. The lock parallel to the weir is not always used, causing a time-dependent characteristic.	In the model it is assumed that the weir is always closed and the lock is therefor always used.	The weirs on some waterways are frequently open, causing the model to overestimate the generalised cost of these waterways. This influences the results when using the generalised cost.
Flood barriers are sometimes closed to protect the land against high water levels.	This is not directly represented in the graph, but is modelled as a disruption of the flood barrier.	The robustness of the available inland waterway network during high water levels cannot be analysed in the model.
Some railways are not structurally used by trains with containers, but only when other routes are disrupted.	Railways not structurally used by cargo trains are not included in the model.	The actual robustness of the modality rail might be higher as more alternatives exist than are represented in the graph model.
The functioning of a single infrastructure element (e.g. a bridge) can be important for multiple modes of transport. When such an element is disrupted, multiple modalities can be affected. It is also possible only a single modality is affected.	This interdependence is represented in the graph using interdependence links, so that a single disruption can affect multiple modes of transport. When interdependence is considered, the disruption of for example a bridge will always disrupt both modalities.	The resulting robustness is probably an underestimation, as for example a disruption of a bridge could also affect a single mode of transport.
Databases describing the infrastructure in the Netherlands are likely not faultless.	The databases are used as is, its quality is assumed.	Errors in the used data can result in errors in the results as well.
Some infrastructure elements consist of multiple parts. For example a lock which consists of multiple (parallel) chambers, a bridge which consists of a fixed and a movable part or a container terminal with multiple quays.	Each infrastructure element is simplified into a single node in the graph.	The robustness of these elements is underestimated, as the model offers a worst-case representation due to the simplification. The different modalities are possibly not equally affected by this simplification, additional research is therefor required to identify the effects.
The initial and last part of the journey (in the regions variant of the graph model) is done using non-national road network, which can be disrupted.	The centroids of the regions are connected to all access points available in the road subgraph of the region. This results in the assumption that each access point has a independent connection to the centroid, the non-national road network is assumed to be ideal.	The assumption that the non-national road network is ideal is incorrect, this is an overestimation of the robustness of the non-national road network.
When the number of vehicles on an infrastructure element comes close to the capacity, congestion will increase the delay (cost) of that infrastructure element. A large amount of congestion can cause an infrastructure element to become practically unusable for transport.	Congestion and capacity are not considered.	It is possible that an unrealistic amount of cargo is transported on an infrastructure element. This would lead to the conclusion freight transport is still possible in the network, while in reality it is not. The functioning of the network is overestimated in this regard.

Real World Phenomenon	Representation in Model	Effect on Results
Multiple factors influence which modalities and paths are used to transport containers. Multiple paths can be used between one origin and destination pair.	(1) The any-path algorithm: it is not determined which modality and path are used, instead only a connection between an origin and a destination is required to transport containers. (2) The all-or-nothing algorithm: The decision factors are simplified to a single generalised cost, on which the modality and path are chosen.	(1) The results offer no information on which modalities and paths are used to transport containers. (2) The shortest path could be incorrect due to errors in the generalised cost (although sensitivity analysis shows that the robustness results are not extremely sensitive to changes in the generalised cost). Furthermore, only a single path (the shortest) is used. These two inaccuracies can lead to errors in the results.
Inland waterways have a CEMT-class which classifies the waterways on their size, barges that transport containers are generally CEMT-class III or higher [57] and container terminals are connected to waterways with CEMT-class III or higher [14, 60, 81].	All inland waterways of CEMT-class II or lower are not included in the graph model.	As almost no containers are transported on inland waterways of CEMT-class II or lower, this has no significant effect on the results.
Many barges that transport containers are larger than CEMT-class III.	It is assumed that transport of containers can take place on all inland waterways of CEMT-class III and higher.	The robustness is overestimated, as some alternative paths are likely not valid in reality.

A.4. Robustness Analysis Method

Real World Phenomenon	Representation in Model	Effect on Results
An infrastructure element can completely fail, cutting off all transport on that infrastructure element. More often a disruption causes a delay for transport on that infrastructure element, causing an increase of the generalised cost. Or a disruption causes the capacity of the infrastructure element to decrease.	Partial failures like increased cost and decreased capacity are not considered, in this research the complete failures of infrastructure elements are studied.	The results only apply to complete failures, while partial failures occur more often. This limits the applicability of the results to policy decisions.
A disruption on a road with a division between opposing lanes of traffic, can affect a single direction of traffic.	In simulations opposing links are removed simultaneously in the event of a disruption. This is done to be consistent with the representation of elements with separated opposing traffic (e.g. two one-way tunnels) with a single node.	The effects of disruptions are larger than they will likely be in the real world. In the model less disruptions are needed to stop the functioning of the synchromodal network.

Real World Phenomenon	Representation in Model	Effect on Results
Each infrastructure element has a (possibly unique) probability of failure.	(1) All graph elements have uniform probability of failure (method U). (2) The links have a probability of failure proportionate to their length, nodes cannot fail (method V).	(1) When the number of nodes per kilometre is not homogeneous, the fraction of graph elements removed and the number of challenges per 100 km of infrastructure can give conflicting results. (2) No dependence on the number of nodes per kilometre being homogeneous, but the effects of nodes failing and the effects of interdependence (represented by nodes) cannot be analysed.
Disruptions can have different causes. Some are caused by failures of infrastructure elements or by failures of the vehicles on the infrastructure, these disruptions are to some extent random. Others are caused by planned maintenance or could be caused by a (terrorist) attack, these disruptions have a more deterministic nature.	(1) Random disruptions are simulated in the graph model and the effects are analysed. (2) Targeted/k-disruptions. Only random at the moment, could possibly change.	(1) The results only offer information on the effects of random disruptions and how networks react to random disruptions. The results cannot be used to plan maintenance in a synchromodal way or to protect the network against worst-case attacks. (2) to write when certain which removal strategies are used.

A.5. Case Studies

Real World Phenomenon	Representation in Model	Effect on Results
The synchromodal network consists of many different infrastructure elements.	Not all infrastructure elements are represented in the graph model, due to limitations of the available data.	Due to a more homogeneous distribution of infrastructure elements per kilometre in the graph model, an uniform probability of failure can be used for the random simulation. The results of the random simulations are sensitive to the addition and removal of graph elements (even when the number of alternative paths does not change).

B

Synchromodal Freight Transport Networks

To avoid cluttering the Chapters with a large amount of images, additional images and tables of the networks are shown in this Appendix. The images and tables of the networks are shown in the following sequence: the representative example of a synchromodal network (Figures B.1 to B.3), the Rotterdam-Antwerp corridor, the Rotterdam-Duisburg corridor and the Netherlands.

B.1. Representative Example of a Synchromodal Network

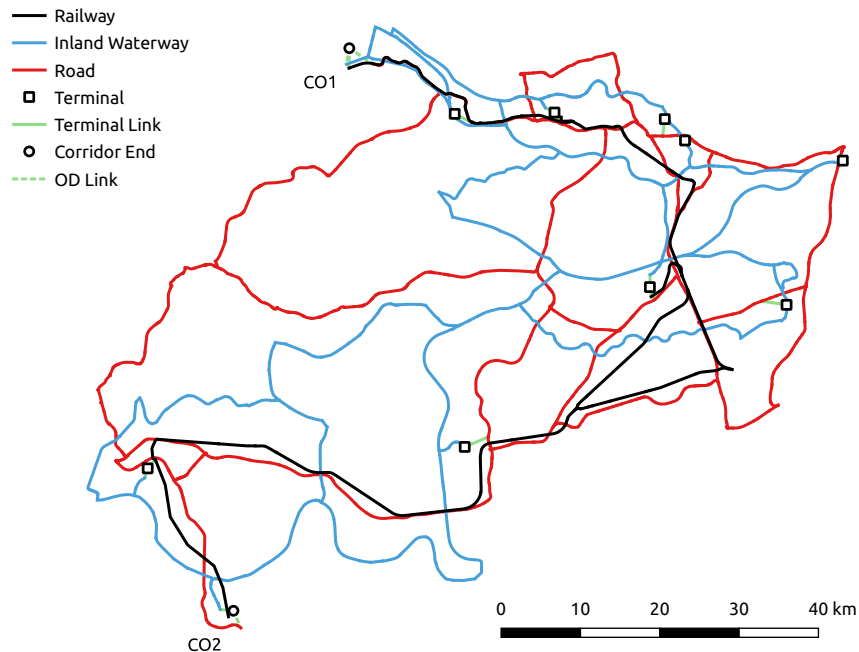


Figure B.1: A map of the representative example of a synchromodal network (corridor variant).

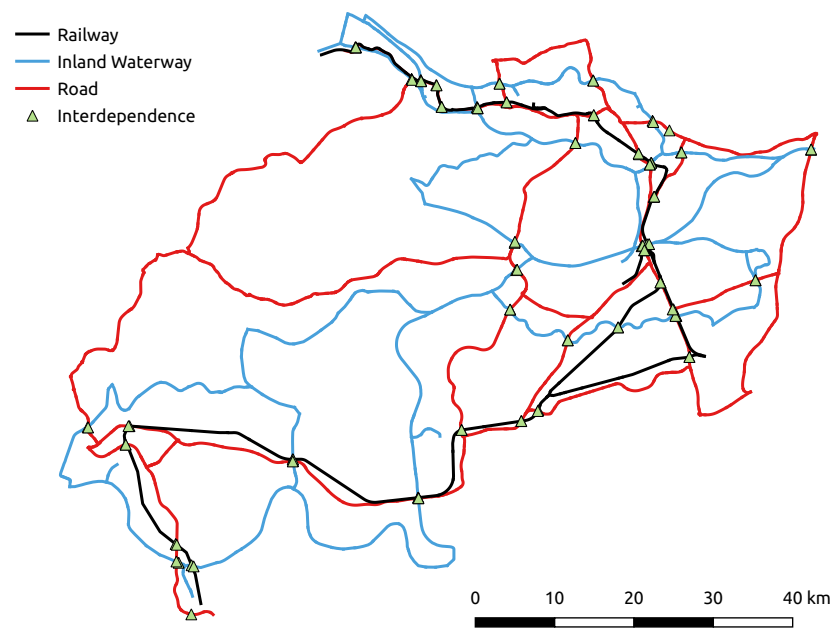


Figure B.2: A map of the representative example of a synchromodal network with the interdependence points.

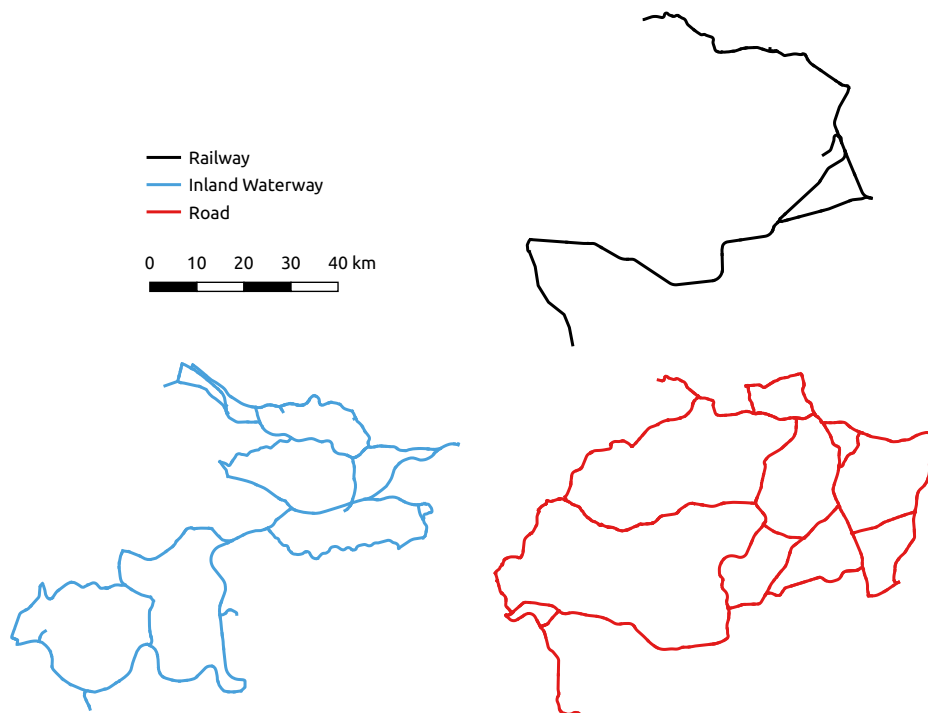


Figure B.3: Individual maps of each of the three modalities (from the top clockwise: rail, road, IWW) of the representative example of a synchromodal network.

Configuration	Nodes	Links	Length	In-Degree Distribution					Connectivity	
				1	2	3	4	5+	Node	Link
Regions (complete)	317	950	1288 km	0	130	174	10	3	5	5
Corridor (complete)	198	462	1288 km	0	133	64	1	0	3	3
Corridor (IWW)	66	148	505 km	2	46	18	0	0	1	1
Corridor (Road)	65	148	549 km	2	43	20	0	0	1	1
Corridor (Rail)	31	62	209 km	2	27	2	0	0	1	1

Table B.1: Some statistics for several configurations of the representative example of a sychromodal network (\bar{G}). For the length only the length of one of two opposing links is counted. When there are multiple origin and destination pairs in the graph (regions variant), the connectivity of the pair with the lowest values is shown.

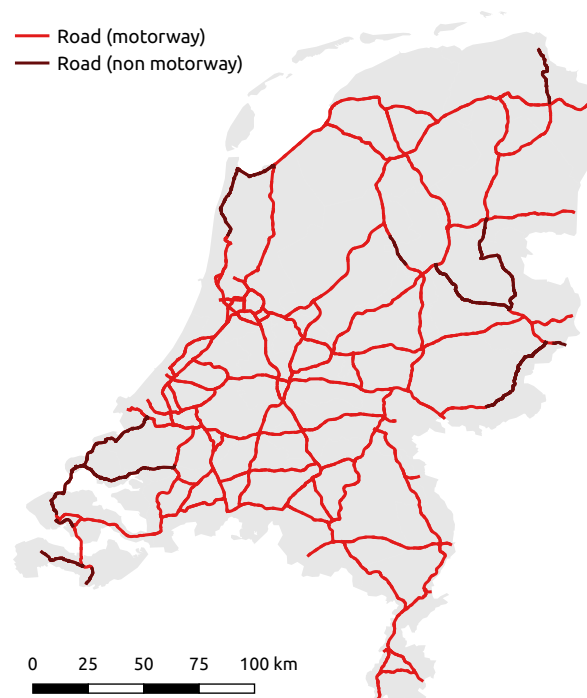


Figure B.4: The national roads in the Netherlands, distinguished into two groups: motorways and non motorways. The non motorways have a lower average speed in the graph model.

B.2. Rotterdam-Antwerp Corridor

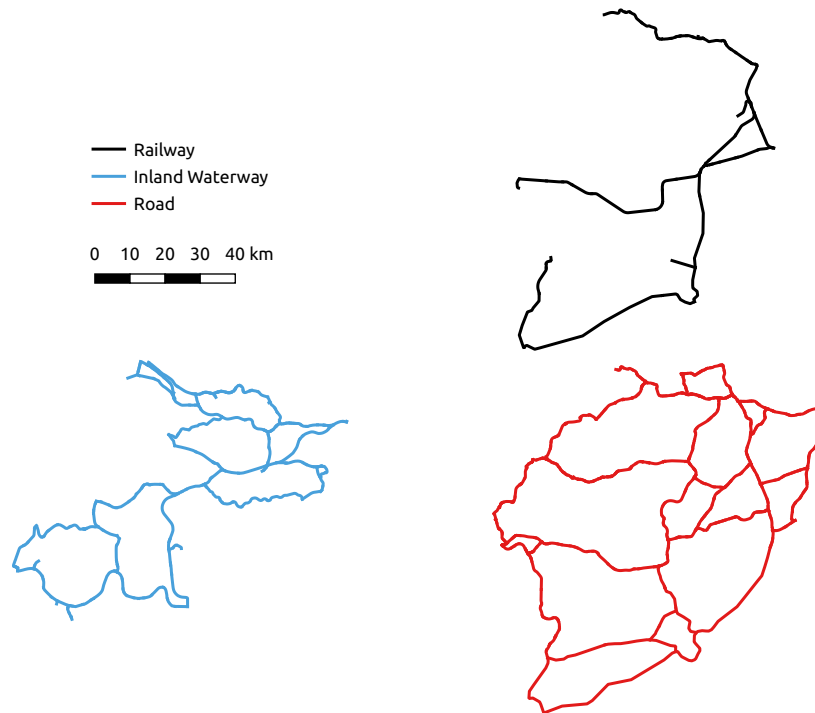


Figure B.5: Individual maps of each of the three modalities (from the top clockwise: rail, road, IWW) of the Rotterdam-Antwerp corridor.

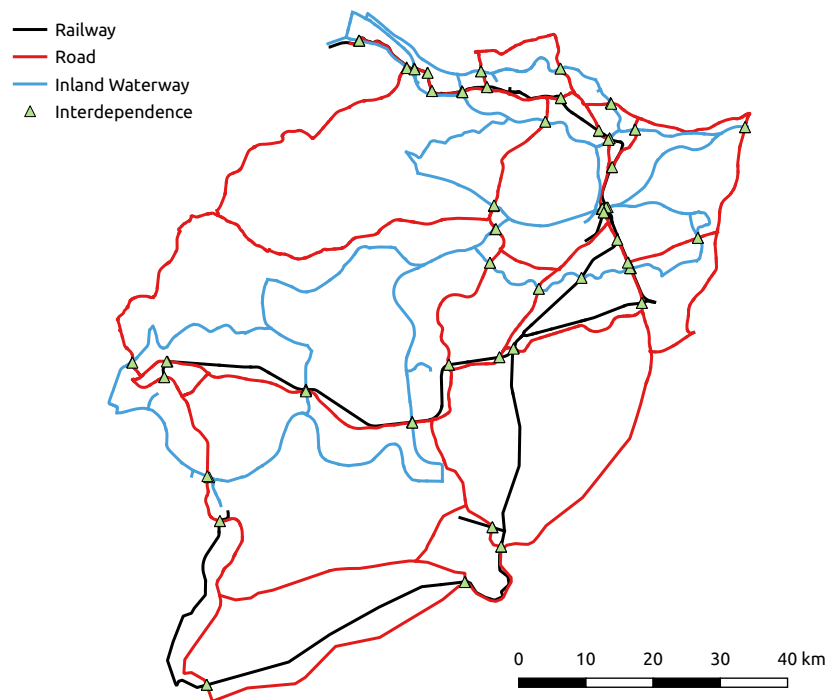


Figure B.6: A map showing the interdependencies for the Rotterdam-Antwerp corridor.

Configuration	Nodes	Links	Length	In-Degree Distribution					Connectivity	
				1	2	3	4	5+	Node	Link
Wa	63	142	502 km	2	43	18	0	0	1	1
Ro	77	180	754 km	2	47	28	0	0	1	1
Ra	24	48	157 km	2	20	2	0	0	1	1
WaRo	138	322	1256 km	0	92	46	0	0	2	2
WaRa	85	190	659 km	0	65	20	0	0	2	2
RoRa	99	228	911 km	0	69	30	0	0	2	2
WaRoT	181	430	1276 km	0	114	66	1	0	2	2
WaRaT	115	258	838 km	0	88	26	1	0	2	2
RoRaT	125	288	1079 km	0	87	38	0	0	2	2
WaRoRa	160	370	1413 km	0	110	50	0	0	3	3
WaRoRaT	221	522	1602 km	0	142	78	1	0	3	3

Table B.2: Some statistics for several configurations of the Rotterdam-Antwerp corridor. For the length only the length of one of two opposing links is counted.

B.3. Rotterdam-Duisburg Corridor

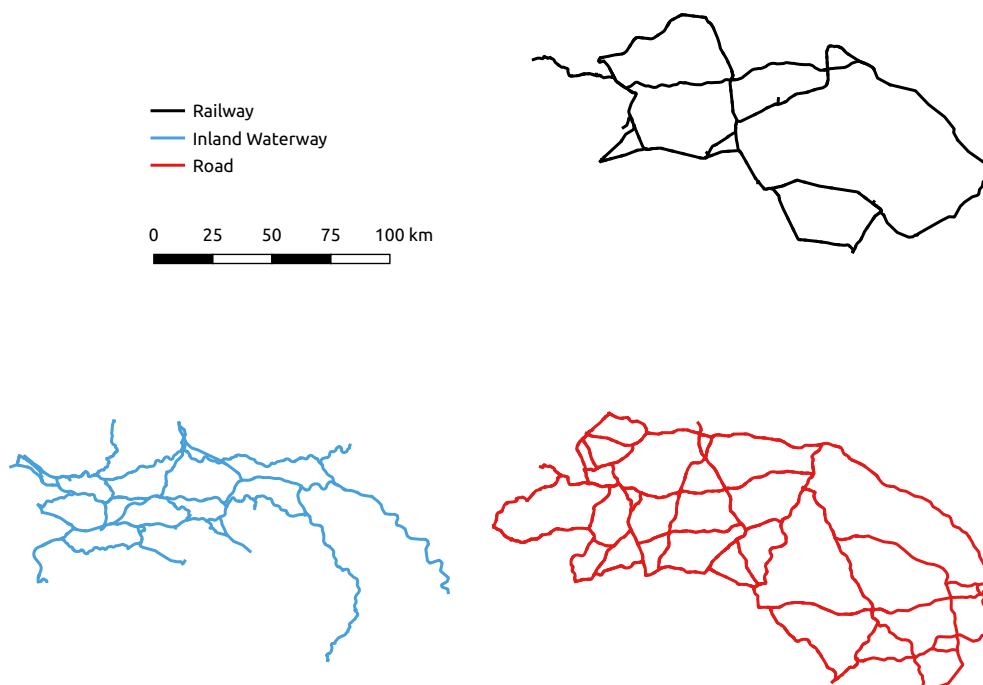


Figure B.7: Individual maps of each of the three modalities (from the top clockwise: rail, road, IWW) of the Rotterdam-Duisburg corridor.

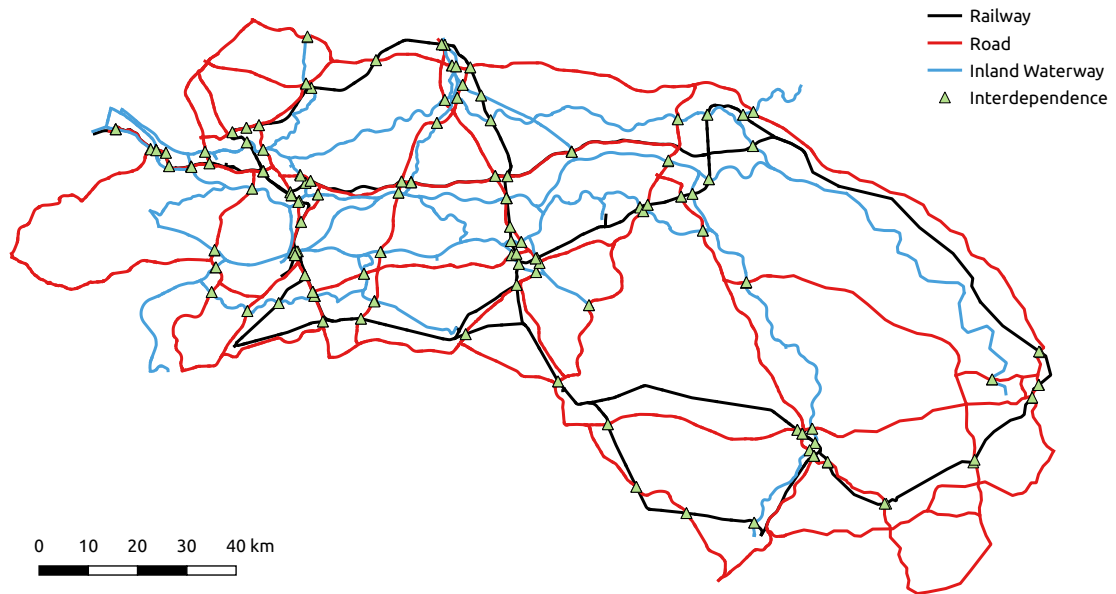


Figure B.8: A map showing the interdependencies for the Rotterdam-Duisburg corridor.

Configuration	Nodes	Links	Length	In-Degree Distribution					Connectivity	
				1	2	3	4	5+	Node	Link
Wa	121	274	809 km	2	87	30	2	0	1	1
Ro	150	360	1601 km	2	89	56	3	0	1	1
Ra	89	194	787 km	2	70	16	1	0	1	1
WaRo	269	634	2410 km	0	178	86	5	0	2	2
WaRa	208	468	1595 km	0	159	46	3	0	2	2
RoRa	237	554	2388 km	0	161	72	4	0	2	2
WaRoT	382	908	2627 km	0	245	130	7	0	2	2
WaRaT	247	560	1695 km	0	185	58	4	0	2	2
RoRaT	267	630	2404 km	0	176	86	5	0	2	2
WaRoRa	356	828	3197 km	0	246	104	6	0	3	3
WaRoRaT	485	1150	3430 km	0	314	162	9	0	3	3

Table B.3: Some statistics for several configurations of the Rotterdam-Duisburg corridor. For the length only the length of one of two opposing links is counted.

B.4. The Netherlands

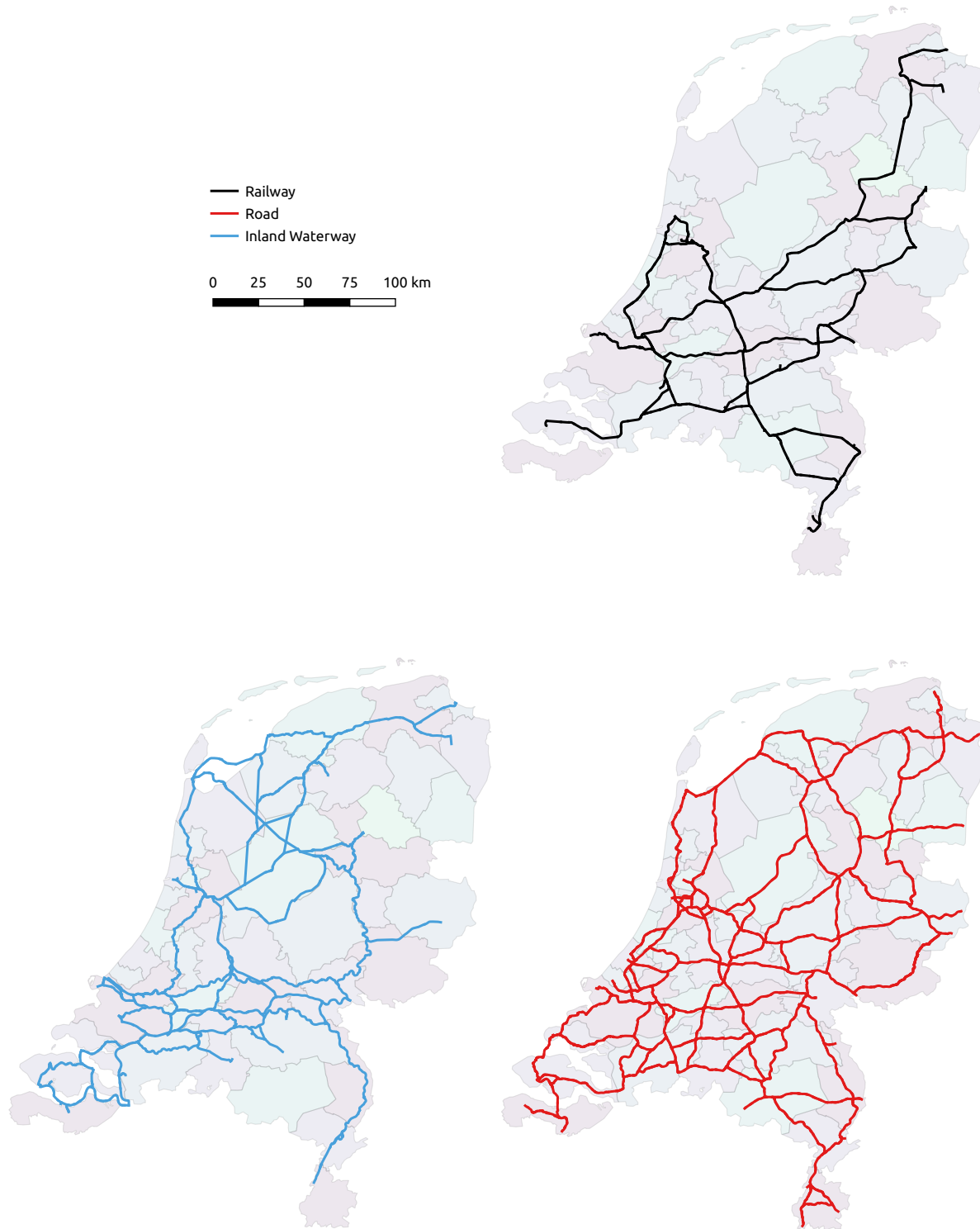


Figure B.9: Individual maps of each of the three modalities (from the top clockwise: rail, road, IWW) of the Netherlands (regions variant).

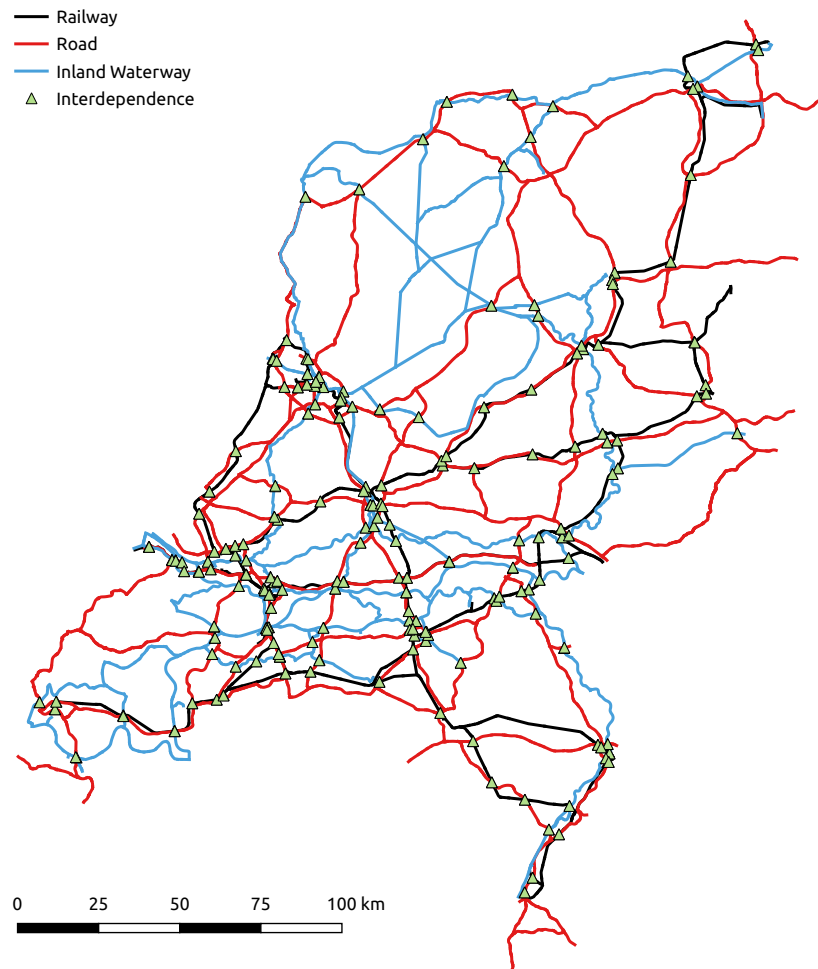


Figure B.10: A map showing the interdependencies for the Netherlands.

Configuration	Nodes	Links	Length	In-Degree Distribution					Connectivity	
				1	2	3	4	5+	Node	Link
Ro	1007	3418	3063 km	0	182	780	6	39	1	1
WaRoT	1366	4284	5247 km	0	440	835	51	40	1	1
RoRaT	1195	3846	4469 km	0	333	803	19	40	1	1
WaRoRaT	1541	4686	6652 km	0	566	882	52	41	1	1

Table B.4: Some statistics for several configurations of the Netherlands (regions variant). For the length only the length of one of two opposing links is counted. As there are multiple origin and destination pairs in the graph, the connectivity of the pair with the lowest values is shown. The connectivity for most pairs is higher, up to 11.

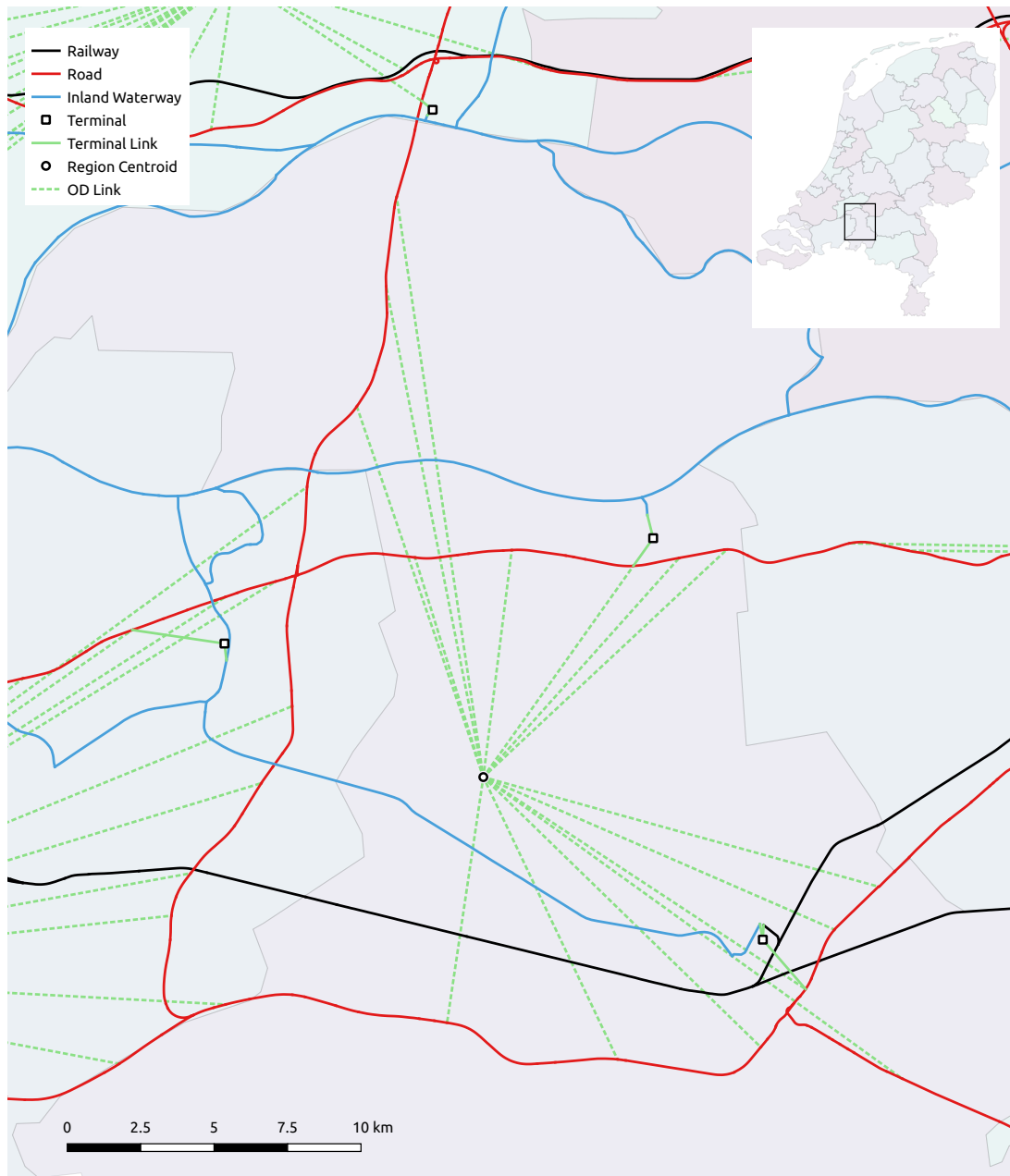


Figure B.11: A detailed view of a part of the synchromodal network in the Netherlands (regions variant).

C

Additional Results of Case Studies

Not all the results of the simulations of the case studies could be presented and thoroughly discussed in this thesis. To not let these results go to waste, they are included in this appendix.

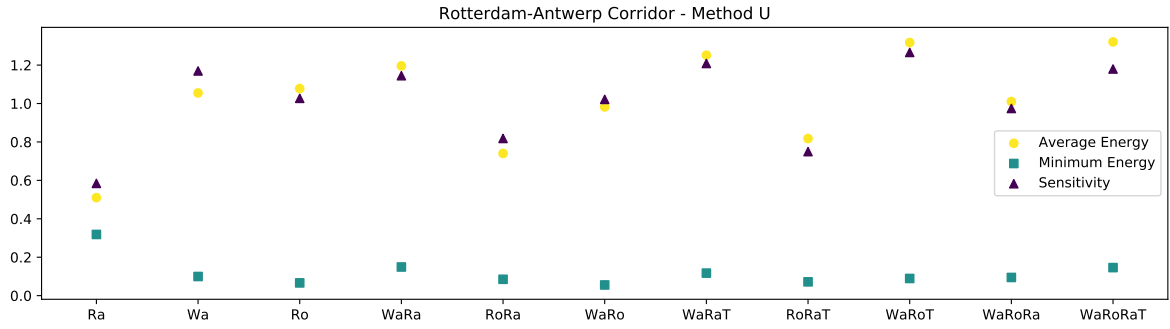


Figure C.1: Comparison of the normalised inverse cost density functions for the eleven configurations of the Rotterdam-Antwerp corridor, using method U. For each configuration the simulation is run a 1,000 times. The following three metrics are used to describe the density functions: the minimum energy ϵ_{min} (higher is better), the average energy ϵ_{avg} (higher is better) and the sensitivity S (lower is better).

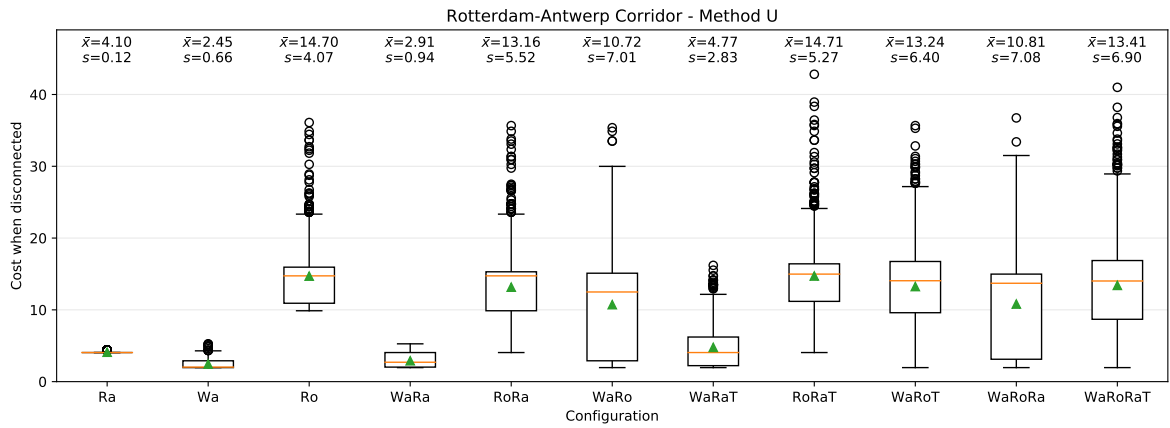


Figure C.2: The cost when disconnected for the eleven configurations of the Rotterdam-Antwerp Corridor, using method U. The simulation is run a 1,000 times.

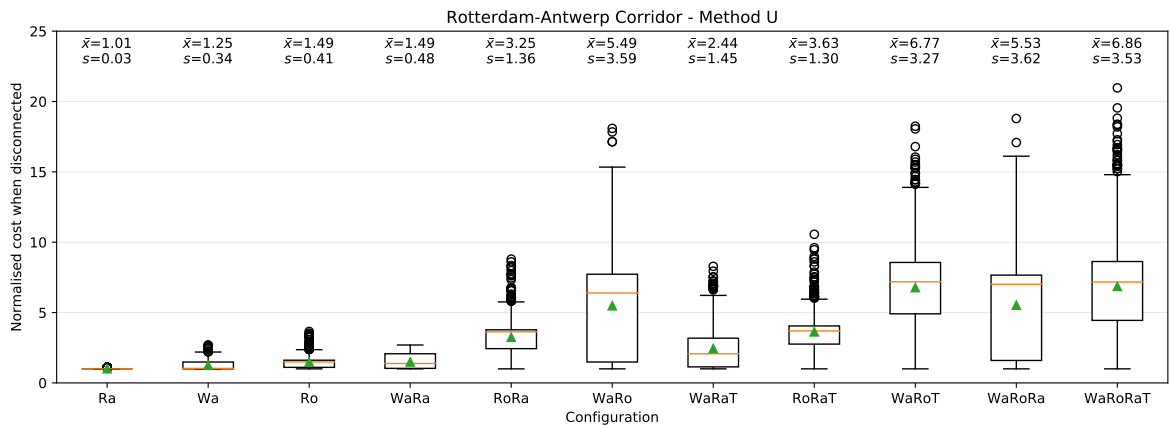


Figure C.3: The normalised cost when disconnected for the eleven configurations of the Rotterdam-Antwerp Corridor, using method U. The simulation is run a 1,000 times.

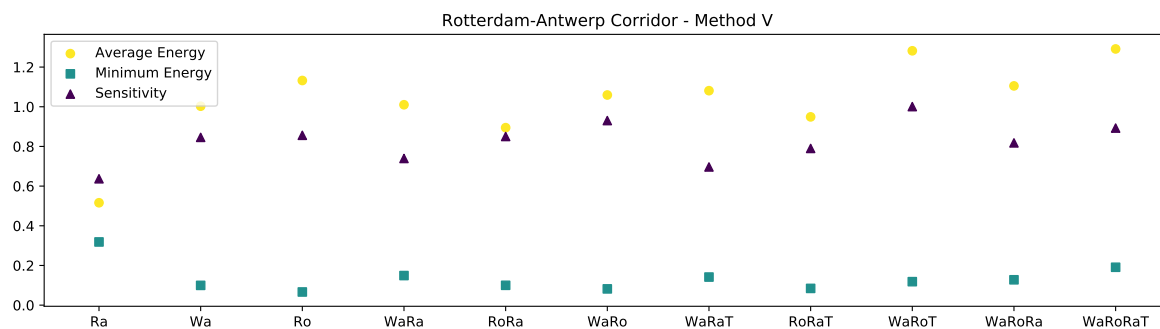


Figure C.4: Comparison of the normalised inverse cost density functions for the eleven configurations of the Rotterdam-Antwerp corridor, using method V. For each configuration the simulation is run a 1,000 times. The following three metrics are used to describe the density functions: the minimum energy ε_{min} (higher is better), the average energy ε_{avg} (higher is better) and the sensitivity S (lower is better).

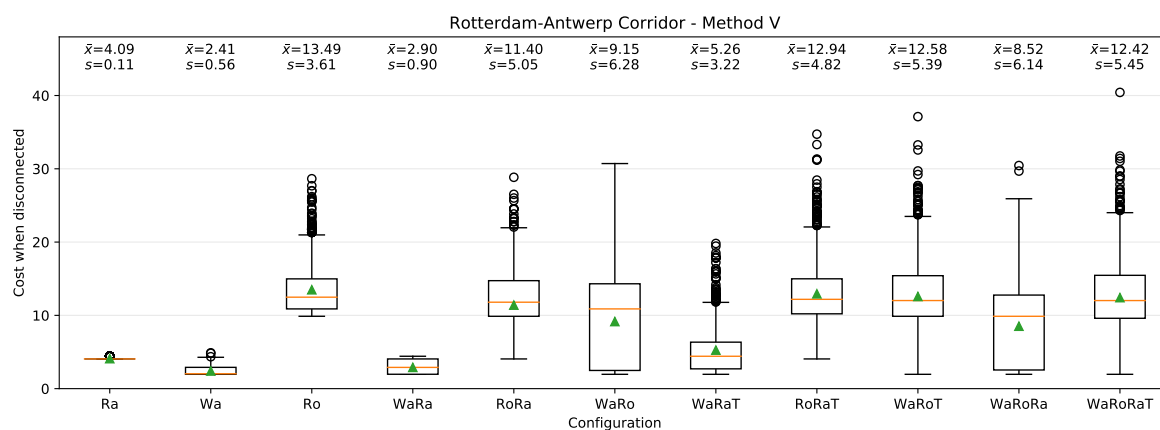


Figure C.5: The cost when disconnected for the eleven configurations of the Rotterdam-Antwerp Corridor, using method V. The simulation is run a 1,000 times.

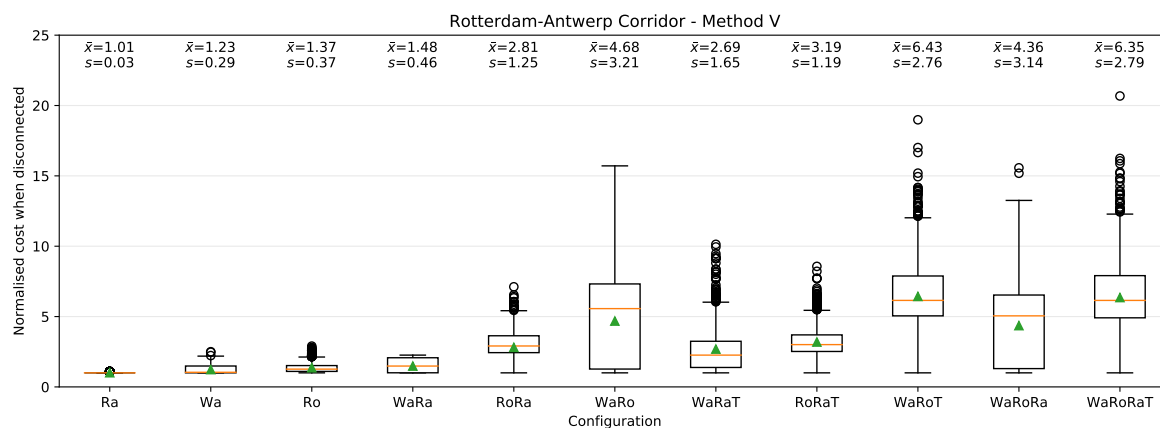


Figure C.6: The normalised cost when disconnected for the eleven configurations of the Rotterdam-Antwerp Corridor, using method V. The simulation is run a 1,000 times.

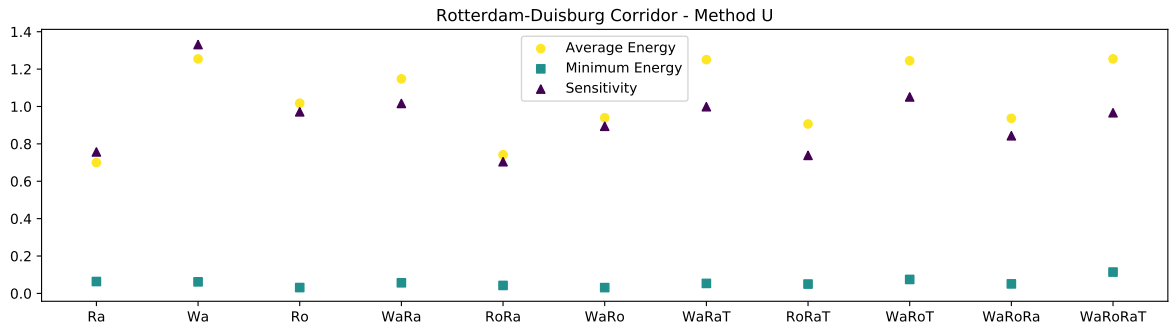


Figure C.7: Comparison of the normalised inverse cost density functions for the eleven configurations of the Rotterdam-Duisburg corridor, using method U. For each configuration the simulation is run a 1,000 times. The following three metrics are used to describe the density functions: the minimum energy ϵ_{min} (higher is better), the average energy ϵ_{avg} (higher is better) and the sensitivity S (lower is better).

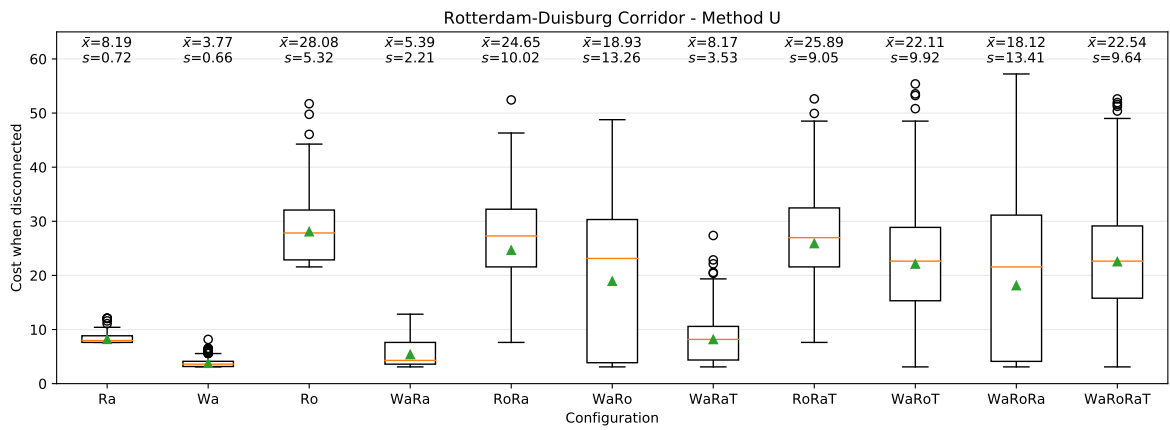


Figure C.8: The cost when disconnected for the eleven configurations of the Rotterdam-Duisburg Corridor, using method U. The simulation is run a 1,000 times.

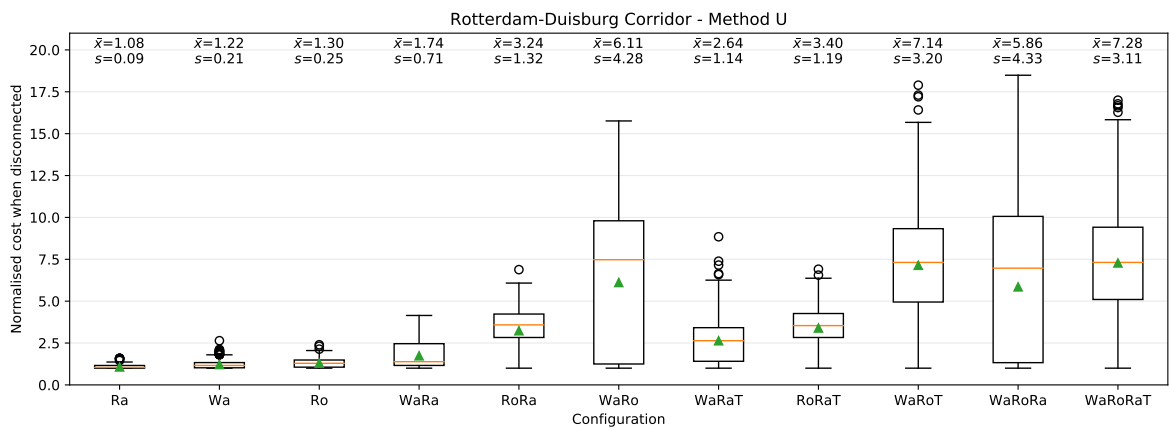


Figure C.9: The normalised cost when disconnected for the eleven configurations of the Rotterdam-Duisburg Corridor, using method U. The simulation is run a 1,000 times.

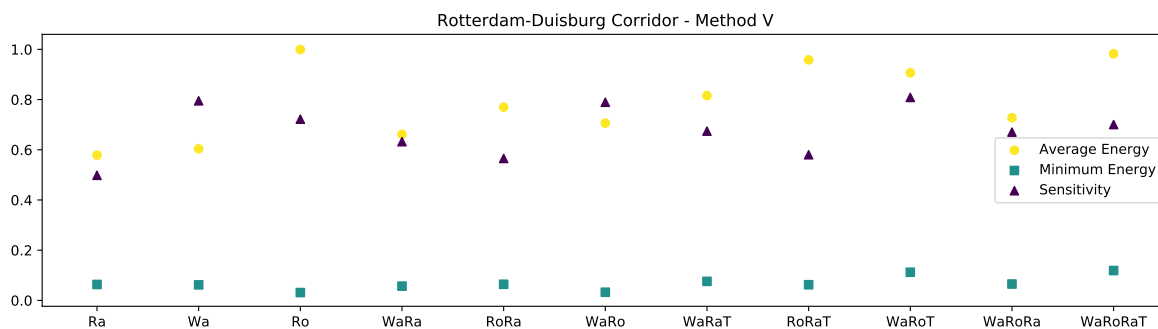


Figure C.10: Comparison of the normalised inverse cost density functions for the eleven configurations of the Rotterdam-Duisburg corridor, using method V. For each configuration the simulation is run a 1,000 times. The following three metrics are used to describe the density functions: the minimum energy ϵ_{min} (higher is better), the average energy ϵ_{avg} (higher is better) and the sensitivity S (lower is better).

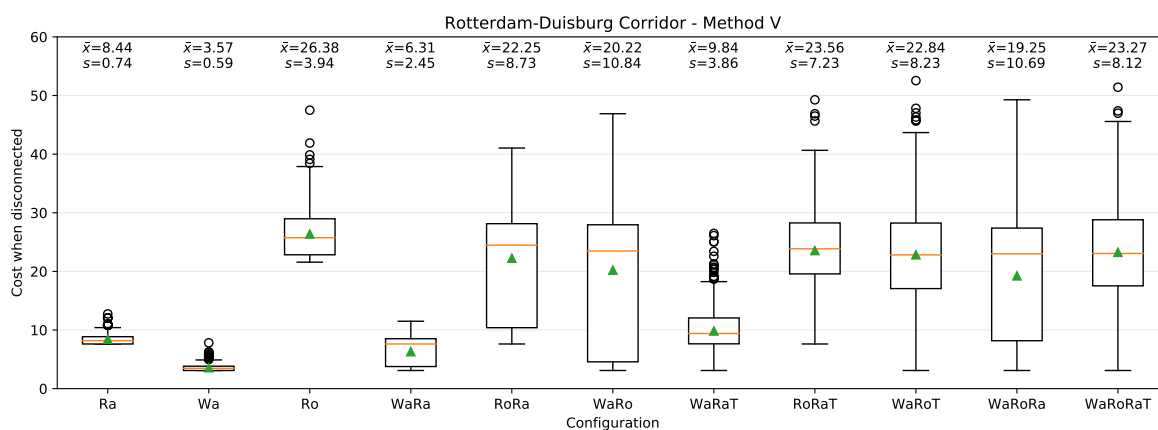


Figure C.11: The cost when disconnected for the eleven configurations of the Rotterdam-Duisburg Corridor, using method V. The simulation is run a 1,000 times.

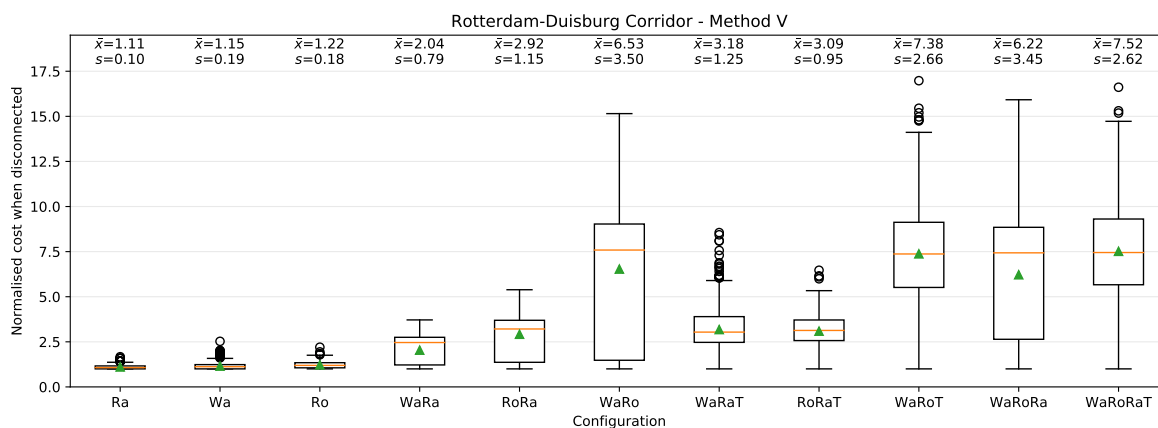


Figure C.12: The normalised cost when disconnected for the eleven configurations of the Rotterdam-Duisburg Corridor, using method V. The simulation is run a 1,000 times.

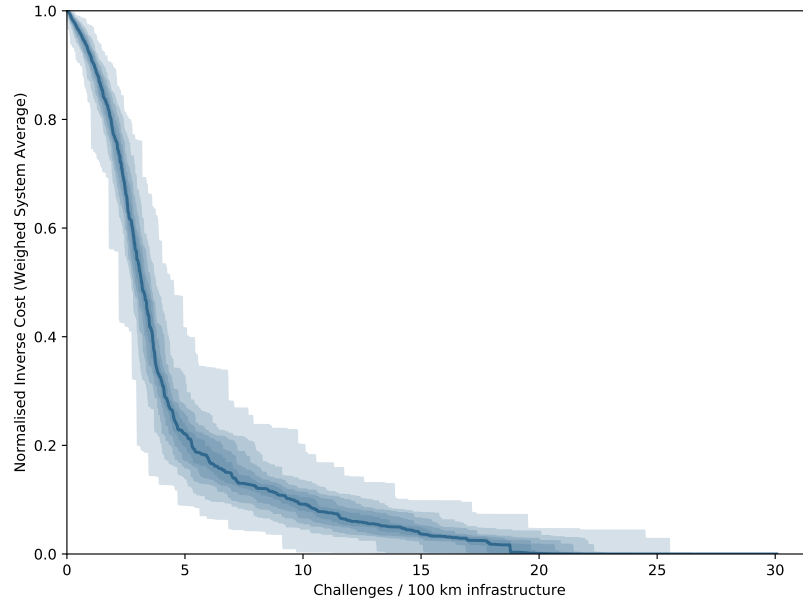


Figure C.13: The normalised inverse cost (weighed system average) in the Netherlands for the number of challenges per 100 km of infrastructure (configuration WaRoRaT), using method U. The simulation is run a 1,000 times for a graph consisting of 6652 km of infrastructure and 758 region pairs. The thick line represents the median, while the light to darker shaded areas represent 100%, 80%, 60%, 40%, 20% of the samples respectively.

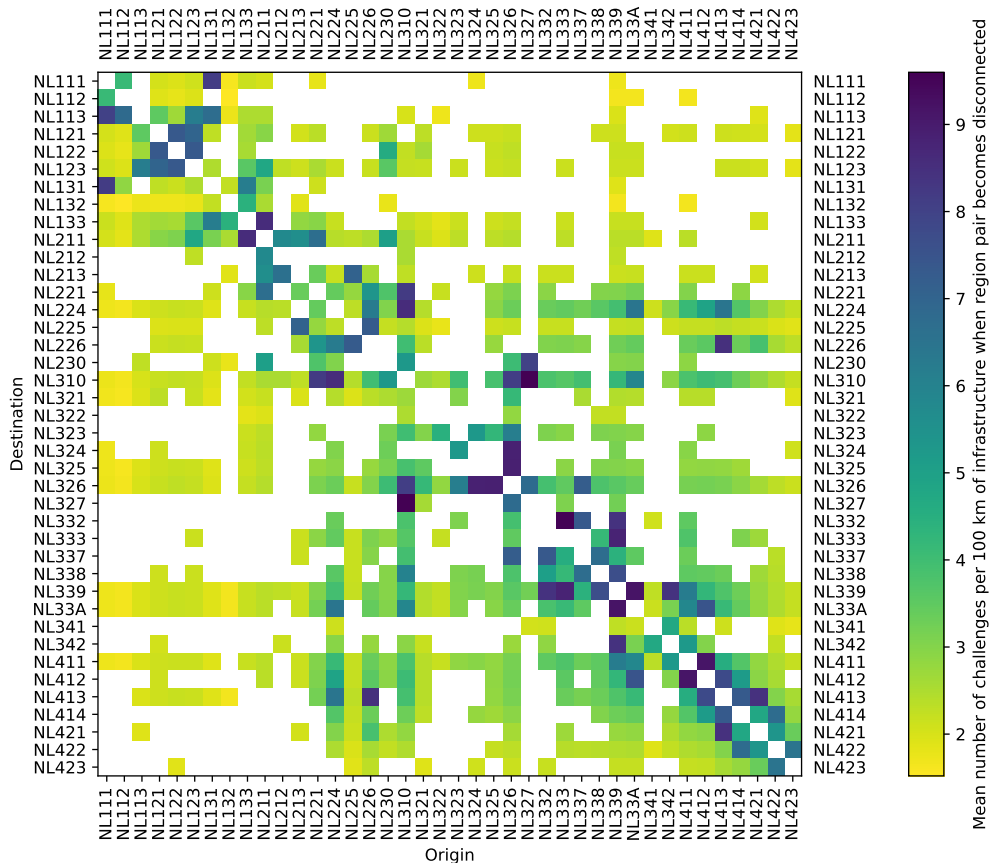


Figure C.14: The mean number of challenges per 100 km of infrastructure at which disconnection occurs for each of the active (with containers transported) region pairs in the Netherlands (configuration WaRoRaT), using method V. The simulation is run a 1,000 times for a graph consisting of 6652 km of infrastructure.

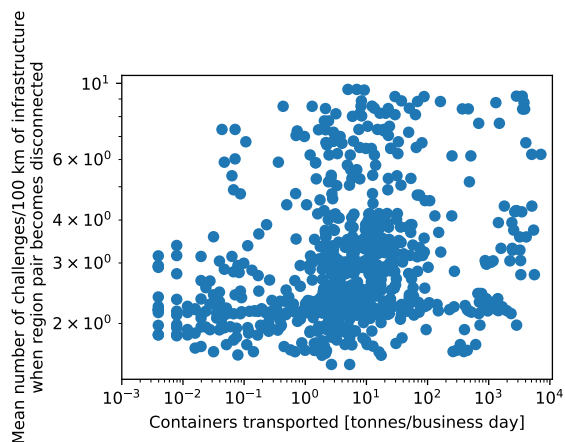


Figure C.15: Correlation plot of the amount of containers (in tonnes/business day, logarithmic) transported between each active region pair versus the mean number of challenges per 100 km of infrastructure (logarithmic) at which disconnection occurs, using method V. The simulation is run a 1,000 times for the configuration WaRoRaT, correlation coefficient $\rho = 0.219$ (logarithmic).

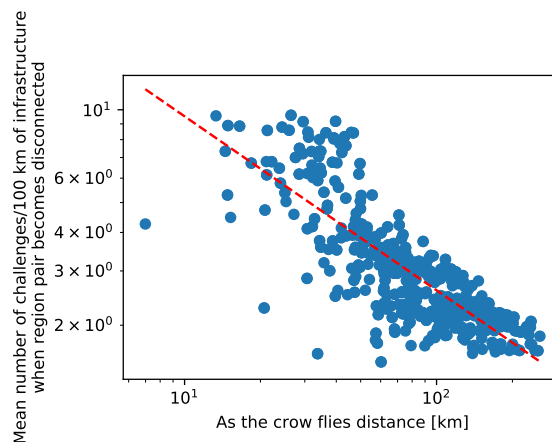


Figure C.16: Correlation plot of the as the crow flies distance (logarithmic) between two each active region pair's centroids versus the mean number of challenges per 100 km of infrastructure (logarithmic) at which disconnection occurs, using method V. The simulation is run a 1,000 times for the configuration WaRoRaT, correlation coefficient $\rho = -0.770$ (logarithmic).

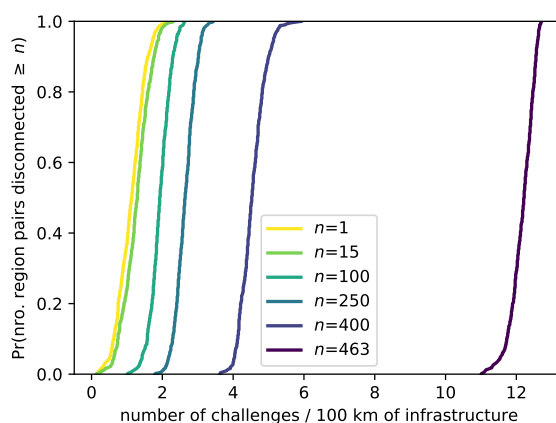


Figure C.17: The probability that at least n number of regions are disconnected for the number of challenges per 100 km of infrastructure for the Netherlands (WaRoRaT), using method V. As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times for a graph consisting of 6782 km of infrastructure.

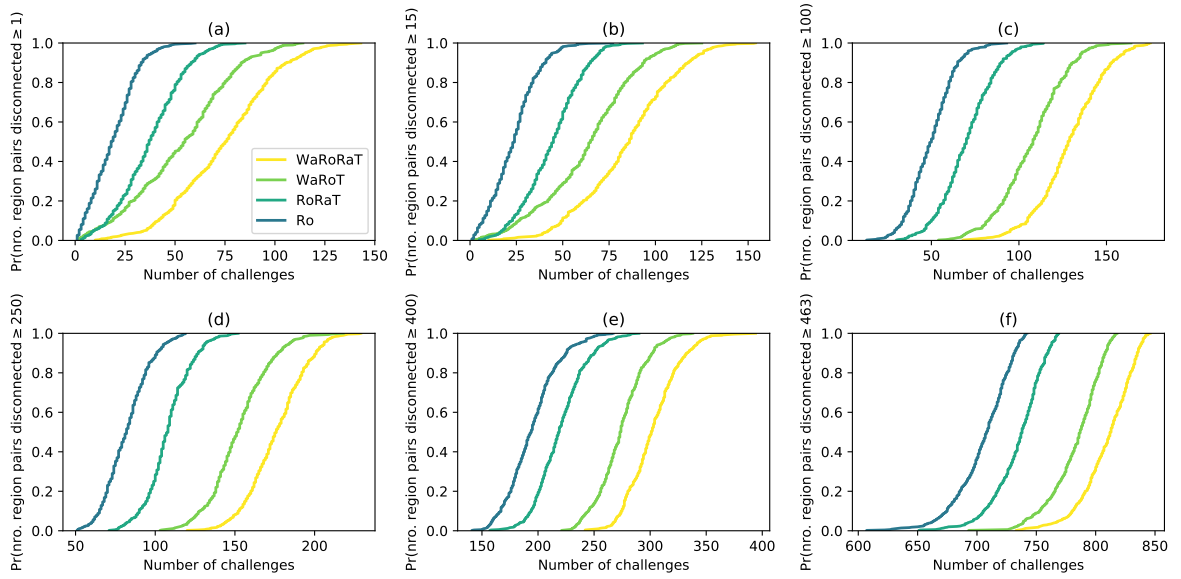


Figure C.18: The probability that at least n number of regions are disconnected for the number of challenges for the four configurations of the Netherlands graph (WaRoRaT, WaRoT, RoRaT, Ro), using method V. As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times. (a) at least 1 region pair, (b) at least 15 region pairs, (c) at least 100 region pairs, (d) at least 250 region pairs, (e) at least 400 region pairs and (f) 463 (which are all) region pairs.

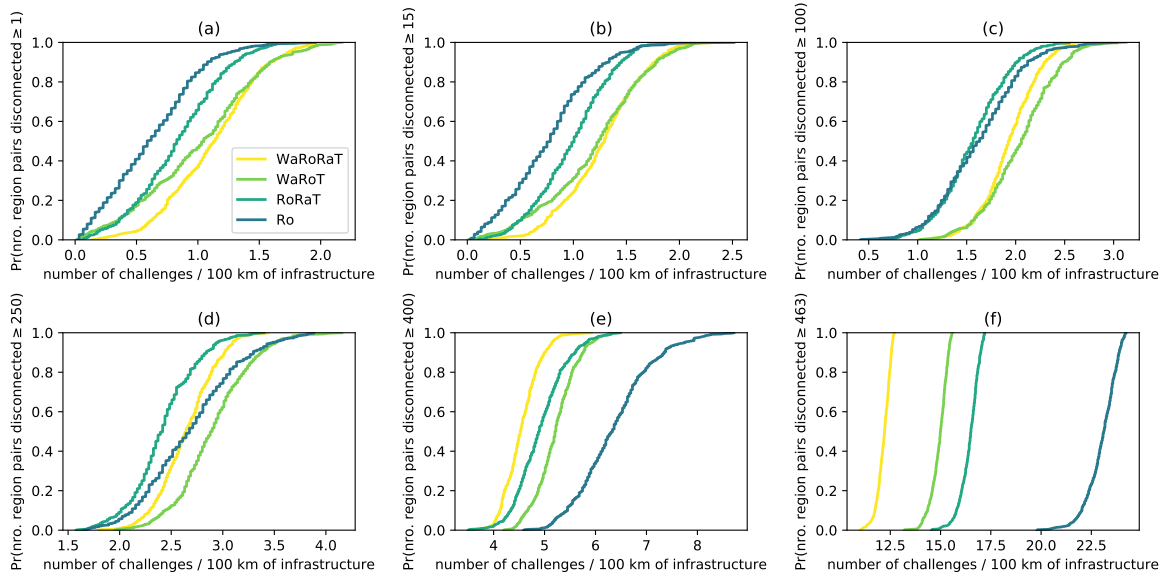


Figure C.19: The probability that at least n number of regions are disconnected for the number of challenges per 100 km of infrastructure for the four configurations of the Netherlands graph (WaRoRaT, WaRoT, RoRaT, Ro), using method V. As both directions ($a \rightarrow b$ and $b \rightarrow a$) have the same robustness, duplicates are removed, which results in 463 unique region pairs. The simulation is run a 1,000 times for graphs consisting of 6782 km (WaRoRaT), 5377 km (WaRoT), 4599 km (RoRaT) and 3193 km (Ro) of infrastructure. (a) at least 1 region pair, (b) at least 15 region pairs, (c) at least 100 region pairs, (d) at least 250 region pairs, (e) at least 400 region pairs and (f) 463 (which are all) region pairs.



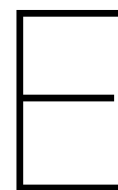
CEMT-classification

CEMT-class	Motor Vessels and Barges			Tonnage (tonnes)	Pushed Convoys			Tonnage (tonnes)
	Max Dimensions (meters)				Max Dimensions (meters)			
	Length	Beam	Draught		Length	Beam	Draught	
I	38	5.0	2.20	250-400				
II	55	6.6	2.50	400-650				
III	80	8.2	2.50	650-1,000				
IV	85	9.5	2.50	1,000-1,500	85	9.5	2.00	1,250-1,450
Va	110	11.4	2.80	1,500-3,000	110	11.4	4.50	1,600-3,000
Vb					185	11.4	4.50	3,200-6,000
VIa					110	22.8	4.50	6,400-12,000
VIb					195	22.8	4.50	6,400-12,000
VIc ^a					280	22.8	4.50	9,600-18,000
VIc ^b					200	34.2	4.50	9,600-18,000
VII					285	34.2	4.50	14,500-27,000

Table D.1: Classification of European inland waterways (CEMT-classes) [57]. Classification of the classes I-III is given for the waterways west of the Elbe (Germany).

^a pushed convoy configuration 2 wide and 3 long.

^b pushed convoy configuration 3 wide and 2 long.



NUTS-Regions

List of the NUTS-3 regions in the Netherlands with their code and name (in Dutch) [16].

NUTS-3 Code	Name	NUTS-3 Code	Name
NL111	Oost-Groningen	NL323	IJmond
NL112	Delfzijl en omgeving	NL324	Agglomeratie Haarlem
NL113	Overig Groningen	NL325	Zaanstreek
NL121	Noord-Friesland	NL326	Groot-Amsterdam
NL122	Zuidwest-Friesland	NL327	Het Gooi en Vechtstreek
NL123	Zuidoost-Friesland	NL332	Agglomeratie 's-Gravenhage
NL131	Noord-Drenthe	NL333	Delft en Westland
NL132	Zuidoost-Drenthe	NL337	Agglomeratie Leiden en Bollenstreek
NL133	Zuidwest-Drenthe	NL338	Oost-Zuid-Holland
NL211	Noord-Overijssel	NL339	Groot-Rijnmond
NL212	Zuidwest-Overijssel	NL33A	Zuidoost-Zuid-Holland
NL213	Twente	NL341	Zeeuwsch-Vlaanderen
NL221	Veluwe	NL342	Overig Zeeland
NL224	Zuidwest-Gelderland	NL411	West-Noord-Brabant
NL225	Achterhoek	NL412	Midden-Noord-Brabant
NL226	Arnhem/Nijmegen	NL413	Noordoost-Noord-Brabant
NL230	Flevoland	NL414	Zuidoost-Noord-Brabant
NL310	Utrecht	NL421	Noord-Limburg
NL321	Kop van Noord-Holland	NL422	Midden-Limburg
NL322	Alkmaar en omgeving	NL423	Zuid-Limburg

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