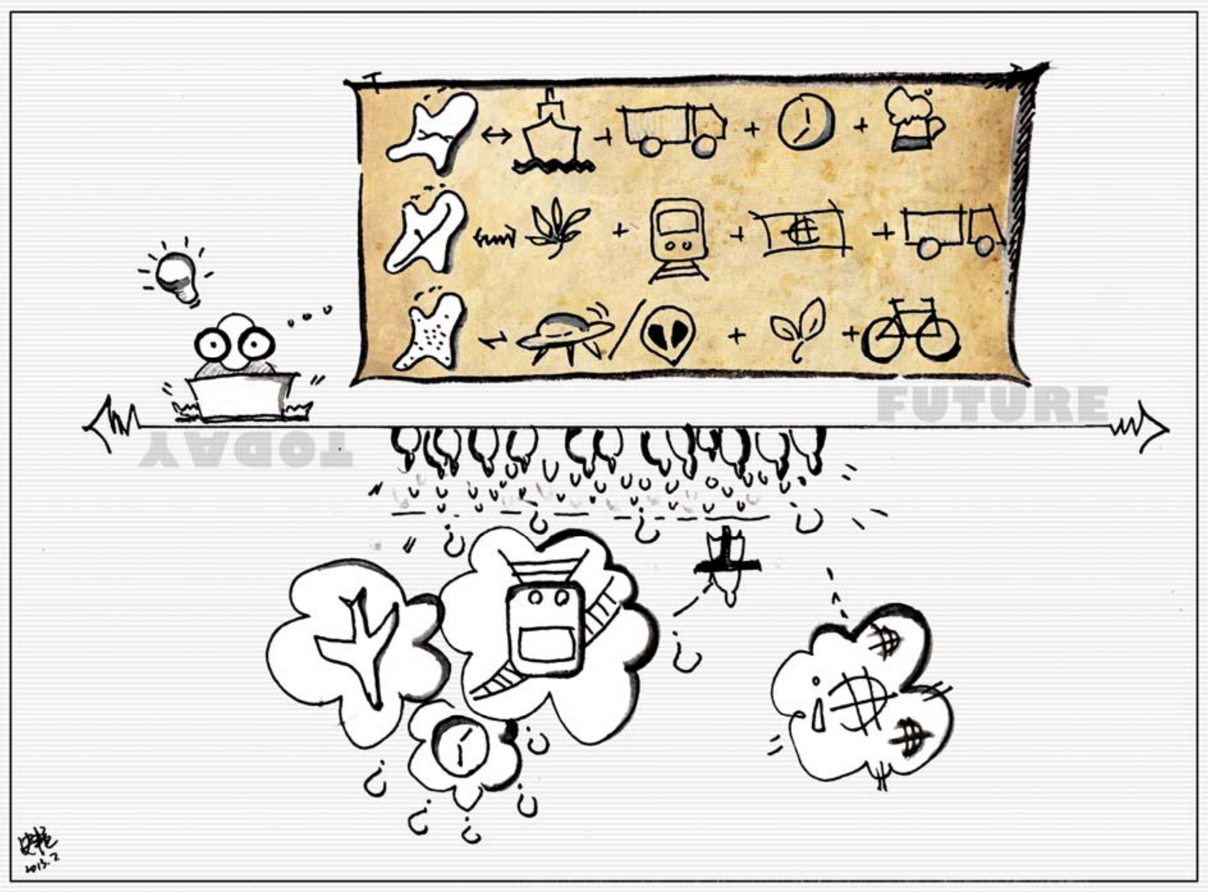

A Freight Transport Model for Integrated Network, Service, and Policy Design

Mo Zhang

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A Freight Transport Model for Integrated Network, Service, and Policy Design

Proefschrift

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Mathematical Symbols

Sets:

Z	is the set of elements consisting the super network, $Z = (N, L)$
N	is the set of the identifications (IDs) of the nodes
O	is the set of regions
T	is the set of terminals
L	is the set of all links
M	is the set of modes, $M = \{road, railway, inland\ waterway\}$
X	is the set of geographic links, $X \subset L$
H	is the set of transhipment links, $H \subset L$
A	is the set of access/egress links, $A \subset L$
G	is the set of pre-/end-haulage links, $G \subset L$
S	is the set of all service links, $\mathrm{S} \subset \mathrm{L}$
SN	is the set of all links consisting the hub-based service network;
$\mathrm{S_i}$	is the set of links consisting a hub-based-service, $\mathrm{S_i} \subset \mathrm{SN}$.
R	is the set of links consisting a route
P	is the set of commodities
B	is the set of candidate terminals,
W	is the set of alternative terminal network configurations

Indices

n	is the index denoting the identification number of a node
o	is the index denoting the identification number of a region which is represented by its centroid

t	is the index denoting the identification number of a terminal in the super network
l	is the index denoting the identification number of a link in the super network
m	is the index denoting a mode
x	is the index denoting a geographic link
h	is the index denoting a transhipment link
a	is the index denoting an access/egress link
g	is the index denoting a pre-/end-haulage link
s	is the index denoting a service link
r	is the index denoting a route connecting an origin-destination pair
p	is the index denoting a commodity type
b	is the index denoting a candidate terminal in terminal network design
w	is the index denoting an alternative terminal network configuration

Variables:

$C_x^{\alpha,p}$	is the total costs of moving one unit of commodity p over geographic link x
$C_h^{\beta,p}$	is the total costs of moving one unit of commodity p over transhipment link h
$C_a^{\theta,p}$	is the total costs of moving one unit of commodity p over access/egress link a
$C_g^{\gamma,p}$	is the total costs of moving one unit of commodity p over pre-/end-haulage link g
$C_s^{\lambda,p}$	is the total costs of moving one unit of commodity p over service link s
f_p^r	is the volume of commodity p moving over route r
e_m^{α}	is the CO_2 emissions per tonne-km incurred in transport by mode m
$c_x^{\alpha,M}$	is the unit mode-related cost of mode m in main haulage
c_p^P	is the unit freight-related time cost of commodity p
d_x^{α}	is the length of link x
v_m^{α}	is the average speed of mode m in main haulage
$c^{\boldsymbol{co_2}}$	is the price for CO_2 emissions measured in tonne of CO_2 emissions
e_h^{β}	is the CO_2 emissions per tonne-km incurred in transhipment h;
ε_h^t	is an alternative specific constant indicating the costs variation caused by specific features of the handling between terminal t and a certain transport mode via a transhipment link h;
c_h^{β}	is the unit handling cost of transhipment link h

f_h^{β}	is the flow over transhipment link h
e_a^{γ}	is the CO_2 emissions per tonne-km incurred in access/egress a
ε_a^{γ}	is an alternative specific constant indicating the costs variation caused by specific features of the access/egress between the region o and the road network;
$c_a^{\gamma,M}$	is the unit mode-related cost of access/egress a
c_p^{P}	is the unit freight-related time costs of commodity p
d_a^{γ}	is the distance of access/egress a
v_a^{γ}	is the average speed of access/egress a
e_g^{θ}	is the CO_2 emissions per tonne-km incurred in pre-/end-haulage g
ε_g^{θ}	is an alternative specific constant indicating the costs variation caused by specific features of the pre-/end- haulage between region o and terminal t
$c_g^{\theta,M}$	is the unit mode-related cost of pre-/end-haulage g
d_g^{θ}	is the distance of pre-/end-haulage g
v_g^{θ}	is average speed of pre-/end-haulage g
$c_s^{\lambda,F}$	is the annual fixed cost of barge operating along link s, $c_s^{\lambda,F} = f(z_s^{\lambda})$;
$c_s^{\lambda,D}$	is the distance-related variable costs of moving containers along link s, (€/t-km), $c_s^{\lambda,D} = f(z_s^{\lambda}, v_s^{\lambda})$;
$c_s^{\lambda,U}$	is the time-related variable costs of containers moving along link s (€/t-h), including mode-related time costs and commodity-related time costs, $c_s^{\lambda,U} = f(z_s^{\lambda})$;
z_s^{λ}	is the maximum barge size navigable along link s;
v_s^{λ}	is the average speed of barges operating along link s;
$u_s^{\lambda,H}$	is the total handling time of a round trip along link s;
$u_s^{\lambda,SH}$	is the total shipping time of a round trip along link s;
d_s^{λ}	is the length of link s;
sns	is the service network structure (see Appendix IV (a) (b) (c));
nr_s^{λ}	is the number of barges needed to serve demand over link s, $nr_s^{\lambda} = f(z_s^{\lambda}, f_s^{\lambda})$;
f_s^{λ}	is the flow along link l_i.

k_s^λ is the total annual transport capacity of the nr_s^λ barges (full load and the maximum

$f_{\mathrm{i,j}}^{o_1, o_2, \mathrm{p}}$ is flow of commodity p from origin o_1 to destination o_2 over link (i, j)

$C_{\mathrm{i,j}}^{o_1, o_2, \mathrm{p}}$ is total costs of link (i, j) as moving one unit of commodity p from origin o_1 to destination o_2

$\delta_{\mathrm{i,j}}^{o_1, o_2, \mathrm{p}}$ is the availability of link (i, j) for moving a unit of commodity p from origin o_1 to destination o_2 $\delta_{\mathrm{i,j}}^{o_1, o_2, \mathrm{p}} = 0$ when the link is not available, $\delta_{\mathrm{i,j}}^{o_1, o_2, \mathrm{p}} = 1$ otherwise

μ is binary array expressing the openness of terminals, $\mu_{w,b} = 1$ if terminal b is opened in terminal network configuration w, $b \in B$, and $\mathrm{w} \in \mathrm{W}$

C^* is the vector of total link costs of the optimal solution at the lower level

f^* is the vector of link flows of the optimal solution at the lower level

n^{obs} is the number of observations

v_l is the observed value of link l

$\tilde{v}_l$ is the calculated value of link l

$\mathrm{C}_{\mathrm{m}}^{\alpha,\mathrm{M}}$ is the array of the unit mode-related costs of main-haulage; $\mathrm{c}_{\mathrm{m}}^{\alpha,\mathrm{M}} = \{\mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{road}}, \mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{rail}}, \mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{IWW}}\}$;

$\varepsilon_{\mathrm{m}}^1$ is the array of parameters relating to the unit model-related costs of main-haulage, $\varepsilon^1 = \{\varepsilon_{\mathrm{road}}^1, \varepsilon_{\mathrm{rail}}^1, \varepsilon_{\mathrm{IWW}}^1\}$;

$\mathrm{c}_{\mathrm{t,m}}^{\beta}$ is the array of handling costs; $t \in$ [1, the number of terminals], $m \in$ {road, rail, IWW};

$\varepsilon_{\mathrm{t,m}}^2$ is the array of parameters relating to the handling costs when transferring one tonne of freight from terminal t to mode m, $t \in$ [1, the number of terminals], $m \in$ {road, rail, IWW};

$\mathrm{c}_{\mathrm{o}}^{\gamma,\mathrm{M}}$ is the array of the unit mode-related costs of access/egress when moving the freight generated in region o to the road network, o ∈ [1, the number of regions];

$\varepsilon_{\mathrm{o}}^3$ is the array of parameters relating to the unit mode-related costs of access/egress, o ∈ [1, the number of regions];

$\mathrm{c}_{\mathrm{o,t}}^{\theta,\mathrm{M}}$ is the array of the unit mode-related costs of pre-/end-haulage when moving the freight generated in region o to terminal t, o ∈ [1, the number of regions], t ∈ [1, the number of terminals within a reasonable distance of region o];

$\varepsilon^4_{\mathrm{o,t}}$ is the array of parameters relating to the unit mode-related costs of pre-/end-haulage, $\mathrm{o} \in$ [1, the number of regions], $\mathrm{t} \in$ [1, the number of terminals within a reasonable distance of region o];

$\mathrm{c}^{\mathrm{P}}_{\mathrm{p}}$ is the array of the unit commodity-related time costs of the freight, $\mathrm{p} \in$ [1, the number of commodity types];

$\bar{c}^{P}$ is the average of the unit commodity-related time costs of all commodity types;

ε^5 is the parameter relating to the average of the unit commodity-related time costs of all commodity types;

q^P_p is the array of the proportion of commodity p in the total volume of all commodities;

ε^6_p is the array of parameters relating to the proportion of commodity p in the total volume of all commodities.

E is the elasticity of mode-related costs to total network flow

Notes 1: variables or parameters

f	flow
c	cost
C	total costs
v	speed
d	distance
e	emissions
ε	variance
u	time
nr	number
k	capacity
δ	link accessibility
μ	terminal accessibility

Notes 2: superscript

M	mode-related costs
P	commodity-related costs
F	fixed costs
D	distance-related costs (euro per tkm)
U	time-related costs (euro per t-hour)
H	handling costs (euro per tonne)
SH	shipping time
α	main-haulage
β	transhipment
γ	access/egress
θ	pre-/end-haulage
λ	service
co_2	CO_2

Chapter 1

Introduction

1.1 Background

European Transport Policy: towards a sustainable transport system

“The goal of the European Transport Policy is to establish a sustainable transport system that meets society’s economic, social and environmental needs” (CEC, 2009). This statement indicates the challenges that the European transport policy makers are faced with when aiming to ensure economic growth and facilitate an increasing freight transport demand with limited transport infrastructures, while keeping the transport system sustainable. This also aligns perfectly with Dutch Freight Transport Policy and the aims of the Project Sustainable Accessible Randstad (DBR) initiated by the Ministry of Infrastructure and Environment, and the Netherlands Organization for Scientific Research (NWO).

The history of European policy making started in 1992 with the White Paper on the Future Development of the Common Transport Policy (EC, 1992), followed and elaborated by the CTP Action Programmes 1995-2000 (CEC, 1995) and 1998-2004 (CEC, 1998), included sustainability and social cohesion into the set of objectives to be achieved by the Common Transport. It explicitly placed on the agenda to limit the carbon dioxide (CO_2) emissions caused by transport. Since 1992, the broadening of the Common Transport Policy agenda has led to the initiative and intensification of policy making at European level (Giorgi and Schmidt, 2002).

During the last decades, the cross-border flows within European continent also increased due to the enlargement of European Union (EU), which removed constraints on cross-border movements, and thus reduced the transport costs encouraging freight transport. In the coming decades, as reported in the European Commission funded FREIGHTVISION project, a continuing growth of global freight flows (Helmreich and Keller, 2011) due to mainly evolvement of global trading networks, trade liberalization, and outsourced manufacturing. The ever increasing freight transport demand brings more and more pressure on the sustainability of the freight transport system. In freight transport policy, especially CO_2 emissions and road congestion take centre stage within the EU.

The transport sector is responsible for 21.7% of the CO_2 emissions in Europe (EU27) in 2010 (EEA, 2012), which makes it a large contributor to greenhouse gas emissions. Moreover, and in contrast to other sectors, the CO_2 emissions from transport activities increased compared with the base year of 1990 (EEA, 2012). Between 1990 and 2008, transport emissions increased by 34% while emissions from other sectors decreased on average by 14% (TE, 2010). Since the sector is 97% dependent on fossil fuels, the environmental concerns also align with the urgency to improve energy security (CEC, 2009).

Next, road congestion forms another major issue as it severely affects the sustainability of the transport system. Congestion causes time losses and additional greenhouse gas (GHG) emissions. UNITE (Unification of accounts and marginal costs for transport efficiency) has estimated the congestion costs in western Europe to represent 1% of the gross domestic product (GDP) (Nash and with contributions from partner, 1999).

The mid-term review of the European Commission's 2001 Transport White paper (CEC, 2006a) further specified that the most critical aspects of sustainability with regard to the European transport system are GHG emissions, energy use, road safety, and traffic congestion. In the developed model, especially sustainability and congestion take centre stage.

Strategy to encourage sustainability: intermodality

Shifting more flows to more sustainable modes (also known as modal-shift), for example rail, inland waterway, and sea transport, was recognized as an important strategy by the European Commission. In 1997, the Communication from the Commission (CEC, 1997a) has set general strategies and actions in this direction. The objective was to develop a framework for an optimal integration of different modes so as to enable an efficient and cost-effective use of the transport system through seamless, customer-oriented door-to-door services whilst favouring competition between transport operators. The 2001 White Paper (EC, 2001) reiterated that intermodality is of fundamental importance for developing competitive alternatives to road transport. "Co-modality", relating to the efficient use of different modes on their own as well as in combination, will result in an optimal and sustainable utilization of resources. Alternatives to congested road corridors include co-modal logistic chains that improve the use of transport infrastructure within and across the different modes (CEC, 2006a).

Many efforts have been made to promote modal shift, while modal split is expected to stabilize in the longer term (CEC, 2006a). Statistics show that in 2007 in total 2,650 billion tkm were produced in the EU-27 when only considering the transport modes for continental transport (road, rail, inland waterways, and pipelines). More than two thirds of the total (72.7%) were attributed to road transport, while rail, pipelines, and inland waterways accounted for, respectively, 17.1%, 5.3%, and 4.9%. This emphasizes that more efforts are needed in order to achieve a larger modal shift (CEC, 2007).

The EU has been promoting intermodal transport since the 1990s through regulatory policies. Pricing, subsidization, and liberalization have been the most used leverages in order to reduce the externalities of intermodal freight transport and to encourage modal shift. We introduce these policy directions in brief below.

Subsidization of intermodal freight transport

The Marco Polo programme has been implemented aiming at fostering combined transport and achieving a shift of freight traffic from road to rail and sea. The programme has offered European Community's funds to support the start-up of new services that have been expected to accomplish this shift. The programme has subsidized the service in the initial operating period when they would otherwise not be profitable. For the following periods, the proponents have needed to show that the services would be profitable and operational without the Marco Polo funds (Site and Salucci, 2009).

The NAIADES programme (CEC, 2006b) is a financial and technical assistance framework in the domain of inland waterway transport. It is intended for the period 2006–2013 and focuses on five strategic areas for a comprehensive inland waterway transport policy: market, fleet, jobs and skills, image, and infrastructure. Issues being addressed under NAIADES include working time arrangements, professional qualification requirements, the examination of administrative and regulatory barriers, the adoption of innovative technologies, such as the River Information Services (RIS), and infrastructure improvements.

Pricing of road freight transport

Road pricing is considered the way forward to restore the balance between modes. In turn, a significant modal shift from road is expected to contribute in resolving both the congestion and the environmental problems facing transport. This was addressed in the 2001 transport White Paper (EC, 2001) focusing on road pricing, in particular for freight transported by heavy goods vehicles. A framework for charging of international heavy goods flows on road was proposed by the European Commission for the amendment of the Eurovignette Directive (EC, 1999b) on the charging of heavy goods vehicles and the rules for the cross-financing of transport infrastructures (CEC, 2003). The directive was approved in 2006 (EC, 2006) with the rules for tolls on the trans-European network. A greater variation was introduced in the tolling rules to reflect congestion or pollution. This directive represents the first step towards accounting for external costs.

Liberalization of freight transport market

Legislative initiatives at EU level have addressed the opening of rail freight services to competition. The 2001 White Paper (EC, 2001) proposed to open up national markets for cabotage, and to further harmonize the safety, interoperability and exclusiveness of a network of rail lines to freight services. The Mid Term Review (CEC, 2006a) also announces the development of a framework strategy for freight transport logistics in Europe. Actions include removing regulatory obstacles to co-modality, and promoting standardization and interoperability. In the waterborne sector, following the 1997 Green Paper (CEC, 1997b), the Commission has supported the liberalization of port services. The further integration of ports into the trans-European Transport Network has been emphasized in the 1999 Communication from the Commission on short-sea shipping (EC, 1999a).

Improving service quality of intermodal freight transport

Improving the quality of service of intermodal transport is necessary to improve the competitiveness of intermodal transport against road transport. The term ‘quality of service’ can be interpreted in two aspects. Firstly, from a social perspective the quality is represented by an efficient use of energy and infrastructure, and limited impact on the surroundings and the environment. Secondly, the demand for quality from the transport market is represented by high operational performance, expressed by high levels of reliability and low operating costs.

Social perspective

Transport is one of the main contributors to GHG emissions, and one third of which are attributed to freight transport (CEC, 2007). Although less emission is already one of the advantages of the intermodal transport against road transport currently, more improvement can be done in order to reinforce or maintain this advantage. Electric locomotives are put in operation to reduce the CO_2 emissions and fossil fuel dependency. Freight train capacities and country-dependent weight restrictions are under discussion, because extra-long trains and heavy trains are proposed as measures to improve the load factors, and thus to improve the energy use efficiency. In addition, cooperation among the operators and freight consolidation are encouraged by experts to increase the competitiveness of intermodal transport because of increased shipping sizes and higher load factor. High load factors, along with environment-friendly energy sources, are necessary preconditions for rail and waterways transport to be sustainable, in comparison with road transport. These preconditions are not easily met today (Kim and Van Wee, 2009).

Market perspective

Improving the intermodal transport service has been extensively discussed and actively implemented in the last two decades, with a focus on the improvement of terminals and the corridors connecting these terminals. One example is the TEN-T programme, aimed at developing an efficient trans-European transport network. The programme started in 2001 and is currently under implementation. The TEN-T programme is the main instrument for EU financing of transport infrastructure developments across all modes.

In addition to the "hard" physical infrastructure (such as road, inland waterway infrastructure, rail tracks, ports, and terminals), "soft" infrastructure also plays a role in the improvement of the quality of intermodal transport. New technologies will change the appearance of the portfolio of transport services on the European network: better services will be provided through seamless integration. The Freight Transport and Logistics Action Plan (CEC, 2007) of the European Commission proposes a series of measures to promote the freight transport logistics, focusing on the quality and efficiency of the movement of freight and on the ease of freight-related information exchanges between modes. All stakeholders involved in freight transport chains are encouraged to participate in this plan. Improved interoperability will not only influence strategic mode choice decisions by improving the service, as intended by the policy, it will also allow new approaches towards mode choice to emerge with shipping and forwarding companies. The e-Customs initiative was introduced by Decision No 70/2008/CE (EC, 2008). The goal is to facilitate information exchange on freight movements via ‘electronic declarations as a rule’, interoperable national computer systems, and single window solutions.

The mid-term review of the EU White Paper on Transport (CEC, 2006c) finds that the measures supporting the market towards modal shift have not been very successful. On the other hand, one could argue that a lack of policy could have led to a higher share of road transport than today. During the last decade, however, the shares of rail and waterways have been increasing slightly, and the forecasts indicate a further shift in flows (Helmreich and Keller, 2011).

Research needs for intermodality

Intermodal transport can help Europe to enhance its competitiveness and at the same time to cope with the ever increasing demand for transport and the necessity to minimize its environmental impacts. With an overview of the European Commission’s research projects concerning the issues regarding intermodal network efficiency, technical improvements of intermodal transport, and applications of ICT to intermodality, the Transport Research Knowledge Centre identified a number of obstacles that prevent the extensive use of intermodal transport (Site and Salucci, 2009). These include the lack of a coherent network of modes and interconnections, the lack of technical interoperability among and within modes, a variety of regulations and standards for transport means, and data interchange and procedures. Many policies have been practiced. More measures leading to intermodal transport have been proposed. A substantial amount of research is focused on proposing solutions to strengthen the intermodal freight transport system in Europe (Escudero et al., 2010; Janic, 2006; Konings et al., 2008; Woxenius et al., 2013). Part of this stream of work is oriented towards developing appropriate methods for quantitative assessment of costs and benefits of solutions. Our work falls into this last category.

The focus of this thesis is a model to support the design of intermodal transport networks. More precisely, this thesis aims to contribute a new model to support policy making for a large-scale intermodal freight transport network. It has to be applicable at the scale of the European Union. Such evaluation models are needed to evaluate the effects of the implemented policies, to estimate the impacts of the proposed policies, and to discover new problems in the transport system. In the next section we describe our objectives and research questions in more detail.

1.2 Research objectives

The *main research objective* is:

Develop a model that supports the intermodal freight network design, which would be based on the design measures concerning transport infrastructure, services, and policies.

As discussed in the previous section, the increased demand for freight transport puts stress on the sustainability of the living environment, and as a result public concerns and governmental strategies come to play a role in the freight transport system. The requirements to ensure the development of freight transport networks are more complex than merely providing sufficient capacity. In the past, many policies have been proposed and implemented aimed at a more sustainable freight transport system. Examples are infrastructure improvements for intermodal transport, subsidization of intermodal transport operators (or users), and new taxation schemes. We need a method to evaluate the impact of these policies in practice while taking into account the complexity of the freight transport network. As we will see in the literature review (Chapter 2), such models do not exist currently. Practically applicable models are needed to support the decision-making process. Therefore, in this thesis, we propose a new model to support the decision-making in freight transport infrastructure network design and optimization.

Research question 1:

What are the challenges in design of the large-scale freight transport infrastructure network design?

“Large scale” here refers to a network which covers a large geographic area (e.g., a national or international network), and contains a detailed description of the network characteristics. A larger network scale is inherent to a higher degree of heterogeneity, in terms of relevant actors, transport demand, options of transport services, etc. These heterogeneities, and especially the combination of them, bring new challenges to freight transport infrastructure network design. We will address the new challenges in Chapter 2.

Research question 2:

Which methods are available to deal with the(se) challenges?

The study of freight transport network design methods started three decades ago. Many methods and models have been developed for various purposes. The second part of Chapter 2 discusses the methods that address the new challenges that we recognized, and reviews the existing models that, were in part developed in response to a number of these challenges.

Research question 3:

Which freight transport network optimization model is needed in order to be able to deal with all of the challenges following from Question 2 in an integrative way?

The heterogeneities of large-scale freight transport are not sufficiently incorporated in the existing network design models. In Chapter 3, we develop a new model specifically aimed at better incorporating the heterogeneities observed in freight transport networks. We address the mathematical specification, solution algorithms, and computational methods.

Research question 4:

How to calibrate and validate the model for practical applications?

The model is developed to better incorporate the heterogeneities in the freight transport networks, for the application of terminal network design and optimization of the Dutch container transport. To this end, the model needs to be calibrated for the freight transport in the Netherlands. We discuss the calibration and validation process as well as the quality of the calibrated model in Chapter 4.

Research question 5:

How can the newly developed model be applied in practice for the strategic planning of infrastructure networks?

This question will be answered by learning from actual applications of the model. The model to support decision-making in the field of freight transport infrastructure network design is developed. The model will be implemented to design and optimize the Dutch container terminal network and propose implementation strategies to the policy makers.

1.3 Research scope

1.3.1 Methodological scope

Decisions: infrastructure network, service network, and regulatory policy

This thesis aims at contributing to the field of freight transport network design with the focus on infrastructure network design, while taking into account the influence of service network design. The configuration of terminal network from the governmental perspective is considered in this research as the main concern in the infrastructure network design. In the dimension of service network design, it focuses on the design of transport operators' service network including the decisions on fleet capacity, frequency, and terminal choice. In addition, since the infrastructure network design closely relates to public policy decision-making, the regulatory policies, such as emission pricing, are also in the scope of the research. We should notice that in addition to the infrastructure network and the service network, other supplementary networks, for example, the documentation transaction network, the money transaction network, and the information interaction network, are also important in operating the freight transport system. However, this thesis will only focus on the infrastructure network, the service network, and regulatory policy.

Model user perspective: government and public/private consortia

The model is developed from the governmental perspective for mid- to long-term strategic planning. The model simulates the decision-making behaviour of transport operators for the purpose of providing insights in the aggregated impacts of various policies on the freight transport network performance. Scenario analyses can be carried out at the international, national, corridor, and regional scale.

Time-span: mid-term to long term

This model is designed for mid- (three to five years) to long- (more than five years) term terminal network design. The focus is modelling the required infrastructure supply. No capacity restriction is to be applied to transport means, infrastructure, or terminals.

Dynamics: static model with fixed volumes of demand

This model aims to capture the behaviours of different actors involved in the mid-term or long-term decisions. It focuses on evaluating a large number of combination of design measures including the infrastructure network configuration, pricing, and collaborative operations in intermodal transport services. The decisions on these measures are not sensitive to the dynamically changing transport demand during a short period (e.g. a day or a week). Therefore, the model is designed as a static model with fixed annual freight transport demand at the level of trade relations. The dynamics in the transport demand, or in the operational decisions of network use are not taken into account.

1.3.2 Empirical scope

Geographic scope: NL with connections to other EU (27) countries excluding UK

Geographically, this research focuses on the Netherlands with connections to other European countries where containers are transported to/from/passing through the Netherlands via road, rail, or inland waterway. Short-sea shipping is not in the scope of this research.

Scale: international, large scale, and detailed in NUTS 3

The model contains geographic information of the EU (27) area, including the road network, the rail network, and the inland waterway network with sufficient navigability for container transport. The demand for freight transport is modelled at NUTS 3 level (the Nomenclature of Territorial Units for Statistics levels) (Eurostat et al., 2010). The model is implemented to the Dutch container hinterland transport. Therefore more the demand database and the operational information database development focuses on the national and international connections for the Dutch container transport.

Mode: road, rail, inland waterway

Based on the character of the freight transport network of the Netherlands, which is a sea port-driven hinterland distribution network, we only functionalize three transport modes in the model, namely, road, rail, and inland waterway. Different navigating conditions are specified for inland waterway transport with it is relevant to service network design.

Commodity: container

The model is generically applicable to freight. The discussion in Chapter 2 about the challenges for freight transport network also concerns general freight. In Chapter 5 describing an application of the model, focus on container transport in needed, mainly due to data availability. Bulk, break-bulk, etc., are not considered in the scope of the application of the model.

1.4 Research relevance

Freight transport infrastructure network design has been developing in the last several decades. A wide range of literature and practical experiences is available. This thesis contributes to the field, particularly from the governmental/collective perspective. It recognizes new challenges for the freight transport network design with the focus on infrastructure network. A new model towards an integrated solution that incorporates these challenges is proposed. The model supports infrastructure network design while taking into account the transport operators' service networks, and transport regulation. The applications of the model provide new insights into freight transport network design. A more efficient and sustainable design of the freight transport infrastructure network may be derived from using the new model as compared to the ones resulted from the models considering them individually. In the remainder of this section, the more detailed scientific and practical contribution of this thesis is identified.

1.4.1 Scientific contributions

The scientific contributions of the thesis can be summarized as follows:

Identifying new challenges for modelling freight transport infrastructure network design.

Chapter 2 provides insight into the new challenges to modelling the freight transport infrastructure network design, related to the large-scale networks, multimodality multicommodity transport with multiple actors, and a diversity of service networks. Reviewing the existing relevant models and the methods contributing to these challenges, we uncovered that these characteristics of freight transport have been studied for different purposes. However, a model which is able to comprehensively incorporate these characteristics and provide integrated network designs is lacking.

Proposing a modelling approach for a multiactor multimodal multicommodity freight transport infrastructure network design which enables integrated infrastructure, service, and policy design in a large-scale network.

Chapter 3 and Chapter 4 develop, calibrate, and validate a new freight transport infrastructure network design model. The model supports infrastructure network design while taking into account the goals of multiple actors. It is able to optimize the infrastructure network performance which representing the goal of the government; optimize the terminal operators' benefit gained from efficient use of terminal capacity; optimize the fleet use and service frequency of the transport operators' services; and search for the optimal door-to-door routes for the shippers in an integrated way. Applying this integrated model provides new insights into the interrelationships among the infrastructure network, the service network, and the regulatory policies.

Providing a network presentation method which is suitable for intermodal freight transport.

Models based on Geographic Information Systems (GIS) are increasingly favoured for freight transport network design due to their advantages in visualization. A super network representation is proposed in Chapter 3. The pre-/end-haulage and hub-network-based networks are specified particularly in the network aiming to capture the features of the relevant services more realistically as compared to the existing models. This enables differentiating the pre-/end-haulage of intermodal transport from the unimodal road transport, and thus is able to quantify the performances of the intermodal transport such as costs, time, and influence on the environment. The transport demand generated in a region is not restricted to be supplied by the terminals locating in the same region. The links representing the pre-/end-haulage captures the attractiveness of a terminals for different regions, and enables modelling the terminal choice, in addition to the classic mode choice, and route choice. This provides new options for modelling catchment area of the terminals, terminal competition and/or cooperation on the basis of a GIS environment.

Sharing the experience in implementing, calibrating, and validating the large-scale GIS-based models.

Calibration and validation are important for development of the complex network design models, although rarely discussed in the literature. Chapter 4 introduces and compares a genetic-algorithm-based calibration method and a feedback-based calibration method. The procedures and results of calibration, and performance of both methods, are extensively discussed. It contributes to bridge the gap between theoretical modelling and the application in practice.

1.4.2 Practical relevance

Providing a model for practical integrated infrastructure, service, and policy design. Chapter 3 develops a multimodal multicommodity freight transport infrastructure network design model. It is generically applicable to freight transport infrastructure network design in terms of the model architecture, methods, and algorithms. The model is initialized for The Dutch container transport in Chapter 4, and is calibrated for the base year 2006. Chapter 5 illustrates an application of the model for the strategic planning of the Dutch container terminal network. The model provides a rather rich information on the impacts of pricing and terminal network configuration on the network costs, emissions, and utilization.

Recommendations for the Dutch hinterland container transport network design. The model evaluates the combined influences of CO_2 pricing, different terminal network configurations, and collaborative transport operators' service network on the Dutch container transport. CO_2 pricing, terminal network configurations, and potential hub-service-networks are used as the design measures to optimize the Dutch container transport infrastructure network. Practical implications are obtained from this application with regard to the modal shift from road to intermodal transport, reduction of CO_2 emissions, terminal location allocation, hub service network, and freight flow accommodation.

1.5 Outline of the thesis

The outline of the thesis is shown in Figure 1.1.

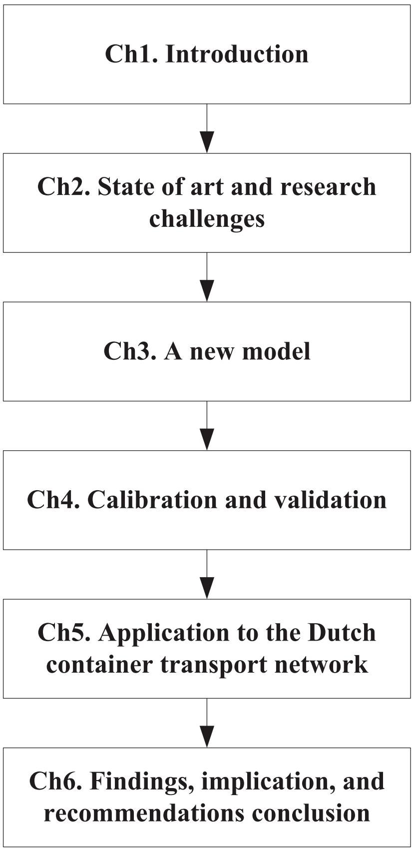

Figure 1.1. Outline of the thesis

In addition to this chapter introduced background, and objectives of the research, Chapter 2 discusses the challenges of modelling large-scale freight transport infrastructure network design. Upon reviewing the body of literature on freight transport network design models, new requirements for such models are derived. In Chapter 3, a new freight transport infrastructure network design model based on the new requirements recognized in Chapter 2 is developed. The model has three main functions: data visualization, flow estimation, and network optimization. Each function is realized by one or two sub-model(s), where each sub-model is formulated based on the previous models reviewed in Chapter 2. However, the integration of these sub-models shows a way to fulfil the new requirements for the large-scale freight transport infrastructure network design models. Chapter 3 explains the interaction between these sub-models and the mathematical specification of the network, flow estimation, and network optimization.

Chapter 4 dealing with calibration and validation of the flow estimation sub-model. Calibration is carried out by parameter estimation, deploying two methods: a genetic algorithm based method, and a feedback-based method. Following the detailed explanation of each method, the performances of these two methods are evaluated. Furthermore, the sub-model of flow estimation is validated by comparing the modelled results with the corresponding observations, testing the stability of the parameter estimation, and analysing the cross elasticities of the cost change for one mode to the transport demand change for all modes.

Chapter 5 applies the model developed and validated in Chapter 3 and Chapter 4 to the optimal design of the Dutch container transport infrastructure network. A large number of alternative combinations of polices are evaluated. Each combination consists of a specific terminal network configuration and a specific price for CO_2 emissions. The results are analysed and interpreted in detail, leading to a number of implications for policy makers.

In Chapter 6, the newly developed model is reviewed, the main findings and their practical implications are highlighted. The thesis ends with identifying potential directions for the further research.

Chapter 2

Freight Transport Infrastructure Network Design: State of Art and Research Challenges

2.1 Introduction

This thesis deals with models for large-scale freight transport infrastructure network design (FTIND), from the governmental perspective. This chapter provides an insight into the new challenges and new requirements for the FTIND models.

The chapter begins by introducing a conceptual model of the freight transport system in general. The main focus is on the freight transport infrastructure network design, with particular interest in FTIND for hinterland transport. In Section 2.4, we discuss the challenges facing FTIND. After providing a review of the existing methods and integrated FTIND models in Section 2.5 and Section 2.6, the features of the model that will be developed are described in Section 2.6. Finally, a summary of this chapter is provided in Section 2.7.

2.2 Freight transport system

The freight transport system consists of the infrastructure, the means, the equipment, and the activities necessary for the movement of freight, and the actors who carry out these activities. Before freight transport became a specific sector of transport system studies, the transport system commonly was presented in layers in the literature. Manheim has proposed a so-called ”total transportation system” with a two-layer framework comprised of three elements: the transportation system, the activity system (social and economic activities), and the flows (volumes of freight moving in the transportation system) (Manheim, 1979). The transportation system and the activity system and the flows were two separate loops. There was no direct relationship between the transportation system and the activity system. They were only connected via the flows. Manheim's model captures the basic relationship in the transport system: transport demand and service supply, interacting with each other via the flows of freight or passengers.

This layered approach has also led to the development of other transportation system models. Borg proposed five-layer model (Borg, 1991)see also (Wandel, 1992)). According to Borg, the transport system is comprised of transport infrastructure, transport operations, material flow, telecommunications infrastructure, and informatics operation. In this framework, the supply side of the transport system is subdivided into infrastructure and operations. This subdivision demonstrates that transport services actually operate as the media connecting the transport demand and the infrastructure supply.

These layer frameworks are also applicable to the freight transport system. We propose a three-layer framework (see Figure 2.1) for the purpose of network design. It is modelled after Borg's framework, but our framework focuses on the functions of each network and the actors who operate the network.

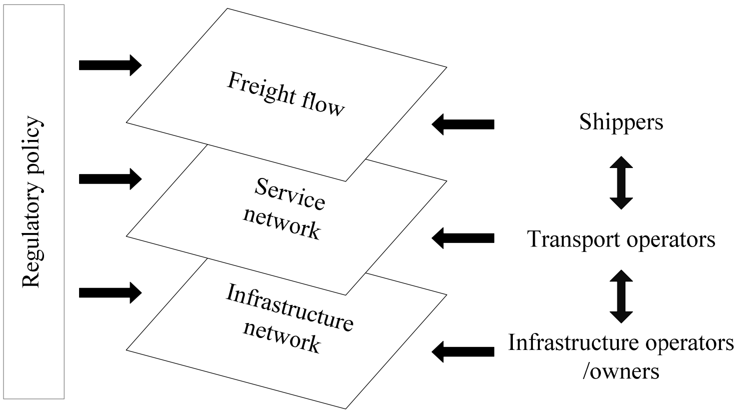

Figure 2.1. Three-layer framework of freight transport

We propose a new framework that is composed of an infrastructure network, a service network, freight flows, and regulatory policy. The infrastructure network includes: roads, rail, and navigable waters, as well as terminals which provide transhipment and connect the road network, the rail network, and the waterway network together. Services between various origins/destinations are developed on the basis of the demand for transport services and the availability of the infrastructure network. Service legs provide transport services between specific demand origins/destinations. A combination of two or more service legs forms a service network. Freight flows refer to the transport consigned from sender to receiver. Freight flows are routed over the infrastructure network via the service network. All of the three layers are impacted by the regulatory policies (e.g., pricing, taxation, and subsidization).

The layers interact with each other through the activities of the relevant actors. The shippers generate the flow demand. Transport operators/carriers, as the owners of the transport capacities, provide the transport services to the shippers. Infrastructure operators (e.g., terminal operators and rail operators) own or rent the infrastructure and provide transport capacities to the transport operators. Moreover, governmental entities involve in all three layers through regulatory policies and management of public assets.

2.3 Freight transport network design (FTND)

If we understand the freight transport system as consisting of layers of networks, and we assume that the actors participate in freight transport activities via an infrastructure network and/or a service network, then we can transform the planning and policy making problems of freight transport into network design problems. This has been discussed extensively in the literature and is recognized as an important approach for freight transport planning (Caris et al., 2008; Crainic and Laporte, 1997). Network design can be applied in a number of ways, including evaluating measures for cost savings, relieving congestion, and/or managing the impact of transport on the environment.

Freight transport infrastructure design (FTIND)

The infrastructure network design for freight transport usually deals with issues such as infrastructure configuration (including adding, expanding, or abandoning segments of roads, rail, inland waterways, or terminals) under a certain budget constraint and providing sufficient capacity while optimizing the network utilization. In addition, it deals with policy making problems, such as pricing, subsidization, and taxation, in order to promote the efficient use of the infrastructure networks.

Since the development of transport infrastructure has been increasingly attracting public attentions, and since the infrastructure network design closely relates to public policy decision-making, choosing a public policy or a combination of public policies with a budget constraint is considered as a typical problem.

Freight transport service network design (FTSND)

Planning and policy making problems associated with the freight service network design include: service selection, traffic distribution, terminal policies, and empty balancing strategies (Crainic, 2000). Service selection concerns the routes on which services will be offered, and the characteristics of each service (e.g. scheduling); traffic distribution concerns the routes used to move the traffic demand; terminal policies concerns mainly the consolidation activities at terminals; and empty balancing concerns the reposition of empty vehicles to meet the needs of the next planning period (Crainic, 2000). These tactical decisions in the freight service network design have an impact on the infrastructure network design, including the capacity of (or a part of) a network, its utilization, and related costs.

Regulatory policies

From the governmental perspective, the public policies for FTND are not only limited to infrastructure configuration, but also have a large influence on the design of infrastructure networks. These policies cover a broad range of regulatory issues, for example, subsidies, taxes, fees, usage permissions, time windows, and promoting technology innovations. Some examples of the latest are new generation engines/vehicles/ships, alternative energies, innovative handling techniques, and information management techniques.

2.4 Challenges for FTIND

In this chapter, we focus on strategic planning, particularly on infrastructure network design, and tactical planning in service network design which assists the infrastructure network design.

The involvement of public concerns, facilitated through the governmental perspective, brings additional complexity into infrastructure network design. In general, a freight transport network consists of multiple modes, for example, road, rail, and inland waterway. Generally, the links in the network (i.e., road/rail/inland waterway segments) are publically owned, while some nodes in the network (i.e., terminals) and the services which are provided over the network are owned by private entities, public entities, or a combination of both. Consequently, multiple actors with multiple objectives are usually involved in the network design.

In the next sections, we discuss the following challenges in FTIND:

- enlargement of spatial scale;
- multimodality;
- multicommodity;
- multiactor;
- service network design.

2.4.1 Challenge I: Enlargement of spatial scale

FTIND on a larger spatial scale brings heterogeneities into the demand for freight transport infrastructure and services.

Since freight transport flows have increased in the last decades, congestion in port areas and urban areas has become a serious problem. The increasing public awareness of environmental problems and quality of life issues, have forced governments to consider the infrastructure network planning in a larger spatial scale, develop long-term strategic planning, and provide a convincing vision for the future infrastructure network to the public. FTIND from the governmental perspective requires an extension of the planning scale.

The enlargement of spatial scale creates additional complexity in network design in three ways. First, more actors with various objectives are involved in the scale of planning, such as ocean carriers, short-sea carriers, port authorities, terminal operators, hinterland transport operators, shippers, and relevant governments at various administrative levels. The complex interrelationships and interactions among these actors result in difficulties in incorporating their objectives into a design. Second, additional types of freight need to be taken into account and these may require among other things different types of transport networks in terms of diversity of modes, speed, costs, and reliability. Last, in order to design a large-scale network, increased amounts of geographic and transport data need to be analysed, which can result in difficulties in solving the network design problems within an acceptable computing time.

In summary, on a large spatial scale FTIND leads to more heterogeneity, more actors, and a heavy reliance on data.

2.4.2 Challenge II: Multimodality

A multimodal network is a transport network where multiple transport modes are combined in providing door-to-door freight transport services.

Due to increased road congestion and impacts on environmental issues, there is increasing intention for freight alternatives to road transport, including rail and/or inland waterway transport. Consequently, the intermodal transport has become an alternative to uni-modal road transport for providing door-to-door freight transport services results in emerging a multimodal freight transport network.

Using multiple modes substantially increases the complexity of the freight transport network, mainly because both mode-choice and terminal-choice need to be considered in routing the freight flows.

Intermodal transport makes consolidation of freight possible. Moving more freight transported by train or barge, in principle, results in lower unit transport costs, due to higher utilization of the capacity of transport means. This is known as economies of density (EOD), where the transport costs are not necessarily linear to the transport flow.

Since more actors are involved in an intermodal transport service, the door-to-door service costs depend on operation of more entities. Handling costs of terminal operators, to a great extent, impact the intermodal transport costs, and thus impact the decision on the usage of the network. The handling costs depend on the terminal throughput and the scale of terminal. For a terminal operating under its capacity, an increase in throughput results in reduced unit handling costs (EOD). If throughput continuously increases and causes congestion in the terminal, the inefficiency in handling would result in an increase in unit handling costs. In order to avoid such result, the terminals usually invest in the capacity enlargement and the technology improvement. So a larger terminal with high throughput is more likely to have lower unit handling costs compared with its smaller counterpart. The cost efficiencies gained by scale are known as economies of scale (EOS). Principally, in the long run, the economies of density, the inefficiency caused by capacity shortage, the scale enlargement and handling technology improvement, the diseconomies of density after scale enlargement, and the economies of scale appear iteratively (Ballis and Golias, 2002). Due to the EOS of terminal handling, the door-to-door intermodal transport costs are not necessarily linear to the transport distance, but also depend on the throughput and the scale of the terminals involved in this door-to-door service.

EOD and EOS also exist in the operation of a service line. The former can be achieved by higher utilization of the fleet capacity with more efficient scheduling. The latter can be achieved by higher utilization of management capacity and improved administrative efficiency.

EOS and EOD are important factors in freight transport that should be taken into account in FTIND, but they also result in difficulties in the network design, especially in solving equilibrium problems and optimization problems. Assuming that EOS and EOD exist in the network, the links representing transhipment or the above-mentioned services may have concave cost-flow functions. Consequently, the functions of route costs where the intermodal transport involves may not be strictly convex and/or monotonic increasing. Therefore, the cheapest route connecting an origin-destination pair is in general not unique. It is difficult to arrive at a convergent status in the flow assignment, and thus difficult or even impossible to find an equilibrium. Some fundamental discussion about the equilibrium-based flow assignment, uniqueness of the equilibrium, and solving methods can be found in the book of Ortuzar and Willumsen (2011).

In short, the multimodality of the network poses a challenge for FTIND due to the additional heterogeneous network use choices, the non-linear cost-volume relation caused by EOD/EOS, and the non-linear cost-distance relation caused by EOS.

2.4.3 Challenge III: Multicommodity

Different commodities can be transported by different transport modes, or use different terminals, between the same origin and destination.

These different commodities have different requirements for transporting the relevant actors have different criteria for choosing the transport mode, including terminal, the means of transport, and the route. The type and level of consolidation of commodities (e.g., container, liquid bulk, or bulk) determines which transport means and handling facilities are required. For example, the value densities and the shipment urgency of the commodities result in different preferences between low transport costs and high transport speed. The sensitivity to damage decides the number and the types of handling allowed. Take bulk and breakbulk as an example. Bulk is flowable and easy to transfer between transport means. It is less vulnerable to loss and damage. Breakbulk usually has a much higher value density and come in all shapes and sizes. The risk of being damaged exists each time they have to be transhipped. Another example is containers. Although containers appear all the same, the cargo in one container can be very different from the cargo in another container in terms of value density, shipment urgency, sensitivity to damage, and other transport conditions.

It is difficult to model or to simulate the choices of the network use for each type of commodity. One reason is the large number of commodities. Another reason is that it is not always possible to identify the commodity type according to the appearance of the freight.

Therefore, it is not easy to find an appropriate way of categorizing commodities in which their characteristics are sufficiently represented for decision-making.

Therefore, multicommodity brings heterogeneous criteria in choices of the network use.

2.4.4 Challenge IV: Multiactor

Different actors can be engaged in the multimodal freight transport usually with different and sometimes conflicting interests.

They are trying to deal with the problems from different perspectives, at different levels, and with different choice criteria. The shippers would like to receive a better service quality at a lower shipping cost. The carriers would prefer a good service network with better scheduling, routing, and crew management. The terminal operators might be considering investing or cooperating with former competitors in order to develop a more efficient terminal network and thus achieve better market coverage. The deep seaport authorities have similar aims as the terminal operators, but are more focused on competition with the other deep sea ports. The governments also have their own objectives in design of the infrastructure network, mainly to fulfil economic, societal, and sustainable requirements.

The question becomes how many objectives and actors should be considered in the design. This question needs to be answered prior to developing a model. Some of the objectives can be positively or negatively related, while other objectives may be independent. This makes difficult to decide the priority of the objectives for modelling and also complex for making the appropriate mathematical optimization strategies.

In summary, multiactor brings heterogeneous design objectives in the FTIND.

2.4.5 Challenge V: Service networks design (SND) in infrastructure network design (IND)

Incorporating SND in IND needs to combine the decision-making at both strategic and tactical. It requires integrating macroscopic planning with microscopic planning.

Decisions made in SND and in IND have a significant influence on each other. Service selection, traffic distribution, terminal policies, and empty balancing strategies are the main decisions made in the freight service network design (Crainic, 2000). As was presented in Figure 2.1, the freight flows are transported over the infrastructure network by the transport service networks. The flows may concentrate on certain routes of a network based on the services provided by the transport operators, especially when they make their network use decisions collaboratively. Flow concentration on the one hand may lead to increase in cost due to capacity shortage. On the other hand, flow concentration may also result in cost reduction due to EOS and/or EOD. The capacity shortage and the change in costs may change the preferences in mode-choice. Therefore, it is necessary to enhance the interaction between SND and IND in the freight transport modelling.

However, the decisions to be made in IND are mainly strategic decisions, while SND concerns tactical decisions. The decisions at strategic level and tactical level have different objectives and different time framework. For example, where to allocate new terminals in the next decade will be decided by IND, while SND solves problems such as which terminals to use, in what frequency, with what kind of fleet, and so on. Two classes of models have been developed in the last decades for SND and IND separately. Reviews on the development in both SND and IND have been provided by Crainic et al. (Crainic, 2000; Crainic and Kim, 2007; Crainic and Laporte, 1997).

We can expect that a model that takes into account the combination of SND and IND will be more complex than models dealing with just one of them. A large number of influencing factors and assumptions need to be specified. Therefore, controlling the complexity of the model appears to be critical, in order to ensure that it is solvable within an acceptable computing time, and so that it has a good capability of interpreting the results.

Incorporating SND in IND faces challenges of dealing with heterogeneous short-term and/or long-term decisions at macro and/or micro scopes.

2.5 Implications for FTIND modelling

Modelling of FTIND is challenging due to an enlarged spatial scale, multimodality, multicommodity, multiactor, and incorporating SND. Before reviewing the integrated FTIND models, we first discuss the methods that have been applied to deal with these challenges (see Table 2.1 for an overview). Some of these methods address two or more challenges.

Table 2.1. Methods used in dealing with FTIND challenges

Challenges		Methods
I	Large-scale	Heuristic methods
II	Multimodality	Network representation; Methods dealing with EOS/EOD
III	Multicommodity	Network representation; Valuation of value of time (VOT)
IV	Multiactor	Methods dealing with EOS/EOD; Multi-objective programming; Heuristic methods
V	Service networks	Methods dealing with EOS/EOD; Heuristic methods

2.5.1 Super network representation

The multimodality and multicommodity character of a transport network have been captured by developing a super network presented by a network consisting of links and nodes (Sheffi, 1985).

The conceptual model consists of two networks, one for road, and one for public transport. Each origin and destination (OD) pair is connected via a group of connected links in both networks respectively. Traffic assignment is processed in two separate procedures. First, the mode-choice of each user is decided according to the cost of trips between the target OD pair in both networks. Transport demand are then assigned to the network of the chosen mode. Transferring between modes is not allowed. This model presents the concept of multimodality, but the possibility of intermodal transport is not modelled.

Southworth and Peterson created a similar multimodal network by connecting the road network, the rail network, and the waterborne network through a series of intermodal terminals (Southworth and Peterson, 2000). Taking a truck-rail-truck shipment as an example (see Figure 2.2), we notice that the origin and destination are located in two versions of the same highway sub-network. Shortest path routing begins by invoking the road sub-network relative to the origin. If a road-rail terminal is involved in the route, the relative rail sub-network is invoked, and the route returns to the destination related road sub-network again via a rail-road terminal. This model, to some extent, provides an approach that deals with large-scale networks by invoking only the necessary part of the entire network when calculating the shortest path between an OD pair. It captures the behaviours in mode-choice, but like Sheffi's model, the mode-choice is made prior to the route-choice.

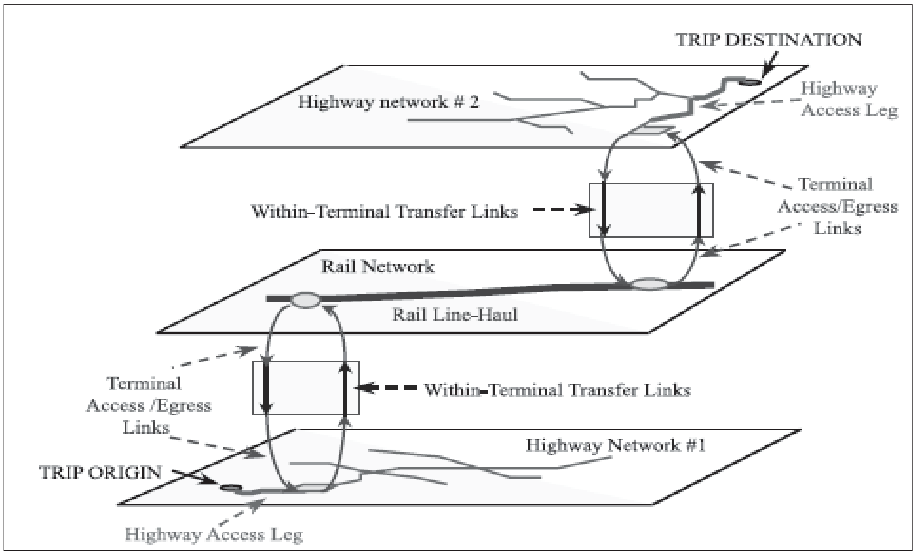

Figure 2.2. Simplified scheme of invoking network (Southworth and Peterson, 2000)

Another class of models performs mode-choice and route-choice in one step by constructing a 'super network'. The so-called 'super network' is a specific type of virtual network (see Figure 2.3 as an example). The basic idea is combining various infrastructure networks (e.g., roads, rail, waterways) into one network, and enabling traffic flows to be assigned among different infrastructure networks through a group of specifically defined nodes. Mode-choice and route-choice can be implemented simultaneously in a virtual network by converting multimodal networks into a uni-modal network, as discussed in the works of Stada and Hauwert (1992), Jourquin (1995) (see also Jourquin and Beuthe, 1996), and Tavasszy (1996).

For example, Jourquin developed a model for extensive freight transport operations (e.g., loading/unloading, transhipping and transiting) that were specified over a super network.

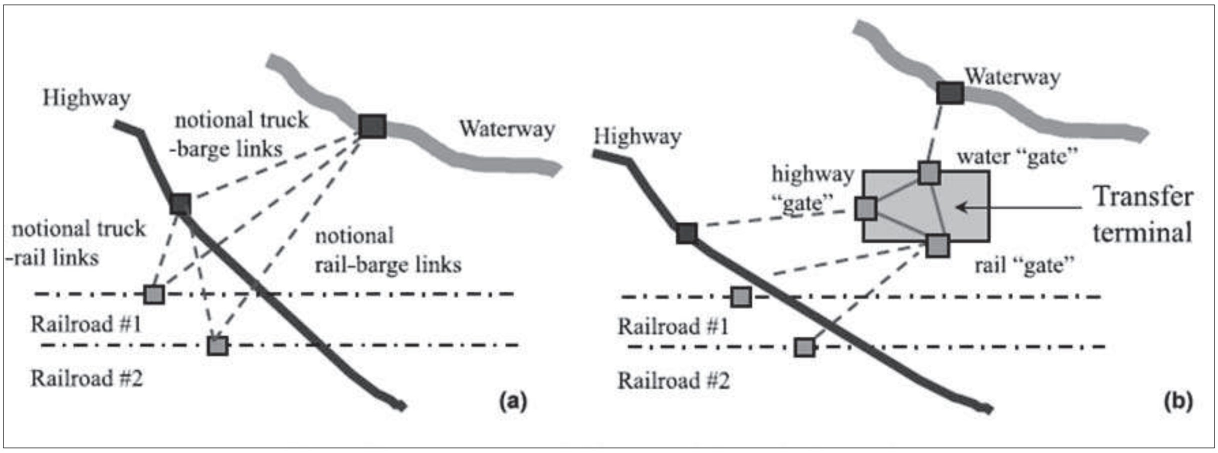

Figure 2.3. Sketch of intermodal transhipment in super network (Southworth and Peterson, 2000)

It was shown that by using the same concept and model architecture additional networks representing different transport means of one transport mode, and/or different commodities, can be combined into one super network. Consequently, the mode-choice, mean choice, terminal-choice, and route-choice can be combined into one procedure providing the optimal solutions over a multimodal multicommodity network.

2.5.2 Methods for capturing the effects of EOS and EOD

Many strategic and/or operational decisions the actors engaged in freight transport make are based on EOS and EOD. For example, some of these decisions include the enlargement of terminal scale, the consolidation of freight with different ODs, and/or using intermodal transport instead of uni-modal road transport.

Most efforts have been made in incorporating EOS and EOD at terminals, and EOD in specific services. Various studies provide calculation of EOS and EOD (Oum and Waters, 1996; Panzar and Willig, 1977). The specifications of link costs in the form of a linear function or a concave function have been the most common method used. In some hub location allocation models, along with the linear cost function applied to each link, a uniformed discount factor has been applied to the interhub links (Ernst and Krishnamoorthy, 1998; Morton O'Kelly et al., 1995; Skorin-Kapov et al., 1996). This factor ensures that the unit costs of the interhub links have been lower than the unit costs of road links or pre-/end-haulage links. The marginal costs on all the interhub links have been assumed at a constant discount, although both large and small flows receive a same discount which has not been the case in practice.

O'Kelly and Bryan generalized the definition of the interhub cost term into a concave increasing function by changing the sign associated with the scalar in the link performance functions, and restricting it as a positive number yields a decreasing function of the link flow (O'Kelly and Bryan, 1998). The costs of interhub links increase concavely with link flows, and the unit costs of the interhub links are always less costly than the other links.

Racunica and Wynter argued that there has been a break-even point on the unit costs of interhub links (Racunica and Wynter, 2005), i.e., the unit costs of interhub links should be higher than the other links until reaching the break-even point, and less thereafter. Thus, based on O’Kelly and Bryan’s approach (O'Kelly and Bryan, 1998), instead of applying a concave term only to the discount, they applied a concavely increasing function directly to the flows of interhub links, to the hub-to-destination links as well. Recently, Kim and Kim (2006) extended the EOS on all links by applying a nonlinear cost function. However, this concave cost function has led to a new challenge for network design. A part of the cost function describing the EOS or EOD would be monotonically decreasing, but the cost function describing the diseconomies of congestion would be convex. If both features of a transport system would be captured by a single cost function, the equilibrium-based flow assignment methods theoretically are not applicable. Recently, Meng and Wang proposed an intermodal hub-and-spoke route choice model (Meng and Wang, 2011), which has been capable to reflect the transition from scale economies to scale diseconomies for carriers or hub operators. Numerical examples have been used to validate the effectiveness of the model, but the model was not calibrated or implemented in practical case study.

Therefore, although there are methods that deal with EOS and EOD theoretically, more efforts are needed before they can be well represented in the FTIND models that are able to provide reliable and practical strategic decisions.

2.5.3 Valuation of Value of Time

Many early studies have provided the formulation for multicommodity network design problems (Crainic and Laporte, 1997; Friesz et al., 1986; Guelat et al., 1990; Harker and Friesz, 1986a, b; Magnanti and Wong, 1984). However, the multicommodity has been defined as multiple products with the same attributes. The appearance of the products, value density, and sensitivity to damage have not been specified.

For the last decade, value of time (VOT) has been used for commodity differentiation, especially when the commodities have the same appearance, and/or when it has not been possible to identify the commodity from the appearance. It has been used to represent the heterogeneous choices when moving different commodities between the same origin and destination. The VOT has usually been defined as consisting of cost components. The first is mode-related, which primarily included the driver’s wages and the depreciation of the transport means during the transport process; and the other is commodity-related, which included interest and depreciation of the freight, as well as the loss of the market value of freight during the transport process, independently of the transport mode.

A number of studies on both the theoretical and empirical estimations of VOT measurement and valuation have been considered (Beuthe and Bouffioux, 2008; De Jong et al., 2004b; EC, 2002; Gorman, 2008; Kreutzberger, 2008; NEA, 2004; Tavasszy and Bruzelius, 2005b;

Zamparini and Reggiani, 2007). European Communities (2002) proposed the average VOT (measured in t-hour[1]) for all types of freight transported by uni-modal road transport or by a train-truck intermodal transport between particular EU member states. De Jong et al. (2004a) estimated the VOT of containers and non-container freight transported in the Netherlands. Tavasszy and Bruzelius (2005a), and Zamparini and Reggiani (2007) and reviewed the methods used in VOT measurement and valuation. Beuthe and Bouffioux (2008) estimated the VOT of freight with different value densities transported over short, median, and long distances. Summaries of the absolute values of VOT obtained from previous studies have also been provided in both of these two, and in Kreutzberger paper of 2008 as well. These summaries cover around 60 studies, primarily conducted in European countries during the period of 1998 - 2005, for the freight transported by intermodal transport or road transport. The results of the analysis by De Jong et al. (2004a) and NEA (2004) indicated that the freight transported by uni-modal road transport has had a higher average VOT when compared to the freight transported by intermodal transport. Gorman (2008) also observed this phenomenon by using data collected in a U.S. Commodity Flow Survey in 1997. Lower VOT enables intermodal transport, which in most cases requires longer transport time, to compete with uni-modal road transport. In this way, the VOT is a dominant factor for mode choice.

Therefore, VOT is an important factor for network use decisions. The valuation of VOT shows a way to reflect the endogenous characteristics of freight in FTIND.

2.5.4 Multi-objective optimization and heuristic algorithms

In order to incorporate multiple actors in the network design, their objectives are taken into account. These objectives can be deduced by the actors' motivations for making decisions on the use of network. In many cases, the objectives of one actor can conflict with the objectives of other actors. It is clear that a model that considers two or more objectives simultaneously would provide more realistic solutions. However, more objectives result in a higher degree of complexity in programming. In this context, multi-objective optimization techniques have been brought into the field of FTIND, aiming to better capture the interaction between the actors when optimizing the network design.

Scalarization and multi-level programming are the two techniques commonly used in network design.

The scalarization technique solves a multi-objective problem by combining the multiple objectives into one single-objective weighted-sum function. The weighting coefficients do not necessarily correspond directly to the relative importance of the objective function. Different weight combinations have to be considered to reproduce a representative part of the Pareto frontier. If the goal of a certain optimization is not to produce the Pareto frontier, then these weights can also be given through the results of the pre-study on the relative importance of various objectives. Then the problem is transformed into a single-objective multi-variable function with a given weight vector (Sharma et al., 2009). The model aims to find optimal

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[1] t-hour is the abbreviation of tonne hour

improvements in the network in terms of network robustness under various transport demand. It minimizes the expected total system travel time and the higher moment for the total system travel time. The Pareto frontier of the minimum standard deviation of the total system travel time and the minimum expected total system travel time have been obtained from this optimization.

Multi-level programming is another technique for the multi-objective optimization aiming at finding a Pareto frontier. Depending on the nature of the problem, the multiple objective functions can be solved sequentially or interactively according to a hierarchy. Friesz et al. (1986) have provided architecture for a sequential programming problem regarding to network design, where a sequential shipper-carrier model has been proposed. The first level in the model performed user equilibrium among shippers in terms of delivery price. The second level minimized the carriers' operational costs while satisfying the fixed demand of the shippers. Each level of the programming problem has been solved individually by an iterative method. Another method for solving the multi-level programming problem is to solve all levels of the problem interactively until all the objective functions have been optimized. This technique is suitable for simulating the situation where the decision of one actor (decision-maker) is constrained by the decision of other actors. A recent example is the model developed by Yamada et al. (2009). They have proposed an infrastructure investment optimization model which has been in the form of bi-level programming. The lower level described the user equilibrium flow on the transport network, and the upper level determined the best combination of investment actions. The iterative procedures simulated that each actor optimized its own objective under the conditions created by the other actors. In addition, Limbourg and Jourquin (2009) have applied a tri-level programming approach to solve a p-hub median problem in which the variation in transhipment costs according to the volume of transhipped containers has been modelled at the lowest level, the flow assignment has been executed at one level higher, and the optimal terminal location allocation problem has been solved at the highest level. The final results indicated the optimal locations for European transfer terminals embedded in a hub-and-spoke network.

Multi-objective optimization problems are often NP-hard problems. Heuristic algorithms are more practical in dealing with such complex problems than the classical methods. Heuristic algorithms provide flexibility regarding the nature of the objective function and the constraints. They have become more popular in the last two decades in the field of FTIND. Among the large variety of Heuristic algorithms, genetic algorithms, the Mont Carlo method, Tabu search, and simulated annealing have been most often used. Yamada et al. (2009) compared the efficiency and the computational performances of GA-based algorithms, Tabu-search based algorithms, and random search methods.

In summary, the multi-objective optimization with the support of heuristic algorithms is a meaningful approach to represent the decisions of multiple actors in the FTIND. When using the multi-objective optimization in the network design, in addition to choosing an appropriate algorithm to ensure reasonable computation time, attention should be paid to correctly expressing the hierarchy and the importance of the objectives of various actors in the network design.

2.5.5 SND modelling methods

Incorporating SND in IND is one way of capturing behaviour of the actors involved in the decision-making at a tactical level.

SND models have been developed since 1970s. Most of the studies dealt with tactical problems as mentioned in 2.4.5, and from the perspective of a single firm. Early service network design models can be found in the studies of Crainic and Rousseau (1986) and Powell and Sheffi (1983, 1989).

Crainic and Rousseau (1986) developed a prototypical multimodal multicommodity service network design formulation for determining the frequencies of various services. It has integrated service selection and routing problems into a general terminal policy making. This formulation has been similar to the path-based multicommodity capacitated network design formulation, but the cost function formulated by Crainic and Rousseau has been generalized, and service reliability was taken into account. Powell and Sheffi (1983, 1989) proposed several variations of service network design models focusing on less-than-truckload vehicle delivery. The model was developed for the decisions concerning services between factories and terminals, exclusively for break-bulks. Service selection problems, routing problems, and the empty balancing problems were all modelled. The frequency of each service and service levels were provided in the model results.

Crainic (2000) has provided a review of service network design modelling where the four groups of problems have been briefly and concretely covered. Wieberneit (2008) has provided a more recent review. The focus of this review has been on truckload planning problems, dynamic service network design problems, and the corresponding solution methods. Bai et al. (2012) has provided an up-to-date review of the solving methods for service design problems.

To our knowledge, there is no IND model which comprehensively incorporates SND problems such as routing, fleet management, and service frequency. However, there are studies showing the potential and starting points of integrating IND and SND into one model. Facility allocation is a specific problem in the scope of SND closely related to IND. Groothedde et al. (2005) developed a many-to-many service network design model. This model was designed for distribution of the fast moving consumer goods, where the feasibility and service level were concerned, to some extent, by the cycle time of the services and the total annual savings gained by using hub-based services instead of uni-modal truck transport. Limbourg and Jourquin (2009) have developed a hub allocation model which provided optimal locations of European transfer terminals in a given hub-and-spoke network. This model takes into account the cost efficiency of terminals gained from the hub-and-spoke networks. In addition, fixed discounts have been given to the hub-hub services. One disadvantage of this model is that the costs of the hub-hub services are independent from the volume transported, whereas, in practice, if the demand is insufficient, the hub-and-spoke services are operationally and economically infeasible and are not able to achieve a cost advantage over road transport.

SND focuses on network design at a tactical level, and has a strong impact on the use of the infrastructure network. There are a large number of SND implications available that are helpful for the development of SND-IND integrated models.

2.6 Integrated FTIND models

As discussed in Section 2.4, in order to better design a freight transport infrastructure network from the governmental perspective, multimodality, multicommodity, multiactor, and service networks should be taken into account. Section 2.5 reviews the implications developed in dealing with one or more of these requirements for FTIND. From the review, it can be concluded that integrated models are needed in order to capture the important characteristics of freight transport system in a more comprehensive way. Table 2.2 summarizes the integrated models in the scope of FTIND, which have been applied to the various areas over the world: Europe, the United States, Asia, and South America (see the column of the 'application area' in Table 2.2). Based on this Table, it can be concluded that each model deals with more than one challenge for FTIND, but none of them deals with all of them. In this section, we select from the Table 2.2 four integrated models for detailed discussion. After comparing them, a model to be developed in this thesis and highlights of some of its new features have been proposed.

Table 2.2. Summary of the reviewed integrated models on FTIND

Model	(Tavasszy, 1996)	(Southworth and Peterson, 2000; Southworth et al., 1997)	(Limbourg and Jourquin, 2009)	(Geerts and Jourquin, 2001; Jourquin and Beuthe, 1996)	(Groothedde et al., 2005)	(Yamada et al., 2009)	(Macharis and Pekin, 2009)	(Crainic et al., 1984; Crainic and Rousseau, 1986)	(Crainic et al., 1990; Guelat et al., 1990)
Large scale	Y	Y	Y	Y	Y	Y	Y	N	Y
Multimodality	Y	Y	Y	Y	Y	Y	Y	Y	Y
Multicommodity	N	Y	N	Y	N	Y	N	Y	Y
Multiactor	N	N	Y	N	N	Y	N	N	N
Service networks	N	N	N	N	Y	N	N	Y	N
Network representation	Y	Y	Y	Y	Y	Y	N	Y	Y
Value of time	Y	N	N	Y	N	Y	N	N	N
Multi-objective programming	N	N	Y	N	Y	Y	N	N	N
Cost efficiencies	N	N	Y	N	Y	N	N	N	N
Heuristic solution methods	N	N	N	N	Y	Y	N	N	N
Function: flow estimation	Y	Y	Y	Y	Y	Y	Y	N	Y
Function: network optimization	N	N	Y	N	Y	Y	N	Y	N
Network representation	VN	VN	VN	VN	VN	VN	SN	VN	VN

Model	(Tavasszy, 1996)	(Southworth and Peterson, 2000; Southworth et al., 1997)	(Limbourg and Jourquin, 2009)	(Geerts and Jourquin, 2001; Jourquin and Beuthe, 1996)	(Groothedde et al., 2005)	(Yamada et al., 2009)	(Macharis and Pekin, 2009)	(Crainic et al., 1984; Crainic and Rousseau, 1986)	(Crainic et al., 1990; Guelat et al., 1990)
Number of modes	3	5	4	9	2	3	4	m.	m.
Mode specifications	Road, rail, IWW	Road, rail, IWW, costal, ocean	Road, rail, IWW, end-haul	Barges, trains, trucks	IWW, road	Road, rail, coastal	Road, rail, IWW, end-haul	n.s.	n.s.
Number of commodity types	n.s.	2	1	10	1	2	1	m.	m.
Categorization of commodities	n.a.	Container, or not	Container	NSTR chapters	Pallet	General cargo, passenger	Container	n.s.	n.s.
The characteristics of commodity captured	n.a.	Requirements for terminal facilities	n.a.	Feasibility for intermodal transport, value of time	Appearance	Requirements for transport facilities, value of time	Appearance	OD demand	OD demand
Cost efficiency	N	n.a.	hub-hub service, transhipment	N	hub-hub service, transhipment	N	n.a.	N	n.a.
Application area	Europe	US	Europe	Europe	The Netherlands, Belgium, Germany	Philippines, Indonesia	Belgium	Hypo-network	Brazil

Model	(Tavasszy, 1996)	(Southworth and Peterson, 2000; Southworth et al., 1997)	(Limbourg and Jourquin, 2009)	(Geerts and Jourquin, 2001; Jourquin and Beuthe, 1996)	(Groothedde et al., 2005)	(Yamada et al., 2009)	(Macharis and Pekin, 2009)	(Crainic et al., 1984; Crainic and Rousseau, 1986)	(Crainic et al., 1990; Guelat et al., 1990)
Solution method for optimization	n.a.	n.a.	d.k.	n.a.	SA	GA, GLS, TB,RS	n.a.	d.k.	n.a.
Cost function	Total costs	Relative modal impedance factors	Total costs	Total costs	Total logistic costs	Total costs	Prices	Total costs	Total costs
Variables in optimization	n.a.	n.a.	Hub location, hub number	n.a.	Hub location, hub-hub service	Facility improvements	n.a.	Frequency of each service	n.a.
Optimization objectives	n.a.	n.a.	Min. total network transport costs, and min. user costs	n.a.	Min. system costs	Min. network costs/benefit, and user equilibrium	n.a.	Min. network costs	n.a.

Y = Included; N = Not included; d.k. = unknown; VN= virtual network; SN= separated networks; HN = hypothetic network; m. = multiple; n.s. = not specified; n.a. = not applicable; IWW = inland waters

2.6.1 Previous integrated FTIND models

Flow distribution model of Southworth et al.

Southworth and Peterson presented a Geographic Information System based (GIS-based) for a large-scale multimodal network of the United States (Middendorf, 1998; Southworth and Peterson, 2000; Southworth et al., 1997). This multi-modal network was composed of five uni-modal networks: road, rail, inland waters, coastal, and ocean shipping. The inland waters network was further segmented to several sub-networks in order to distinguish the different types of ships navigating in the coastal areas or in the Great Lakes area. Transhipment was modelled by an extensive transfer representation as shown in Figure 2.2. Sub-networks were connected through a series of predefined intermodal road-rail, road-water and water-rail terminals. They were able to be invoked when necessary.

The model was designed to support the simulation of routing for about five million origin-to-destination intermodal freight transport movements reported in the 1997 U.S. Commodity Flow Survey. Calculating shortest routes and assigning relevant flows to the routes were the main objectives in the mathematical specification. The shortest path routing was based on the resistance of a link instead of the link cost with practical meaning. The resistances were determined by the type of link (i.e., the main or distributed) and the type of commodities carried (i.e., break-bulk, bulk, or container). The commodity dependent resistance of a link captured not only the appearance of the commodities, but also the difference in the transport costs. Mode-choice was realized by introducing the ‘relative modal resistance factors’ to each sub-network. These factors were not used to estimate the freight transport costs. They were used only to guarantee that a majority of the flows were realistically routed. The features of a network such as congestion effect, cost efficiencies, value of time, were not modelled in detail, but only conceptually indicated by the factors of link resistance and relative modal resistance.

Table 2.3 summarizes the model, in terms of the challenges dealt with and the methods used.

Table 2.3. Summary of the challenges in Southworth et al. model

	Challenges dealt by the model	Remarks
Large scale	x	Super network
Multimodality	x	Super network
Multicommodity	x	Super network
Multiactor		
Service networks		

Trans-European FTIND model of Jourquin et al.

Jourquin et al. developed another GIS-based FTIND model (Jourquin and Beuthe, 1996; Jourquin et al., 1999) which focused on the European network. This model conducted mode, mean, and route choice. Unlike the CFS network, this model realized multimodal multicommodity by generating the virtual links for each possible transport mean on each physical link for each type of commodity. It was able to assign ten types of commodities to the network with the option of nine means (five types of barges, two types of trains, and two types of trucks). Specific cost functions were applied for moving the freight by different means in different regions. Congestion was taken into account by giving the calibrated speed to each link, which was not dependent on the flow, thus the cost functions were linear to transport distance. The model was used to analyse the competitive position for freight of European rail, road, and inland waterway transport.

After facilitating large amounts of data, Geerts and Jourquin (2001) developed an updated version of the model to predict the modal shifts in the scenarios of modifying the infrastructure network, allowing extra operating time, and internalizing external costs.

With the purpose of network optimization, The model was further developed. EOS was integrated into the model by establishing a discount for the hub-hub links in the form of a percentage of the total link cost. It was applied to help solving a p-hub location problem aiming at providing the optimal location for the hub terminals (Limbourg and Jourquin, 2009).

This model has broadened its application scope beyond network design and operations research. (Jonkeren et al., 2011) have applied this model to estimate the impact of future climate change on the market share of the inland waterway transport in main European natural waterways. In addition, the extension of integrating the service networks is also recognized by the model developer (Jourquin et al., 2009a; Jourquin et al., 2009b).

Table 2.4 summarizes the model in terms of the challenges dealt with, and the methods used.

Table 2.4. Summary of the challenges in Jourquin et al. model

	Challenges dealt by the model	Remarks
Large scale	x	Super network
Multimodality	x	Super network, VOT
Multicommodity	x	Super network
Multiactor	x	Super network, Multi-objective programming with hierarchical objectives, EOS and EOD
Service networks	x	(No application for freight transport published yet)

Bi-level infrastructure network design model of Yamada et al.

Yamada et al. (2009) introduced another FTIND model in a geographic scope of south-eastern Asia. Three modes (road, rail, sea) were modelled. Modal choice and route-choice were carried out simultaneously by converting the multi-modal network into a uni-modal virtual network. The transhipment at terminals was presented similarly way as in the model of Jourquin et al. Additionally, Yamada's model described the activity of waiting for the vehicle under the assumption of the limited vehicle availability. The model dealt with both freight and passengers by defining them as multiclass users, meaning that they were allowed to access the same physical links with different costs. Generalized costs composed of fares and time costs were defined for each mode and each user-class. The fare was a fixed value independent of the transport volumes. Time costs consisted of the costs of delay and time value for each use-class. Congestion was modelled by a cost-and-delay function which correlated the time costs and the transport volumes over a link. This model was developed for the purpose of the network optimization by bi-level programming where the lower level describes the multi-modal multiuser equilibrium flow on the transport network, and the upper level determined the best combination of investment actions by using genetic algorithm (GA) based procedures. The model was applied to identify and select a suitable combination of actions from a number of possible network modification actions for Indonesia and the Philippines. Table 2.5 summarizes the model in terms of the challenges dealt with and the methods used.

Table 2.5. Summary of the challenges in Yamada et al. model

	Challenges dealt by the model	Remarks
Large scale	x	Super network, heuristic algorithm
Multimodality	x	Super network, VOT
Multicommodity	x	Super network, VOT
Multiactor	x	Multi-objective programming with hierarchical objectives
Service networks		

Multimodal SND model of Groothedde et al.

Groothedde et al. (2005) developed a multimodal SND model based on the assumption that shippers would collaboratively operate a hub-based intermodal transport network for the purpose of achieving EOS. This model was used to find the optimal hub location, to assign the non-hub origins and destinations to the hubs, and to optimize the hub-hub networks based on minimization of the total network logistic costs. A virtual network was developed for simulating the distribution of pallets among 79 ODs by truck or intermodal truck-barge-truck. VOT was not specified in the cost function, but the total logistic costs, including the variable costs and the inventory costs, were used in both the flow assignments and hub network optimization. Cost efficiency in intermodal transport was captured by taking into account the utilization of barge capacity between two hubs. In terms of solving methods, the shortest path algorithm was used for the flow assignment, while simulated annealing was used for the network optimization. Table 2.6 summarizes the model, in terms of the challenges dealt with, and the methods used.

Table 2.6. Summary of the challenges dealt in Groothedde et al. model

	Challenges dealt by the model	Remarks
Large scale	x	Super network
Multimodality	x	Super network, VOT
Multicommodity		
Multiactor	x	Multi-objective programming with hierarchical objectives, EOD, Heuristic algorithm
Service networks	x	Super network, heuristic algorithms

This model, to some extent, integrates the infrastructure network (hub allocation) and the service network design (fleet design). However, it only simulates the choices of a single type of actor (collaboratively operating shippers, who are also the joint transport service provider) when distributing one type of commodity (pallets). The EOS which could be achieved by the terminals or the transport providers (who are not shippers) were not taken into account in this model.

2.6.2 The model to be developed in this thesis

After analysing the existing FTIND models (see Table 2.2), it is evident that none of them was dealt with all five challenges proposed in Section 2.4. However, in order to evaluate and/or optimize the freight transport network from the governmental perspective, a model able to represent and simulate a freight transport system in an integrated way is needed. Therefore, a new FTIND model is developed, aiming at better incorporating the characteristics of freight transport networks and optimizing the infrastructure networks from the governmental perspective. This model should be able to estimate multicommodity freight flows over multimodal infrastructure networks and service networks, and to optimize the infrastructure networks by taking into account decisions of the multiple actors. Databases of freight transport demand, features of the infrastructure network, selective services, transport and transhipment costs, emissions and external costs are to be embedded in the model. Data and results can be visualized transport mode and commodity group, on a GIS map, at segmental level, terminal level, corridor level, regional level, national level, and network level. The main features of the model are listed in Table 2.7.

Table 2.7. The features of the model to be developed in this thesis as compared to those of the four existing models

Model features	New model	(Southworth et al. 1997, 2000)	(Limbourg and Jourquin, 2009)	(Yamada et al., 2009)	(Groothedde et al., 2005)
Large scale	Y	Y	Y	Y	Y
Multimodality	Y	Y	Y	Y	Y
Multicommodity	Y	Y	N	Y	N
Multiactor	Y	N	Y	Y	N
Service networks	Y	N	N	N	Y
Network representation	Y	Y	Y	Y	Y
Value of time	Y	N	N	Y	N
Multi-objective programming	Y	N	Y	Y	Y
Cost efficiencies	Y	N	Y	N	Y
Heuristic solution methods	Y	N	N	Y	Y
Function: flow estimation	Y	Y	Y	Y	Y
Function: network optimization	Y	N	Y	Y	Y
Network representation	VN	VN	VN	VN	VN
Number of modes	4	5	4	3	2
Mode specifications	Road, rail, IWW, end-haul	Road, rail, IWW, costal, ocean	Road, rail, IWW, end-haul	Road, rail, coastal	IWW, road
Number of commodity types	5	2	1	2	1
Categorization of commodities	Containers	Container, or not	Container	General cargo, passenger	Pallet

Model features	**New model**	**(Southworth et al. 1997, 2000)**	**(Limbourg and Jourquin, 2009)**	**(Yamada et al., 2009)**	**(Groothedde et al., 2005)**
The characteristics of commodity captured	Value	Requirements for terminal facilities	n.a.	Requirements for transport facilities, value of time	Appearance
Cost efficiency	Hub-hub service, transhipment, fleet	n.a.	hub-hub service, transhipment	N	hub-hub service, transhipment
Application area	The Netherlands	US	Europe	Philippines, Indonesia	The Netherlands, Belgium,
Solution method for optimization	GA	n.a.	d.k.	GA, GLS, TB,RS	SA
Cost function	Total costs	Relative modal impedance factors	Total costs	Total costs	Total logistic costs
Variables in optimization	Terminals, services, CO_2 price	n.a.	Hub location, hub number	Facility improvements	Hub location, hub-hub service
Optimization objectives	Min. total transport costs, min. total emissions, min. user costs	n.a.	Min. total network transport costs, and min. user costs	Min. network costs/benefit, and user equilibrium	Min. system costs

Y = Included; N = Not included; d.k. = unknown; VN= virtual network; SN= separated networks; HN = hypothetic network; m. = multiple; n.s. = not specified; n.a. = not applicable; IWW = inland waters

Table 2.8 compares the model to be developed in this thesis with the four existing integrated models (see Table 2.3 to Table 2.6). This model integrates the advantages of the existing models and is able to deal with all of the five challenges in FTIND from the governmental perspective.

Table 2.8. Summary of the challenges dealt in the model to be developed in this thesis

	Challenges dealt by the model	Remarks
Large scale	x	Super network
Multimodality	x	Super network, VOT
Multicommodity	x	Super network, VOT
Multiactor	x	Super network, Multi-objective programming with hierarchical and non-hierarchical objectives, EOS, Heuristic algorithms
Service networks	x	Super network, EOS and EOD

2.7 Summary and discussion

This chapter has provided the background of freight transport network design by focusing on the infrastructure network design from the governmental perspective. Insights into the new challenges, the new requirements for FTIND models, and the various modelling methods have been extensively discussed. After an in-depth discussion and comparison of the four existing integrated models, the new model to be developed in this thesis has been briefly introduced.

We have argued that involvement of the public concerns, represented by the objectives from the governmental perspective, has brought complexity into infrastructure network design. Governments are often concerned with network design on a regional or national scale. The enlargement of the network scale increases the level of heterogeneity of the network, among other factors, in terms of the number of actors involved, diversity of transport demand, and the variety of supply of transport service (including the variety of service networks). These heterogeneities, especially combination of them, bring new challenges to the freight transport infrastructure network design. Large-scale, multimodality, multicommodity, multiactor, and new service networks have been identified as the five main challenges.

Identification of the challenges has given direction to the state of the art in FTIND modelling. It has been found that (1) the super network representation has been able to deal with multimodality and multicommodity; (2) mathematical methods dealing with consolidation effects have been helpful for presenting multimodality and multiactor; (3) the methods for commodity-related costs' measurement and valuation have contributed to identifying multicommodity; (4) multi-objective programming and heuristic solving techniques have provided possibilities for dealing with multiactor and the enlarged spatial scale of a network.

A review of the relevant implementation of FTIND has shown that (1) there are models developed for specific FTIND problems, but none of them dealt with all five challenges; (2) the important characteristics of freight transport, for example, capacity constraints, congestion, and EOS, have been studied and applied to different purposes, but we with a lack of models taking these factors all into account; (3) the cost efficiencies have existed in many forms in a transport system, and different actors might benefit from them, but only EOS at terminals and EOD in interhub transport have been captured in the simplified ways; (4) GIS-based models have been increasingly favoured for the freight transport network design whereas the computation capability might be a significant limit in solving the complicated network design problems, thus requiring more efficient and reliable optimization algorithms.

Based on the state of the art in FTIND, the requirements for a new integrated FTIND model have been proposed. This single model will take into account, in combination, a large spatial scale, multimodality, multicommodity, multiactor, and potential collaborative service networks. Since there is no one-picture for the optimal future infrastructure network, a good infrastructure network design should also take into account the future freight transport demand, price, and development of new technologies. The new proposed model will able to estimate multicommodity flow distribution over a large-scale multimodal network by taking into account the objectives of different actors. This is expected to be very helpful for the network design from the governmental perspective in order to make strategic plans while considering the operational benefit of the network users. The model will also be functioned for the network design by taking into account sustainability as an objective in addition to the operational costs incurred in the network. This model, by integrating the SND into IND, in addition to transport costs and handling costs, will also be able to capture the transport network features, for example, transport time, fleet size, service frequency, network capacity utilization, and environmental impacts. The model with the multi-objective optimization will enable the FTIND to take into account pricing policies, terminal network configuration, and collaborative hub-based service networks.

The mathematical formulation of the new model will be introduced in the next chapter. The model is implemented, validated, and applied in the later chapters of this thesis.

Chapter 3

Freight Transport Infrastructure Network Design: A New Model

3.1 Introduction

In Chapter 2, we addressed several challenges while modelling the infrastructure dynamics and the choice behaviour of the relevant actors. Decision-making on the network use is also more complex with the enlargement of the spatial scale of network design and inclusion of the public concerns. It is shown in the previous chapter that important characteristics of freight transport are multimodality, multicommodity, and multiactor. In addition, it is found that these important aspects of freight transport are not sufficiently incorporated in the FTIND models.

In this chapter, a new model, which aims to better incorporate the characteristics of the freight transport network and to optimize the infrastructure network from the governmental perspective is proposed. The following Section 3.2 lists the main functions of the model. Section 3.3 to Section 3.5 explain the specifications of the model by focusing on the network specification, cost functions, and bi-level network optimization modelling, respectively. This chapter ends by providing a graphic illustration of the model's architecture and discussing the important arguments.

3.2 Main functions of the model

The model has two main functions: freight flow assignment and the infrastructure network optimization.

The flow assignment aims to assign the transport demand to the network according to the transport supply (including infrastructure, services, and regulation). It provides the fundamental support for performing a scenario analysis, network performance evaluation, and flow prediction. This model is designed to distribute the transport demand between origins and destinations (ODs) in the multimodal network in order to achieve a complex understanding of the spatial transport demand over each segment of the road, rail, and/or inland waterway. This connects the economic production/consumption models to the transport models. The OD matrix and the specifications of the network features are required as input, while the flow-map over the network is the output.

The new function specifically developed in this model is infrastructure network optimization that incorporates the service network design as compared to the existing FTIND models (for a review of the existing models, see the literature review in Chapter 2). This model is able to evaluate numerous design measures consisting of the infrastructure modifications, regulatory policies, and potential hub-based services, as well as to provide potential design measures for optimizing the performance of the freight transport network in terms of costs, network utilization, pollution, and other objectives specified by the users of the model. All the input data and the results are able to be visualized in geographic information system (GIS). Examples are shown in Appendix I.

These functions are realized through the modelling in three dimensions:

1. Network specification is the basis for the flow assignment and for the network optimization. It implements the features of the infrastructure network;
2. Flow assignment modelling aims to simulate the choices of the network users when transporting the freight from its origin to its destination; and
3. Optimization modelling is for the purpose of evaluating the network performance in each scenario estimated by using the flow assignment model and searching for the optimal alternatives.

The following three sections describe the formulation of these three dimensions of modelling.

3.3 Network specification

The multimodal network is represented by a super network and is specified in a GIS. The super network built in this model includes a road network, a rail network, and an inland waterway (IWW) network with the shuttle transport services, and the hub services. The infrastructure networks of the three transport modes (road, rail, inland waterway) and the specifically-defined potential hub service networks are “connected” through terminals. The intermodal accessibility of each terminal is specified through transhipment services provided by the terminal. Moreover, pre-/end-haulage and access/egress from the origin/destination in the multimodal network are particularly specified.

3.3.1 Super network representation

The super network can be described as $Z = (N, L)$. N and L denote the identifications (IDs) of the nodes of the network and the links of the network, respectively. Each link is associated with its fore-node and end-node. Each node is identified by its geographic coordinates. The nodes representing the ends of the real geographic links (i.e., a segment of road, rail, or IWW) are denoted as n_i^m ($i \in N, m \in M$). m denotes the mode of the geographic link to which the node belongs, *M= {road, rail, IWW}*. The nodes representing the terminals are denoted as n_i^t $(i \in N, t \in T)$. A terminal is tagged by a terminal ID t. Set T contains the IDs of all terminals. The accessible modes of the terminal are attached to $t \in T$. Besides the fore-/end-nodes of the real geographic links and the terminals, a centroid n_i^o $(i \in N, o \in O)$ is identified by the geographic coordinates of the geographic geometric centroid of the region. The centroids are virtual nodes in the network. They do not represent any infrastructure but each centroid represents the location of the transport demand of a region, and thus each centroid is associated with the ID of a region, $o \in O$. O consists of the set of the IDs of all regions.

The super network is constructed by connecting the nodes according to the certain rules. Using the categorization of the nodes, links can be categorized automatically based on the node types of their fore-nodes and end-nodes. In this module, five sets of links are generated, $L = X \cup H \cup G \cup A \cup S$. The link l_x^m $(x \in X \subset L, m \in M)$represents the real geographic link x of mode m. The transhipment links $l_h^{t,m(t)}$ $(h \in H \subset L, t \in T, m \in M)$ are generated by connecting the terminal node n^t to a number of the closest nodes of mode m. $m(t)$ represents the modes which are accessible at the terminal t. The links that describe the pre-/end-haulage between terminal t and centroid o are denoted as $l_g^{o,t}$ $(g \in G \subset L, t \in T, o \in O)$. They are generated by connecting the centroid n^o to the terminals located within a certain geographic radius of centroid o. The radius is region-specific and is determined by the maximum pre-end/haulage of the shipments starting or ending in this region. The centroids are also connected to the terminals within a predefined radius by virtual links (centroid-terminal connector). The access/egress links l_a^o $(a \in A \subset L, o \in O)$ describe the access/egress between the road network and region o. The length of an access/egress link indicates the average distance of accessing from any place of the region to the road network and egressing from an appropriate segment of the road network to a destination in the region. The fifth type of links is service link, which are also virtual links, particularly defined for the service network design. Each service link is denoted as $l_s^{t_i, t_j}$ $(s \in S \subset L, t \in T)$ represents a leg of one or more service(s) between terminal t_i and t_j. A service link may be parallel to one geographic link or several adjacent geographic links of the same mode.

Figure 3.1 shows a graphical representation of the network.

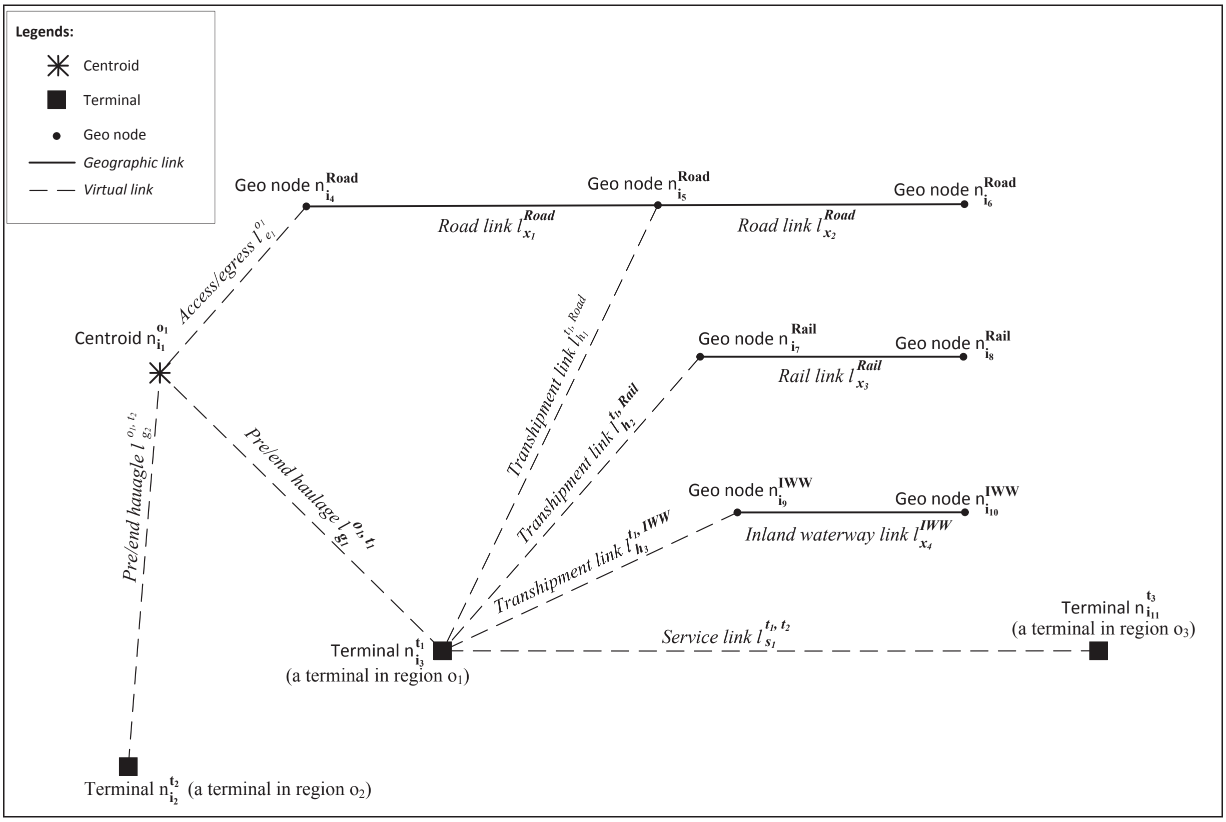

Figure 3.1. Network representation outline of the model

Note: A centroid represents the location of the transport demand of a region; a terminal presents a terminal; a geo node represents a node on a segment of road, rail, or inland waterway; a geographic link is generated by connecting two geo nodes (not necessary being a straight line) which presents a link existing in the real world (i.e., a segment of road, rail, or IWW); a virtual link is generated by connecting one geo node and one virtual node which presents transhipment, access/egress to road network, or pre-/end-haulage.

This network representation is different from the examples in Figure 2.3. Comparing with the example of Figure 2.3 (a), the transhipment with an extra movement is represented. The flows are not routed directly between two transport modes but via transhipment at the terminals. This modification allows the differentiation between pre-/end-haulage and uni-modal road transport. The example of network representation shown in Figure 2.3 (b) is more complex than that is in the present model. Representing a network as in Figure 2.3 (b) provides possibilities to capture other activities incurred within a given terminal during transhipment, such as, storage or value-added services. The network representation as shown in

Figure 3.1 is chosen because the focus is transport network design rather than the supply chain design. It presents transhipment as a critical activity of the multimodal transport, but does not describe other details. This simplification has also an advantage of saving the computation time.

3.3.2 Network attributes

The attributes of each node or each link are associated with the node or the link in the GIS databases respectively. An ID with its unique longitude and latitude is associated to each node, including the artificially generated centroids. The mode of each node is identified. It can be geo-node-road, geo-node-rail, geo-node-waterway, centroid of a region, or terminal. A centroid ID is given if the node presents a centroid. A terminal ID is given if the node represents a terminal, and an extra code identifying the modes, which are served by the terminal, is associated to the node as well. Detailed node attributes are summarized in Appendix II.

The attributes of the geographic links or of the service links mainly identify the length, mode, capacity of the link, as well as the average speed and costs of moving one unit of freight over the link. The commodities are grouped by their trade values, and the relevant VOT is associated to each type of commodity. For each transhipment link, the ID of the terminal connected by the link is attached to the link, and the mode of the geo-node connected by the link as well. For each pre-/end-haulage link, the ID of the terminal (along with the modes it serves) and the ID of the centroid connected by the link are attached to the pre-/end- haulage link. For each access/egress link, the ID of the centroid connected by the link is attached. Besides, some reference attributes for example, throughput, border counts, or ship lock costs are associated to the corresponding type of links. The detailed attributes of links are listed in Appendix II.

In the model, the flows are assigned over the multimodal network by simulating the behaviour of shippers in mode, terminal , and route choice; while incorporating the terminal operators' and the transport operators' responses to the transport demand change, such as taking benefit from cost efficiencies and consolidations.

3.3.3 Total costs of a route

We assume that the users make their decisions depending on the total route costs including transport costs, transhipment costs, VOT, etc. Over the virtual multimodal network, the combined mode-terminal-route choice is carried out in one procedure based on the rule of minimization of the total route costs. The total costs for moving one unit of each type of commodity are defined based on the cost structures in practice for each transport mode and transhipment, including any additional taxes. A route may consist of road links, rail links, IWW links representing the shuttle barge services, IWW links representing the hub-based barge services, and/or the transhipment links. Five different cost functions are applied to calculate the total link costs of each type of links. The results are attached to the corresponding links in the super network for calculating the total route costs.

The total costs of moving one unit of commodity p over route r are specified as follows.

$$\boldsymbol{C_r^p} = \left(\sum_{\boldsymbol{x \in R \cap X}} \boldsymbol{C_x^{\alpha,p}} + \sum_{\boldsymbol{h \in R \cap H}} \boldsymbol{C_h^{\beta,p}} + \sum_{\boldsymbol{a \in R \cap A}} \boldsymbol{C_a^{\theta,p}} + \sum_{\boldsymbol{g \in R \cap G}} \boldsymbol{C_g^{\gamma,p}} + \sum_{\boldsymbol{s \in R \cap S}} \boldsymbol{C_s^{\lambda,p}} \right) \cdot \boldsymbol{f_{p,r}}, \quad \forall\, \boldsymbol{X, H, G, A, S, R \subset L}. \tag{3-1}$$

where

Sets:

L	is the set of all links in the super network;
X	is the set of geographic links, $X \subset L$;
H	is the set of transhipment links, $H \subset L$;
A	is the set of links representing links of access/egress links, $A \subset L$;
G	is the set of pre-/end-haulage links, $G \subset L$;
S	is the set of service links, $S \subset L$;
R	is the set of links of the route;
P	is the set of commodities;

Variables:

$C_x^{\alpha,p}$	is the total costs of moving one unit of commodity p over geographic link x;
$C_h^{\beta,p}$	is the total costs of moving one unit of commodity p over transhipment link h;
$C_a^{\theta,p}$	is the total costs of moving one unit of commodity p over access/egress link a;
$C_g^{\gamma,p}$	is the total costs of moving one unit of commodity p over pre-/end-haulage link g;
$C_s^{\lambda,p}$	is the total costs of moving one unit of commodity p over service link s;
f_p^r	is the volume of commodity p moving over route r.

A route is composed of the link set R. Based on the representation of the network, each link belongs to one of the five sets of links, i.e., geographic links X, transhipment links H, pre-/end-haulage links G, access/egress links A, and service links S. The total costs of moving one unit of commodity p over link l is described by $C_x^{\alpha,p}$, $C_h^{\beta,p}$, $C_a^{\theta,p}$, $C_g^{\gamma,p}$, and $C_s^{\lambda,p}$, depending on to which link set l belongs. The aggregation of the unit total costs incurred on the links belonging to link set R is the total costs of moving one unit of p over route r. f_p^r denotes the flow of commodity p over route r. It should be noted that we assumed the transport operators as the end-users of the freight transport network, and the relevant costs borne by the transport operators are used to describe the price charged by the transport operators for the transport services.

3.3.4 Total costs of a geographic link

The total costs of moving one unit of commodity p over geographic link x are specified as follows.

$$\boldsymbol{C_x^{\alpha,p} = c_x^{\alpha,M} \cdot d_x^{\alpha} + c_p^{P} \cdot (\frac{d_x^{\alpha}}{v_m^{\alpha}}) + e_m^{\alpha} \cdot d_x^{\alpha} \cdot c^{co_2}}, \forall\, \boldsymbol{x \in X \subset L}, \qquad \textbf{(3-2)}$$

where

Sets:

L is the set of links;

X is the set of geographic links, $X \subset L$;

Parameters:

e_m^{α} is the CO_2 emissions of moving one tkm[2] of freight over mode m;

Variables:

$c_x^{\alpha,M}$ is the unit mode-related costs of mode m in main haulage;

c_p^{P} is the unit freight-related time costs of commodity p;

d_x^{α} is the length of link x;

v_m^{α} is the average speed of mode m in main haulage;

c^{co_2} is the price for CO_2 emissions per tCO_2[3].

The mode-related costs $c_x^{\alpha,M}$, commodity-related costs c_p^{P}, and CO_2 emission costs c_{co_2} are the components of the total costs of a geographic link. The mode-related costs are further specified in two parts: (i) the distance-related part, which depends on the distance between the origin and the destination, including maintenance, repairs and fuel; and (ii) the time-related part, which is the time costs depending on the transport mode, directly borne by the transport operators including depreciation, interest, facility tax, licences and permits, insurance, wages, and business costs. The commodity-related time costs mainly include interest, depreciation, and loss of the market value of the freight during the transport process, and are independent of

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[2] tkm is the abbreviation of tonne-km.

[3] tCO_2 is the abbreviation of tonne of CO_2 emissions.

the transport mode. As such, they lead to heterogeneous mode choices when moving different commodities between the same OD pair. The transport operators dealing with a high commodity-related time cost have a high likelihood of choosing a fast transport mode. Therefore, we used commodity-related time costs to describe the heterogeneity of multicommodity in mode choice.

3.3.5 Total costs of a transhipment link

The total costs of moving one unit of commodity p over transhipment link h are specified as follows.

$$\boldsymbol{C_h^{\beta,p} = ⨍(c_h^{\beta}, f_h^{\beta}) + e_h^{\beta} \cdot c^{co_2} + \varepsilon_h^{t}, \forall\, h \in H \subset L,} \tag{3-3}$$

where

Sets:

L is the set of links;

H is the set of transhipment links, $H \subset L$;

Parameters:

e_h^{β} is the CO_2 emissions per tkm incurred in transhipment h;

ε_h^{t} is an alternative specific constant indicating the various costs caused by specific features of the handling between terminal t and a certain transport mode via transhipment link h.

Variables:

c_h^{β} is the unit handling cost of transhipment link h;

f_h^{β} is the flow over transhipment link h;

c^{co_2} is the price for CO_2 emissions per tCO_2.

Transhipment costs are not defined by the time-related costs or the distance-related costs, owing to the complexity of terminal activities. Depending on the services provided by a certain terminal, there might be the other value-added services provided during transhipment (e.g. storage). The cost structure of transhipment is different from that of transport. Despite the emission costs, the transhipment costs borne by the transport operators are defined as the costs borne by the terminal operators with the assumption of complete competition and long-term operation. The costs of terminal operators are the handling costs which depend on the terminal throughput and the scale of the terminal due to EOS and EOD (see Subsection

2.4.2). As we have discussed in Subsection 2.4.4, the unit handling costs decrease with increasing of the throughput (flow over the terminal) but often not monotonically. Ballis and Golias (2002) show the relationship between terminal scale and handling cost by a group of convex curves (Figure 3.2). In order to simplify the computation induced by the flow-related cost function, the diseconomies of scale associated with capacity enlargements were neglected, instead, a monotonic decreasing function was applied describing the handling costs variations (see Figure 3.3 as an example).

In addition, the term ε_h^t is used in function (3-3) to capture the phenomenon that the transhipment costs of different terminals may differ, even if they have the same scale and the same throughput. This may be caused by the operating features (e.g., number of employees, type of handling equipment).

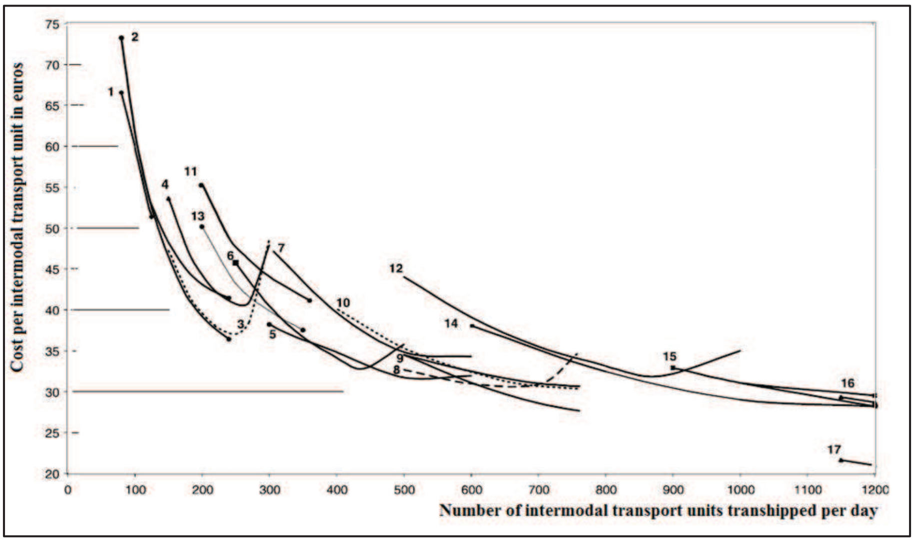


Figure 3.2. An example of ccomparative cost analysis for the alternative terminal design (including infrastructure, personnel, and truck times) (Ballis and Golias, 2002)

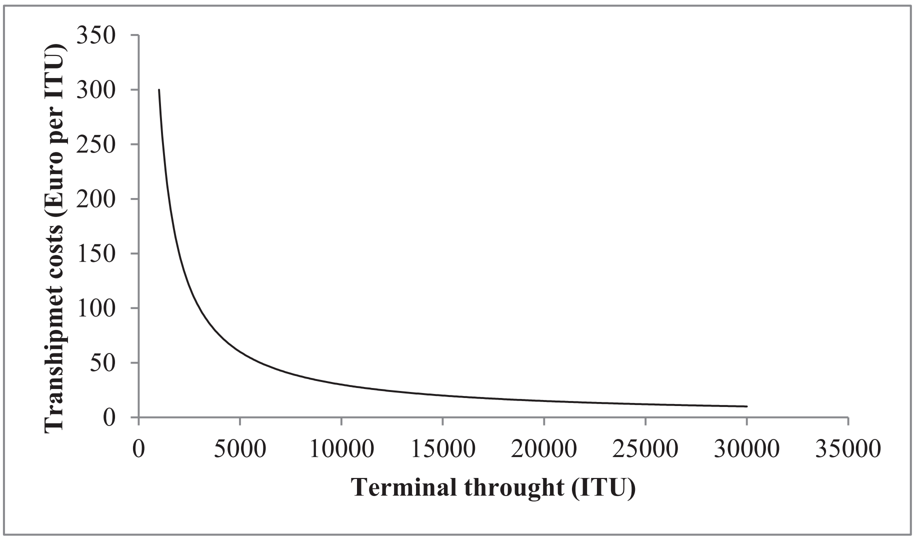


Figure 3.3. Simplified function reflecting economies of scale at terminals

3.3.6 Total costs of an access/egress link

The total costs of moving one unit of commodity p over access/egress link e are specified as follows.

$$\boldsymbol{C_a^{\theta,p} = c_a^{\gamma,M} \cdot d_a^{\gamma} + c_p^{P} \cdot \left(\frac{d_a^{\gamma}}{v_a^{\gamma}}\right) + e_a^{\gamma} \cdot d_a^{\gamma} \cdot c^{co_2} + \varepsilon_a^{\gamma}, \qquad \forall\, a \in A \subset L,} \tag{3-4}$$

where

Sets:

L is the set of links;

A is the set of links representing links of access/egress links, A$\subset L$;

Parameters:

e_a^{γ} is the CO$_2$ emissions per tkm of access/egress;

ε_a^{γ} is an alternative specific constant indicating the various costs caused by specific features of the access/egress between region o and the road network.

Variables:

$c_a^{\gamma,M}$ is the unit mode-related cost of access/egress;

c_p^{P} is the unit freight-related time costs of commodity p;

d_a^{γ} is the distance of access/egress link e;

v_a^{γ} is the average speed of access/egress;

c^{co_2} is the price for CO$_2$ emissions per tCO$_2$.

Access/egress usually means the trucking haulage connecting an origin/destination to a network (Middendorf et al., 1995; Southworth and Peterson, 2000; Southworth et al., 1997). In this model, we use the term ‘access/egress’ to describe the connection to the highway network exclusively, because the costs of accessing/egressing to/from a highway network, rail network, or IWW network are different. The access/egress costs between the highway network and the region centroid describe the average transport costs of trucking between any location within the region and the highway’s entrance. The access/egress costs vary across the regions due to the different transport conditions, for example, the level of road facilities, the average traffic density, and other geographic features (e.g., mountain area or delta area). We express the varieties of the access/egress costs per region by the alternative specific constant ε_a^{γ} in function (3-4).

3.3.7 Total costs of a pre-/end-haulage link

In addition to the ‘access/egress’, we use the term ‘pre-/end-haulage’ to describe the haulage connecting a location within a region to a terminal. The total costs of moving one unit of commodity p over pre/end-haulage link g are specified as follows.

$$\boldsymbol{C_g^{\gamma,p} = c_g^{\theta,M} \cdot d_g^{\theta} + \tau^{\mathrm{p}} \cdot \left(\frac{d_g^{\theta}}{v_g^{\theta}}\right) + e_g^{\theta} \cdot d_g^{\theta} \cdot c^{co_2} + \varepsilon_g^{\theta}}, \qquad \forall\, \mathbf{g} \in \mathbf{G} \subset \mathbf{L}, \qquad (3\text{-}5)$$

where

Sets:

L	is the set of links;
G	is set of pre-/end-haulage links, $G \subset L$;

Parameters:

e_g^{θ}	is CO$_2$ emissions per tkm of pre-/end-haulage;
ε_g^{θ}	is an alternative specific constant indicating various costs caused by specific features of the pre-/end- haulage between region o and terminal t.

Variables:

$c_g^{\theta,M}$	is unit mode-related cost of pre-/end-haulage;
d_g^{θ}	is distance of pre-/end-haulageg;
v_g^{θ}	is average speed of pre-/end-haulage;
c^{co_2}	is the price for CO_2 emissions per tCO_2.

The pre-/end-haulage costs are related to both the features of the terminal, and the features of the region. We express the varieties of the pre/end-haulage costs per region-terminal pair by the alternative specific constant ε_g^{θ} in function (3-5).

3.3.8 Total costs of service links

We define several types of hub service networks structures (see Figure 4.6 for examples). The link costs of the hub services depend on the transport demand, barge size, service frequency, and other factors. Because the form of cost function of a link varies for different service schemes, a simple analytical cost showing the relevant variables and parameters is presented as follows. Examples of detailed cost functions of service links being a part of specific types of service network are given in Appendix IV.

The total costs of link l being a leg of service S_i is:

$$\boldsymbol{C_s^{\lambda,p} = f(c_s^{\lambda,F}, c_s^{\lambda,D}, c_s^{\lambda,U}, nr_s^{\lambda}, z_s^{\lambda}, k_s^{\lambda}, v_s^{\lambda}, u_s^{\lambda,H}, u_s^{\lambda,SH}, f_s^{\lambda}, d_s^{\lambda}, sns),}$$
$$\forall\, \boldsymbol{s \in S_i, S_i \subset SN} \qquad \textbf{(3-6)}$$

where

Sets:

SN is the set of all links consisting the hub-based service network;

S_i is the set of links consisting a hub-based-service, $S_i \subset SN$.

Parameters:

$c_s^{\lambda,F}$ is the annual fixed cost of barge operating along link s, $c_s^{\lambda,F} = f(z_s^{\lambda})$;

$c_s^{\lambda,D}$ is the distance-related variable costs of moving containers along link s, (€/t-km), $c_s^{\lambda,D} = f(z_s^{\lambda}, v_s^{\lambda})$;

$c_s^{\lambda,U}$ is the time-related variable costs of containers moving along link s (€/t-h), including mode-related time costs and commodity-related time costs, $c_s^{\lambda,U} = f(z_s^{\lambda})$;

z_s^{λ} is the maximum barge size navigable along link s;

v_s^{λ} is the average speed of barges operating along link s;

$u_s^{\lambda,H}$ is the total handling time of a round trip along link s;

$u_s^{\lambda,SH}$ is the total shipping time of a round trip along link s;

d_s^{λ} is the length of link s;

sns is the service network structure (see Appendix IV (a) (b) (c));

Variables:

nr_s^{λ} is the number of barges needed to serve demand over link s, $nr_s^{\lambda} = f(z_s^{\lambda}, f_s^{\lambda})$;

f_s^{λ} is the flow along link l_i.

k_s^λ is the total annual transport capacity of the nr_s^λ barges (full load and the maximum number of turnarounds, $k_s^\lambda = f(z_s^\lambda, v_s^\lambda, d_s^\lambda)$;

In this formulation, the volumes of transport demand and the required service level represented by the service frequency determine the unit transport costs of a service. The flows between the inland terminals themselves are not served by the hub services. We simplified the cost function by introducing the following assumptions. First, the barges operating on a service link have the same loading capacity (measured in TEUs), and are the largest enabled to navigate along the service link. Second, the barges deployed are maximally utilized at the annual scale in terms of the number of voyages. Third, the annual fixed costs of operating a barge ($c_s^{\lambda,F}$), the distance related variable costs ($c_s^{\lambda,D}$), and the time-related variable costs ($c_s^{\lambda,U}$) are independent from the load factor of a barge. The annual fixed costs include the costs of depreciation, maintenance, and the interests of the capital. The distance-related variable costs mainly include fuel costs. The time-related variable costs mainly refer to the crew costs. It is reasonable to argue that a full-load barge may be more costly in these three types of costs, but this is not taken into consideration in the modelling, because of the very small cost variation they can cause in the total costs of an OD trip.

3.4 Bi-level network optimization modelling

The network optimization is realized by a bi-level optimization model.

The upper-level searches for the optimal alternatives leading to the optimal network performance, which is represented by the optimization objective(s). The objective(s) can be one or a combination of the costs or CO_2 emissions minimization, or the modal-share optimization. The network performance of each alternative is evaluated on the basis of flow assignment, and in the scope of link, region, corridor, country, or entire network.

The objectives of terminal operators and transport service operators are taken into account in the lower-level modelling. In order to incorporate the economies of density at the terminals and in the services, two pre-processing procedures are added to the flow assignment performed at the lower-level. One minimizes the service costs, given the predicted demand for the hub-based-services. The other calculates the flow-related transhipment costs of the terminals. The flow assignment minimizes the user costs given the costs of each (possible) route. These two pre-processing procedures and the flow assignment perform iteratively to achieve the equilibrium of flow assignment at the network level. A simplified flow chart is shown in Figure 3.4.

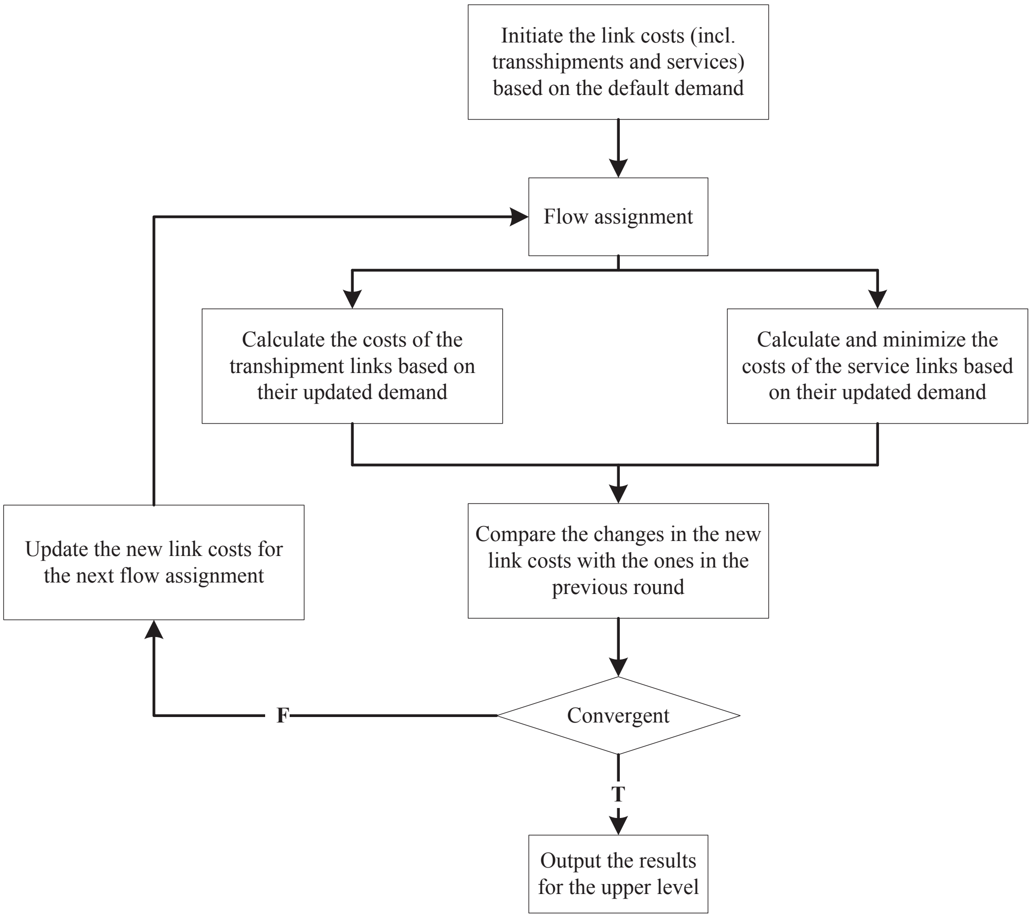


Figure 3.4. Flow chart of the programming procedure for the flow assignment considering flow-related transhipment costs and hub-based-service costs

An alternative may consist of one or of a combination of different design measures, namely, infrastructure modifications, regulatory policies, and potential hub-based services. The objectives of optimization can be the costs minimization, the network utilization maximization, the pollution minimization, etc. In order to simplify the formulation, we take a specific example to explain the logic and the mechanism of the mathematical specification of this model. The capability of the optimization function of this model is not limit to this example. In the following example, we assume that each alternative is defined as a scenario consisting of a certain terminal network configuration with (or without) feasible hub-based barge services, and a certain CO_2 charge.

3.4.1 The upper level problem formulation

We evaluate the network performance based on the total network costs consisting of the internal costs and the costs of CO_2 emissions of all the links in the network. The internal costs include distance-related transport costs, mode-related time costs, commodity-related time costs, and transhipment costs. The costs of CO_2 emissions are expressed in the monetary terms per unit of quantity (euro per tCO_2). The optimization problem is as follows:

$$\boldsymbol{MIN} \;\; \boldsymbol{f}\left(\boldsymbol{\mu},\, \boldsymbol{C}^{*}, \boldsymbol{f}^{*}, \boldsymbol{c}^{\boldsymbol{co_2}}\right), \tag{3-7}$$

Subject to:

$$\boldsymbol{\mu}_{\boldsymbol{w},\boldsymbol{b}} = \begin{cases} \mathbf{0} \\ \mathbf{1} \end{cases} \tag{3-8}$$

$$\sum \boldsymbol{C}_{\boldsymbol{w}}^{*} \leq \sum \boldsymbol{C}_{\boldsymbol{w}} \tag{3-9}$$

where

Sets:

B is the set of candidate terminals,

W is the set of alternative terminal network configurations

Variables of the model:

μ is binary array expressing the openness of terminals, $\mu_{w,b} = 1$ if terminal b is opened in terminal network configuration w, $b \in B$, where B is the set of candidate terminals, and $\mathrm{w} \in \mathrm{W}$, where W is the set of different terminal network configurations (2^{n} configurations);

C^{*} is the vector of total link costs of the optimal solution at the lower level;

f^{*} is the vector of link flows of the optimal solution at the lower level;

c^{co_2} is the price for CO_2 emissions per tCO_2.

3.4.2 The lower level problem formulation

Given the fixed transport demand, the total costs of each link are directly related to the way of assigning the flows over the multimodal network. The transport operators may choose different modes and/or routes respecting configuration of the same terminal network and the same CO_2 charge. We capture this phenomenon in the lower level programming. The minimum total network costs $\sum \boldsymbol{c}_{\boldsymbol{k}}^{*}$ of each alternative, which is obtained from the lower level, are evaluated at the upper level. The optimization problem is as follows:

$$\boldsymbol{MIN} \sum_{i,j,o_1,o_2,p} f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} \cdot C_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} \cdot \delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}}, \tag{3-10}$$

$$\forall (i,j) \in L, o_1 \in O, o_2 \in O, p \in P,$$

Subject to:

$$C_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} = f^1\,(f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}})\,|_{(i,j)\in H}, \forall (i,j) \in H; \tag{3-11}$$

$$C_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} = f^2\,(f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}})\,|_{(i,j)\in S}, \forall (i,j) \in S; \tag{3-12}$$

$$\delta_{i,j} = 0\,|_{\delta_i\ =0}, \forall (i,j) \in L, i \in T; \tag{3-13}$$

$$\delta_{i,j} = \delta_{j,i}, \forall (i,j) \in L, (i,j) \in L; \tag{3-14}$$

$$\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} + \delta_{\mathrm{j,l}}^{o_1,o_2,\mathrm{p}} \leq 1|_{(i,j)\in H \text{ and } (j,l)\in H}, \forall (i,j) \in L, (i,l) \in L; \tag{3-15}$$

$$\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} + \delta_{\mathrm{j,l}}^{o_1,o_2,\mathrm{p}} \leq 1|_{(i,j)\in G \text{ and } (j,l)\in G}, \forall (i,j) \in L, (j,l) \in L; \tag{3-16}$$

$$\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} + \delta_{\mathrm{j,l}}^{o_1,o_2,\mathrm{p}} \leq 1|_{(i,j)\in E \text{ and } (j,l)\in E}, \forall (i,j) \in L, (j,l) \in L; \tag{3-17}$$

$$\sum_i f_{i,o_1}^{o_1,p} = f^{o_1,p}, \forall (i,o_1) \in A, o_1 \in O, p \in P; \tag{3-18}$$

$$\sum_i f_{i,o_2}^{o_2,p} = f^{o_2,p}, \forall (i,o_2) \in A, o_2 \in O, p \in P; \tag{3-19}$$

$$\sum_{i,j} f_{i,j}^{o_1,p} = \sum_{i,j} f_{i,j}^{o_2,p}, \forall (i,j) \in L, o_1 \in O, o_2 \in O, p \in P; \tag{3-20}$$

$$f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} \geq 0, \forall (i,j) \in L\,; \tag{3-21}$$

where

Sets:

L is the set of links;

H is the set of links representing transhipment between terminal and rail/inland waterway, $H \subset L$;

A is the set of links representing access/egress, $A \subset L$;

G is the set of links representing pre- and end- road haulage, $G \subset L$;

S is the set of links representing links of hub services, $S \subset L$.

O is set of regions;

T is the set of terminals;

Variables:

$f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}}$ is flow of commodity p from origin o_1 to destination o_2 over link (i,j);

$C_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}}$ is total costs of link (i,j) when moving one unit of commodity p from origin o_1 to destination o_2 ;

$\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}}$ is the availability of link (i,j) for moving a unit of commodity p from origin o_1 to destination o_2 ; $\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} = 0$ when the link is not available, $\delta_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}} = 1$ otherwise.

The lower level minimizes the total network costs when assigning the transport demand, over the network with given terminal configuration and CO_2 charge. Constraint (3-13) prohibits assigning flows to the 'closed' terminals. Constraint (3-14) defines the availability of links in both directions. The flows are not allowed to be moved over two adjacent access/egress links. The same rule applies to the pre-/ and end road haulage and transhipment links between terminal and rail/inland waterway (Constraints (3-15)(3-16)(3-17)). Constraints (3-18) and (3-19)(3-12) ensure that all flows are assigned over the network. Constraint (3-20) balances the flow generation and attraction at the network level. Constraint (3-21) prevents any negative flows over the network. Equation (3-11) and (3-12) indicate dependency of the cost of transhipment and that of the service link(s) on the flows they handle. The total flows they handle are treated as parameters in this combined route choice model, which is independent from the flow, denoted as $f_{\mathrm{i,j}}^{o_1,o_2,\mathrm{p}}$, of commodity p from origin o_1 to destination o_2 over link (i,j). The transport capacities of all modes, in terms of transport means and infrastructure, and of all terminals are assumed to be unlimited, bearing in mind that the model is developed for the long-term strategic planning.

3.4.3 Solution methods and algorithms

A derivative all-or-nothing (AON) algorithm based on the Dijkstra method (Dijkstra, 1959) is used in this model for the flow assignment. Principally, an AON algorithm is used to assign the demand of each OD pair to the route between the OD pair, which has the lowest total route costs. Two limits of the AON algorithm are that: 1) the capacities of the candidate routes are assumed to be unconstrained; and 2) the heterogeneity of network use decisions is not taken into account. The capacitated or equilibrium algorithms are the two alternatives to AON. We choose AON because of that we plan to use this model for aggregated flow assignment, on annual basis. Capacity shortage is rarely observed on an annual basis. If there is no capacity constraint in the network, the results from the AON algorithm or from the other two alternative algorithms are probably the same. Using the AON algorithm saves much computing time due to needless iterative procedures for achieving the equilibrium.

The upper level solves the combinatorial optimization problem to find the combinations of design measures which achieves the minimal total network cost. A genetic algorithm (GA) (Goldberg, 1989b) is used to solve the optimization problem at the upper level because of the numerous number of candidates and the non-convexity of the cost function. We designed GA by applying the 'roulette wheel selection', 'n-point half-uniform crossover', 'uniform mutation', and 'elitist' strategies (Christopher et al., 1995; Costa and Oliveira, 2004; Spears and De Jong, 1991; Wardlaw and Sharif, 1999). The process of optimization is given below while the detailed flow chart is presented in Appendix III.

Inner loop: flow assignment

Step 1: Initiate the network features according to the reference scenario;
Step 2: Load solution *j, j∈ [1, number of solutions of this generation]* of generation *i* of the network. The transhipment costs of each terminal and the transport costs of each service leg are given according to the costs in the base year;
Step 3: Run the multicommodity AON flow assignment;
Step 4: Update the transhipment costs of each terminal based on the transhipment cost-flow function and the flow assigned to the terminal in this run; meanwhile, calculate the costs of each service leg, as presented in equation (3-6) of the service simulation sub-model;
Step 5: Iterate Step 3 and Step 4 until the difference of the transhipment costs and the costs of the service legs in two adjacent runs are accepted by the predefined tolerance level;
Step 6: Calculate the system costs and the CO_2 emissions of this solution;
Step 7: If *j+1= the number of solutions of this generation*, then go to Step 2 of the outer loop;
Step 8: Load solution *j+1* of generation *i* to the network, and then go to Step 3.

Outer loop: optimization

Step 1: Generate the first generation of solutions. Go to the inner loop for solution 1 of this generation;
Step 2: Find the “best” solution of this generation;
Step 3: If *i+1=the number of generation*, then go to Step 6;
Step 4: Generate the next generation by applying GA techniques ‘roulette wheel selection’, ‘half-uniform crossover’, ‘uniform mutation’, and ‘elitist’;
Step 5: Iterate Step 2 to Step 5;
Step 6: Return the “best” of all solutions of all generations, and stop.

3.5 Modularized framework of the model

This model was developed in the GIS development environment of TransCAD®. The model visualizes attributes of infrastructure, freight flows over thee network, and network performances including among other factors, costs, utilization, and CO_2 emissions. Data or the results can be visualized over the geographic network at the link, terminal, regional, and network level, per mode, commodity type, and/or for combination of some of these.

We chose to code the model in a modularized architecture due to (1) to allow flexibility to realize new functions by reorganizing the modules; (2) to be open to further developments by plugging-in new modules; and (3) to allow convenience to protect, maintain, and update the databases which are embedded in the model.

Figure 3.5 illustrates the framework of the modularized model. It consists of 6 functional modules (P1 to P6) and 5 embedded databases (D1 to D5). The demand module (P1) processes and prepares the OD demand matrices for the flow assignments. The demand matrices are loaded from the demand database (D1) which stores the OD transport demand per mode (or for all modes) per commodity group on an annual basis. The commodity groups are defined on the basis of the commodity values. The supply module (P2) processes or updates the inputting infrastructure (and/or service) network features according to the scenario defined by the combination of design measures generator (P3). All the demand data, infrastructure network feature data, and service network feature data are supported by the GIS (D2). The combination of design measures generator (P3) generates design measures from the policy pool (D5). Each combination of design measures consist one scenario for the flow assignment or the network optimization. The flow assignment module (P4) executes the mode-terminal-route choices and assigns the OD demand which is determined by the demand module of the network where the features are defined by the supply module. The optimization module (P5) optimizes the infrastructure network with user defined optimization objectives. The calibration module (P6) provides several models for calibrating the alternative specific constants of the flow assignment model in order to ensure that the estimated flows in the base year are similar to those in the actual situation.

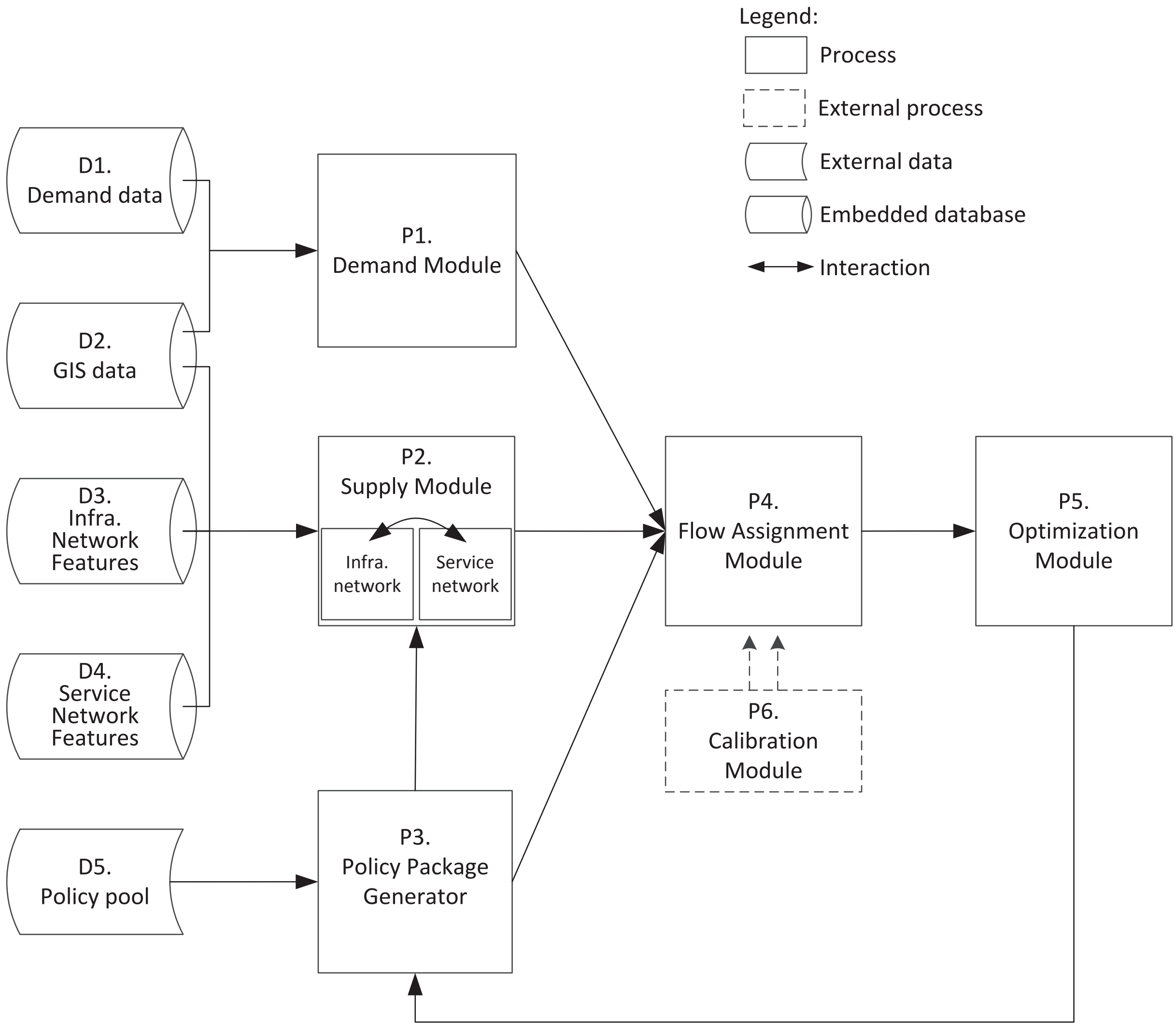


Figure 3.5.General framework of the model

3.6 Summary and discussions

In the previous chapter, the new challenges and new requirements for the freight transport infrastructure network design (FTIND) from the governmental perspective is discussed, and a new model is proposed aiming at fulfilling these requirements better than the existing models.

The model is developed in a geographic information system (GIS) environment mainly for the purpose of visualization. Models based on GIS are increasingly favoured for freight transport network design due to their advantages in visualization. A super network representation is proposed. The pre-/end-haulage and the hub-based service networks are specified particularly in the network aiming to better capture the features of the relevant services as compared to the existing models. This enables differentiating pre-/end-haulage of intermodal transport from unimodal road transport, and thus is able to quantify the performances of intermodal transport such as costs, time, and the impacts on environment. It also enables modelling the terminal choice, in addition to the classic mode and route choice. This provides new options for modelling the terminal competition and/or cooperation on the basis of a GIS environment.

In addition to the infrastructure network, a network representing collaborative hub-based services is integrated into the super network. Economies of scale and economies of density are considered in the model for both terminals and hub-based barge services.

The model supports infrastructure network design while taking into account the goals of multiple actors involved through bi-level network optimization programming. The formulation described is an example of the terminal network optimization. The goal of the government is assumed to be the reduction of the total network costs and the CO_2 emissions through the terminal network configuration and CO_2 pricing. This is reflected at the upper level of the problem. The terminal operators' aims are assumed to be attracting more flows, achieving economies of density and economies of scale, and thus providing handling services at lower costs. The transport operators are assumed to choose the least expensive transport mode, terminal, and route in order to reduce costs. Meanwhile, they are also assumed to collaborate, and if possible, operate the hub-based inland waterway transport services in order to save costs by improving the efficiency of capacity utilization. The objectives of the terminal operators and the transport service operators are taken into account through adding two pre-processing procedures to the flow assignment performed in the lower-level modelling. In addition, the model incorporates the commodity-related time costs (also known as Value of Time) in order to capture different decisions on the network use for the commodities with different values.

The network optimization is realized by the scenario-based optimization. The model generates a large number of scenarios (including terminal network configurations, CO_2 prices, and hub-based services individually, or in combination), evaluates the performances of these scenarios, and searches efficiently for the most optimal solutions. The optimization problem is solved by bi-level optimization, where the upper level searches for the optimal combinations of design measures, while the lower level performs multicommodity flow assignment over the large-scale multimodal network.

The model is generically applicable to the freight transport infrastructure network design in terms of the architecture, methods, and algorithms. It is also applicable to the design measures other than the terminal network configuration, CO_2 price, or specific service network. For instance, taxation and subsidization are some examples. The measurement of externalities is not limited to CO_2. It is also applicable to NO_x, noise, and number of fatalities with supplementary data. The optimization objectives can be customized by the model's users. The evaluation of network performance can be carried out at the link, terminal, regional, and network level, per mode, commodity type, and/or for combination of some of these.

Chapter 4

Freight Transport Infrastructure Network Design: Calibration and Validation

4.1 Introduction

In the previous chapter, the new model for integrated network design is specified. However, it is not possible to empirically specify the model based entirely on observations. There are unknown parameters and unknown errors. Calibration provides the values to these unknowns. In order to maximize the fit between the model and the real world observations, the quality of the outputs needs to be evaluated, and the validity of the model needs to be guaranteed.

This chapter introduces the calibration and validation of the flow assignment sub-model. Flow assignment is one of the key functions of the model, allowing simulating decisions on the network use by transport operators, i.e., mode, terminal, and route choice. Flow assignment, essential for the scenario analyses and the optimization of the network, is presented in the next chapter (Chapter 5). After looking at the challenges of calibrating a large-scale model in Section 4.2, the calibrating parameters of the flow assignment sub-model are discussed in Section 4.3. In Section 4.4, a genetic algorithm (GA) based calibration approach and a feedback-based calibration approach are introduced in order to calibrate the flow assignment sub-model. The model is calibrated for the base year 2006. The observed data are introduced in Section 4.5. Both approaches are applied to calibrate the model. The calibration results are reported in Section 4.6, along with the evaluation of the performance of each calibration approach. Section 4.7 further validates the calibrated model. This chapter ends with a discussion of the advantages and disadvantages of these two calibration approaches.

4.2 Calibrating a large-scale flow assignment sub-model

Calibration involves estimating the values of various constants and parameters in the model structure (Edwards and Engineers, 1999). By estimating these unknowns, we can define or approximate the relations between the modelled results and the corresponding observed results. Commonly used calibration method estimates the unknown constants and unknown parameters by solving the problem with known input and known corresponding output. Calibrating a large-scale multimodal multicommodity flow assignment model is much more complex than calibrating the uni-modal single commodity model with a small number of OD pairs. This is because of the following reasons:

Large number of variables

The assigned flows over the network are the integrative result of a series of complex decisions. These numerous influencing factors also need to be taken into account. Some examples include distance related costs, time related costs, the availability of transport modes, the accessibility of intermodal transhipment facilities, the traffic condition of each region, the service level of each terminal, and the specific regulations of each region. The enlargement of the network brings more transport or logistic considerations into the decision-making process. In order to simplify the real situation while simulating the key characteristics of the system, the appropriate variables enabling representing the situation for a certain spatial area, a certain time span, or a certain type of commodity should be captured.

Large number of elements in each variable

The large-scale model usually covers the large network in terms of geographic scope. When the infrastructure in the network is described in much detail, each of the variables describing the network features is likely to be composed of a large number of elements. Therefore, it is difficult to trace the impact of each element on the entire network. Even if they are able to be traced, it is impossible to calibrate each one of them individually. For example, take the average regional speed of trucking: for the European road network with one commodity type at NUTS 0 level (27 regions identified), 27 elements need to be calibrated to represent the average speed of trucks; contrary, for a tri-modal network with 5 commodity types at NUTS 3 level (1303 regions identified), the number of elements which represents the trucking speed is 19,545, even if the pre/end haulage is not differentiated from the uni-modal road transport. Since the modelled flow assignment is an integrative result of the interactions of all of these elements, it is almost impossible to manage them individually.

Availability of reference data

It is very difficult to acquire appropriate and adequate data that can be used as the observations for calibration. It is even more difficult when the data is required transport mode instead an overall flow, because usually road, rail, and inland waterway transport are administered by different organizations. Each of these organizations uses its own statistical approach for questionnaire design, sampling, measuring, and data processing Thus it is almost impossible to obtain a complete set of data, which would contain the observed flows of road, rail, and inland waterway transport at more detailed level (e.g., per segment of road, rail, or inland waterway) for the same statistic year.

We are aware that a lot of efforts have been put into calibration in previous models (Jourquin, 2005; Yamada et al., 2009). However, only few discussions can be found about calibrating flow assignment models. One example is the multimodal multicommodity model NODUS (Jourquin, 2005). It consists of 12,000 nodes, 265,000 virtual links, 9 modes (2 types of truck, 2 types of train, and 5 classes of barge), and 10 types of commodities (NSTR groups). The model is calibrated by adjusting the speed of some links and the parameters in the cost functions. The quality of calibration was evaluated by comparing the modelled modal shares of road, rail, and inland waterway transport per NSTR category (10 commodity types). A good fit resulted from this calibrating method. This indicates that each modality in the network bears the right amount of freight flows, but it does not guarantee that the flows are transhipped at the right terminals or are appropriately assigned to the right routes. Yamada developed another multimodal multiuser freight transport network design model (Yamada et al., 2009) with 3 modes (road, rail, and sea) and 2 types of users (freight and passenger). The network is composed of 424 nodes with 331 freight OD pairs, 340 passenger OD pairs, and 1871 links. The modal split estimated for this model was validated by comparing the modelled link flows with the actual (or aggregated) link traffic counts. The node flows were not specifically calibrated. As a result, when the model is used for node flow estimation, for example, for the prediction of terminal throughput, it is difficult to specify the validity or reliability of the results.

The present model consists of 32,767 nodes and 41,522 links, 720*720 OD pairs, 3 modes (road, rail, and inland waterway), and 5 types of commodities (grouped by commodity values). We formulate the calibration of the model as solving a parameter estimation problem. As mentioned earlier, many factors may influence the decision-making of the transport operators, and thus may influence the flow assignment. Therefore, selection of the number of variables and their parameterization according to the available observations is carried out first. Then, we search the optimal values for these parameters. These values, in combination, lead to the satisfactory fit.

Since the flow assignment simulates three decision-making behaviours, i.e., mode, terminal , and route choice, we tested the simulation quality of the model for these three aspects. First, the performance of mode choice is evaluated by comparing the modal split per region with the corresponding data calculated from the Dutch freight transport survey (CBS, 2006). Second, the performance of terminal choice is evaluated by comparing the modelled flows passing through some Dutch terminals with the actual throughput of these terminals. These were selected according to the availability of data. Third, the performance of route choice is evaluated by comparing the modelled flows passing through the border crossing points of the railways and some ship locks of inland waterways with the actual border counts and the actual ship lock counts.

4.3 Parameterizable variables

The calibration of this model is formulated as a parameter estimation problem. The objective is to minimize the sum of the coefficients of variation of the root mean square errors (CVRMSE) between the modelled link flows and the observed link flows of the reference links. The mathematical expression of CVRMSE is shown in Equation (4-1).

$$\boldsymbol{MIN\ (CVRMSE) = MIN\ (\frac{\sqrt{(\sum_{l=0}^{n^{obs}} (v_l - \tilde{v}_l)^2)/n^{obs}}}{(\sum_{l=1}^{n^{obs}} v_l)\ /n^{obs}})} \qquad (4\text{-}1)$$

where

Variables:

n^{obs} is the number of observations;

v_l is observed value;

$\tilde{v}_l$ is calculated value.

There are other indicators that can be used as the objective for calibration, for example, modal-share, flow counts, throughput of terminals, and distribution of trip distance. The observations can also be in various scopes, including among others whether the network is global, national, regional, whether it is per corridor, terminal, link, or per commodity type, and whether it is import or export. The CVRMSE of link flow is chosen because it provides the most details that could be obtained based on the available observations. Moreover, it also reflects the combined effects of the decisions of the network use. The minimization problem is formulated as follows.

The modelled link flow $\boldsymbol{\tilde{v}_l}$ is the sum of the flows of all of the OD pairs passing through link l, where link l takes a part of the shortest path of each of these OD pairs. In the model, the flow assignments are primarily determined by costs and time. The time is represented by distance/speed. As defined in equation 3-1 to 3-4, in the basic scenario, where the hub services are not available and no CO_2 price is charged, the total route costs depend on mode-related costs, commodity-related time costs, handling costs, the average speed of passing through a link, the total length of the links composing the route, the average distance of the access/egress of a region, and the average distance of pre/end haulage between a region and a terminal. The influencing factors are described by the following equation in detail.

$$\boldsymbol{\tilde{v}_l = f(c_x^{\alpha,M}, c_h^{\beta}, c_a^{\gamma,M}, c_g^{\theta}, c_p^{P}, v_m^{\alpha}, v_a^{\gamma}, v_g^{\theta}, d_x^{\alpha}, d_a^{\gamma}, d_g^{\theta}) \forall X, H, A, G \subset L}$$
$$\boldsymbol{\forall\, x \in X \subset L,\ \forall\, h \in H \subset L,\ \forall\, a \in A \subset L,\ \forall\, \mathrm{g} \in \mathrm{G} \subset \mathrm{L}, and\ l \in \mathrm{L}} \qquad (4\text{-}2)$$

where

Sets:

L is the set of all links in the super network;

X is the set of geographic links, $X \subset L$;

H is the set of transhipment links, $H \subset L$;

A is the set of links representing links of access/egress links, $A \subset L$;

G is the set of pre-/end-haulage links, $G \subset L$.

Variables:

$c_x^{\alpha,M}$ is the unit mode-related costs of mode m in main haulage;

$c_a^{\gamma,M}$ is the unit mode-related cost of access/egress a;

c_h^{β} is the unit handling cost of transhipment link h;

c_g^{θ} is unit mode-related cost of pre-/end-haulage g;

c_p^{P} is the unit freight-related time costs of commodity p;

v_m^{α} is the average speed of mode m in main haulage;

v_a^{γ} is the average speed of access/egress a;

v_g^{θ} is average speed of pre-/end-haulage g;

d_x^{α} is the length of the link x;

d_a^{γ} is the distance of access/egress link a;

d_g^{θ} is distance of pre-/end-haulageg g;

ε_h^{t} is an alternative specific constant indicating the costs variation caused by specific features of the handling between terminal t and a certain transport mode via a transhipment link h;

ε_a^{γ} is an alternative specific constant indicating the costs variation caused by specific features of the access/egress between the region o and the road network;

ε_g^θ is an alternative specific constant indicating the costs variation caused by specific features of the pre-/end- haulage between the region o and the terminal t.

Except for the length of the geographic links (d_x^α), all other terms depend on the specific conditions of each link. Due to the data availability, it may be only possible to estimate the average value in a certain time span or with a certain geographic scope. Taking the unit mode-related cost of access/egress ($c_a^{\gamma,M}$) as an example, it expresses an average value of a region. Therefore, principally, all of these terms (excluding the length of each geographic link, d_x^α) are not accurately known, thus are options to be calibrating parameters. However, some of these parameters are interdependent. For example, the mode-related cost of the pre-haulage from a region to a terminal is dependent on the average speed of the pre-haulage from the region to the terminal, as well as the average distance of the pre-haulage generating within the region to the terminal. In this case, we added one extra parameter to represent the combined effect of these factors. This also simplifies the calibration process and saves computation time. The five types of calibrating parameter are explained as follows.

1. ε_h^t: is an alternative specific constant indicating the various costs caused by specific features of the handling between terminal t and a certain transport mode via transhipment link h;
2. ε_a^γ: is an alternative specific constant indicating the various costs caused by specific features of the access/egress between region o and the road network, which represents the combined effect of the unit mode-related cost of an access/egress ($c_a^{\gamma,M}$), the distance of the access/egress link (d_a^γ), and the average speed of the access/egress of the link (v_a^γ);
3. ε_g^θ: is an alternative specific constant indicating various costs caused by specific features of the pre/end haulage between region o and terminal t, which represents the combined effect of the unit mode-related cost of a pre-/end-haulage (c_g^θ), the distance of the pre-/end-haulage (d_g^θ), and the average speed of the pre-/end-haulage (v_g^θ).
4. In addition to these three calibrating parameters, we treated the unit mode-related costs of each mode in the main haulage ($c_x^{\alpha,M}$) as a calibrating parameter, in order to represent the average mode-related costs of geographic links in the entire network.
5. We calibrate the unit commodity-related time costs (c_p^P) as well because of the composition of commodities transported to/from a region may differ from one region to another. We present the composition of commodities and the associated commodity-related time costs by estimating the distribution of the commodity-related time costs to the proportion of each type of commodity in the total volume.

The calibration model is formulated as the following.

$$\boldsymbol{MIN \quad CVRMSE = f(\tilde{v})} \tag{4-3}$$

$$\boldsymbol{\tilde{v}_l = f\left[\left(c_x^{\alpha,M} + \varepsilon_m^1\right), \left(c_{t,m}^\beta + \varepsilon_{t,m}^2\right), \left(c_o^{\gamma,M} + \varepsilon_o^3\right), \left(c_{o,t}^{\theta,M} + \varepsilon_{o,t}^4\right), c_p^P\right]} \tag{4-4}$$

of which: $c_p^P = f\left(\bar{c}^P + \varepsilon^5, q_p^P + \varepsilon_p^6\right)$

where

Variables:

$\mathrm{C}_{\mathrm{m}}^{\alpha,\mathrm{M}}$: is the array of the unit mode-related costs of main-haulage;

$\mathrm{c}_{\mathrm{m}}^{\alpha,\mathrm{M}} = \{\mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{road}}, \mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{rail}}, \mathrm{c}_{\mathrm{x}}^{\alpha,\mathrm{IWW}}\}$;

$\varepsilon_{\mathrm{m}}^1$ is the array of parameters relating to the unit model-related costs of main-haulage, $\varepsilon^1 = \{\varepsilon_{\mathrm{road}}^1, \varepsilon_{\mathrm{rail}}^1, \varepsilon_{\mathrm{IWW}}^1\}$;

$\mathrm{c}_{\mathrm{t,m}}^{\beta}$ is the array of handling costs; $t \in$ [1, the number of terminals], $m \in$ {road, rail, IWW};

$\varepsilon_{\mathrm{t,m}}^2$ is the array of parameters relating to the handling costs when transferring one tonne of freight from terminal t to mode m, $t \in$ [1, the number of terminals], $m \in$ {road, rail, IWW};

$\mathrm{c}_{\mathrm{o}}^{\gamma,\mathrm{M}}$ is the array of the unit mode-related costs of access/egress when moving the freight generated in region o to the road network, $\mathrm{o} \in$ [1, the number of regions];

$\varepsilon_{\mathrm{o}}^3$ is the array of parameters relating to the unit mode-related costs of access/egress, $\mathrm{o} \in$ [1, the number of regions];

$\mathrm{c}_{\mathrm{o,t}}^{\theta,\mathrm{M}}$ is the array of the unit mode-related costs of pre-/end-haulage when moving the freight generated in region o to terminal t, $\mathrm{o} \in$ [1, the number of regions], $\mathrm{t} \in$ [1, the number of terminals within a reasonable distance of region o];

$\varepsilon_{\mathrm{o,t}}^4$ is the array of parameters relating to the unit mode-related costs of pre-/end-haulage, $\mathrm{o} \in$ [1, the number of regions], $\mathrm{t} \in$ [1, the number of terminals within a reasonable distance of region o];

$\mathrm{c}_{\mathrm{p}}^{\mathrm{P}}$ is the array of the unit commodity-related time costs of the freight, $\mathrm{p} \in$ [1, the number of commodity types];

$\bar{c}^P$ is the average of the unit commodity-related time costs of all commodity types;

ε^5 is the parameter relating to the average of the unit commodity-related time costs of all commodity types;

q_p^P is the array of the proportion of commodity p in the total volume of all commodities;

ε_p^6 is the array of parameters relating to the proportion of commodity p in the total volume of all commodities.

4.4 Calibration approaches

As explained in the previous section, the calibration process can be described as the search for a combination of parameters with the objective of minimizing the CVRMSE as defined in equation (4-3) and (4-4). The characteristics of this parameter estimation problem include the following:

- each parameter is an array with a large number of elements;
- the value change of each element may have an influence on the CVRMSE;
- the influence of each element is not traceable at the global level, but is predictable to some extent.

We chose a genetic algorithm based (GA-based) method and a feedback-based method for model calibration. In the next section, we will discuss the reason for choosing these methods and the calibration procedures in more detail.

4.4.1 GA

Generally, the GA method has advantages in the search for satisfactory solutions when this solution is composed of a large number of variables and each variable has a specified range. Furthermore, GA has fewer restrictions on searching paths. Although GA cannot guarantee arriving at the optimum solution, this is not its crucial disadvantage in our case since a satisfactory solution is sufficient for this parameter estimation problem. Therefore, we see GA as an option that can be used for this problem.

The GA-based calibration is formulated as a bi-level optimization problem. The lower level models the multicommodity flow assignment over the multimodal network, while the upper level searches for an optimal parameter combination which leads to the minimal CVRMSE. The bi-level optimization problem is formulated as follows:

Upper level:

See equations (4-3) and (4-4).

Lower level:

See equations (3-10) to (3-21) in Chapter 3

Each solution is an array of the values of calibrating parameters ($\boldsymbol{\varepsilon}^{1} \sim \boldsymbol{\varepsilon}^{6}$). The algorithm is supposed to find the most "optimal" combination of the values of parameters resulting in a "satisfactory" fit between the modelled results and the observations. The problem is solved by the double-loop iterative procedures. The computation process starts from the outer loop.

Outer loop: optimization

Step 1: Generate the first generation of solutions. Go to inner loop for solution 1 of this generation;
Step 2: Find the "best" solution of this generation;
Step 3: If *i+1=the number of generation*, then go to Step 6;
Step 4: Generate the next generation by applying GA techniques 'roulette wheel selection', 'half-uniform crossover', 'uniform mutation', and 'elitist';
Step 5: Iterate Steps 2 to 5;
Step 6: Return the "best" of all solutions of all generations, and stop.

Inner loop: flow assignment

Step 1: Initiate the network features according to the reference scenario;
Step 2: Load solution *j, j∈ [1, number of solutions of this generation]* of generation *i* of the network;
Step 3: Run the multicommodity AON flow assignment;
Step 4: Calculate the CVRMSE of the investigating indicator of this solution;
Step 5: If *j+1= the number of solutions of this generation*, then go to Step 2 of the outer loop;
Step 6: Load solution *j+1* of generation *i* to the network, and then go to Step 3.

4.4.2 Feedback-based calibration

Feedback is widely used in the control theory. When variables of a system are designed to follow a certain reference, we can bring a loop into the system to manipulate the inputs in order to obtain the desired effect on the output. Figure 4.1 illustrates the mechanism of a simple feedback system. We applied this mechanism to calibrate the model. If a link is treated as a system, the observed link flows are the "desired output". By comparing the modelled link flow and the flows from observation, we can obtain the error. By assuming that the negative relation between the link cost and the link flow is valid, we can adjust the error to some extent by adjusting the link cost, i.e., the relevant parameters.

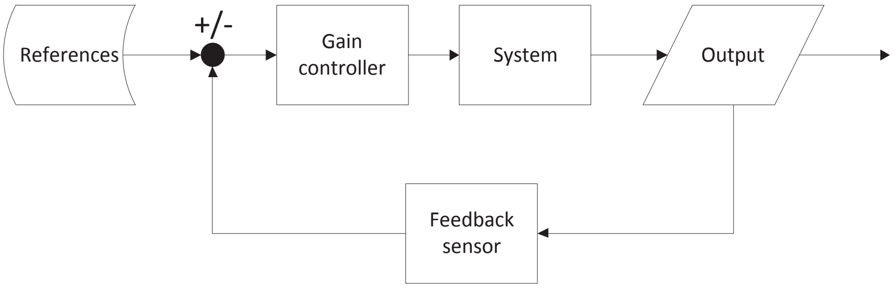


Figure 4.1. An example of a feedback loop

We chose the feedback-based approach because the impact of each element is not traceable at the global level, but is still predictable to some extent. For example, we will not know whether the CVRMSE will decrease if the access/egress cost of a certain region is increased, but we can expect that increase in the access/egress cost might result in a decrease in the modal share of road transport in the region if there are the alternative modes. The procedures of feedback-based calibration are described as follows.

Step 1: Initiate the parameters;
Step 2: Execute multimodal multicommodity AON flow assignment and obtain the modelled link flow v_{l} ;
Step 3: Calculate the CVMRSE.
Step 4: If CVERMSE <0.2, stop; otherwise go to step 5.
Step 5: Calculate the difference of the modelled result v_{l} and observation $\tilde{\mathrm{v}}_{\mathrm{l}}$, update link cost with a small gain Δ. The updated link cost is c_{l}'

$$\boldsymbol{c_l' = \left(\frac{\nu_l - \tilde{\nu}_l}{|\nu_l - \tilde{\nu}_l|}\right) \cdot \Delta + c_l \ , if\ |\nu_l - \tilde{\nu}_l| > 0.1}$$

$$\boldsymbol{c_l' = c_l \ , if\ |\nu_l - \tilde{\nu}_l| \leq 0.1}$$

Step 6: Go to step 2.

Because the model is very complicated, to calibrate the model with the feedback-based approach is very likely to arrive at a local minimum. Therefore, pre-phase experiments are needed to find an efficient way to calibrate this model. In the pre-phase, we need to design the starting points and the gain step for each variable.

4.5 Initializing the model for the Netherlands container terminal network optimization

As shown in the modularized framework of the model in the previous section, the model is supported by five databases. The architecture of the model, the methods and algorithms used in the model are generically applicable for freight transport infrastructure network design. For each specific application, we need to initialize the databases. In the next chapter, we will apply the model to the strategic planning for the Dutch container transport network. Therefore, in the remaining part of this chapter, we carry out the calibration particularly for this application. In this section, we introduce the five databases to be used in the application of the Dutch container transport network design. The function and necessity of each database was explained in Section 3.6.

4.5.1 Demand data

For the specific application of the Dutch container transport network, the database of container transport demand for the Netherlands in 2006 was used within the demand sub-model. This database was developed based on the results of the survey provided by the Central Statistics Bureau of the Netherlands CBS (2006). The survey records approximately 24,000 container shipments transported to/from/through the Netherlands.

The regional demand is modelled based on the topology published by Eurostat (Eurostat, 2006). The centroids of the regions at NUTS (the Nomenclature of Territorial Units for Statistics levels) 0, 1, 2, and 3 as defined by Eurostat et al. (2010) are defined in GIS and connected to the transport networks. Representing the ODs in this setting provides flexibility for data fusion if multiple data sources with different statistics levels have to be applied. In addition, it allows the output of aggregated results at the various levels for various regions.

According to the survey of CBS, not every region has transport demand. In order to save computing time, we aggregated the demand in some regions into the demand sub-model based on the topology published by Eurostat (Eurostat, 2006). The regions were aggregated according to two rules: (1) the demands of the regions are small enough, and thus it is not possible to exceed the capacity supplied by the existing infrastructure; and (2) aggregation of these regional demands will not affect the flow assignment within the Netherlands. Table 4.1 shows a summary of the NUTS level defined in the model for different countries.

Table 4.1. Summary of the regions identified in the model

NUTS level	Countries
None	IS, IE, UK, CY, GI, MT, AL, AD, BA
NUTS 0	EE, LV, LT, TR, GR, RO, BG, NO, SE, FI, DK, PT, LU, LI, HR, SI, RU, UA
NUTS 1	HU, AT, ES
NUTS 2	CZ, IT, CH
NUTS 3	FR, DE, Netherlands, BE

Note: For the explanation of the country codes, see the Eurostat glossary (Eurostat, 2011).

The demand database contains matrices of the demand for transport to/from/through the Netherlands by road, rail, and inland waterway, with the commodity specifications for the years 2006 and 2010 (estimations), 2020 and 2040 (projections) (De Langen et al., 2012; NEA et al., 2013).

4.5.2 GIS data

A GIS-based European multimodal freight transport network is developed in the environment of TransCAD. Figure 4.2 shows the components of the virtual multimodal network. The combined network is shown in Figure 4.3.

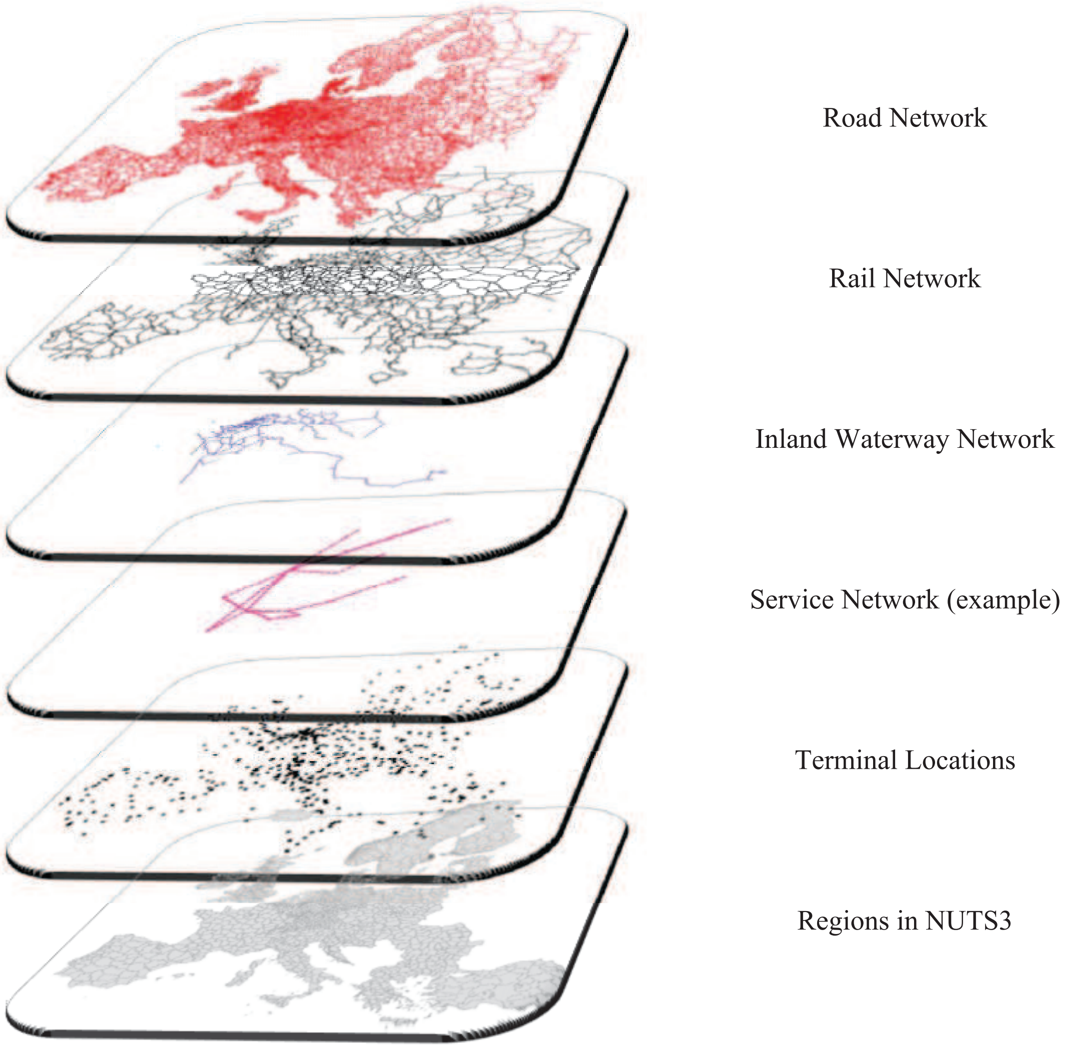


Figure 4.2. Visualization for the European road, rail, and IWW network, terminal locations and OD regions at NUTS 3 level

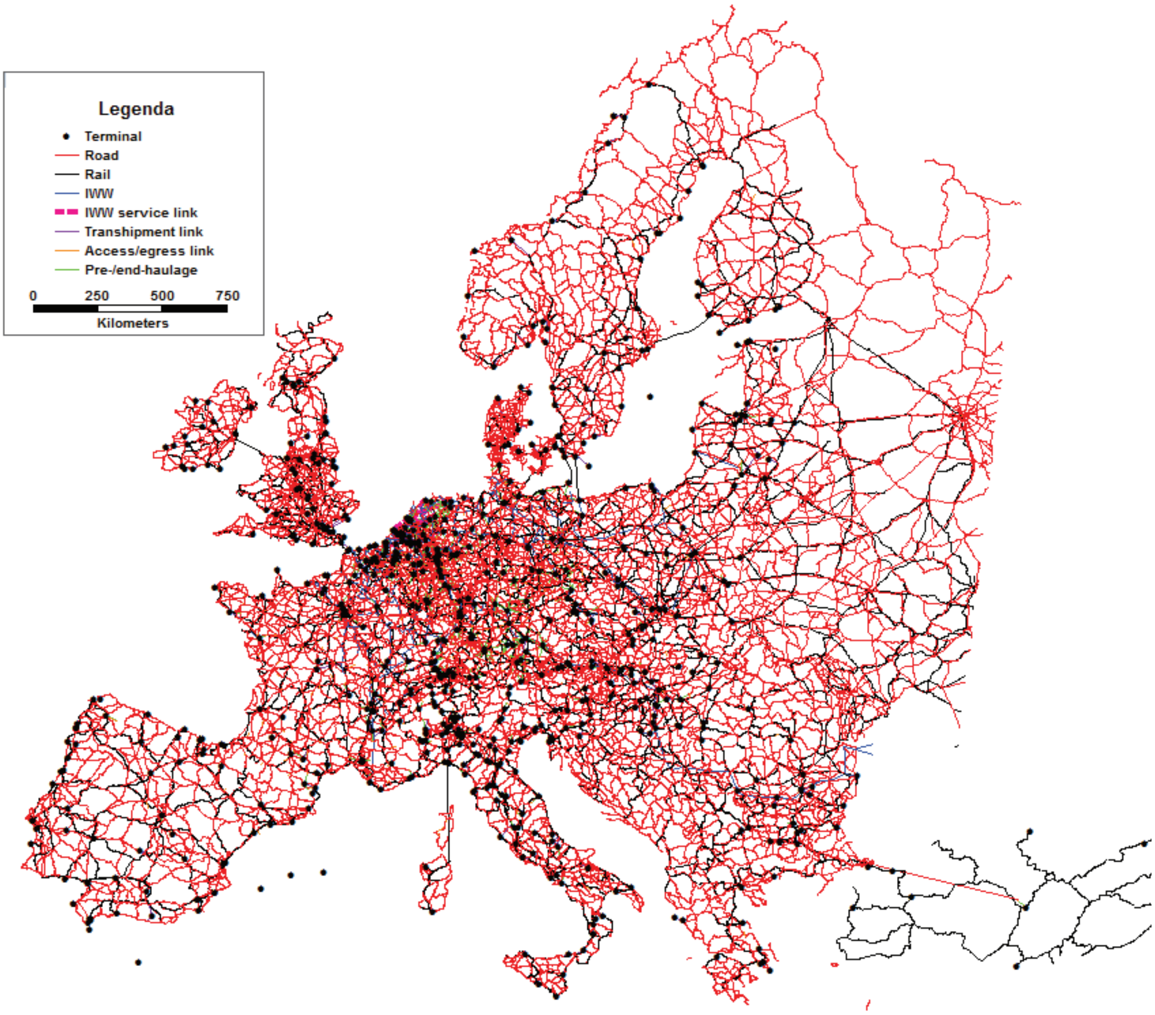


Figure 4.3. GIS-based multimodal European transport network used in the model

Notes: GIS data of road, rail, IWW network sourced from the GIS database of TransTools (EC JRC IPTS, 2005).

The entire super network is composed of 32,767 nodes (including 31,368 geographic nodes, 654 terminals, and 720 centroids) and 41,522 links (including 40,041 geographic links, 1365 transhipment links, 762 pre-/end-haulage links, 720 access/egress links, and 20 service links). The geographic data, for example, the geographic coordinates of the geographic nodes, the length and mode of the geographic links, and the topology were adapted from the GIS database of TransTools (EC JRC IPTS, 2005). The 654 intermodal terminals were also connected to the super network. The information for the Dutch terminals was obtained from Rail Cargo (a Dutch public-private initiative for rail freight transport) (Cargo, 2011) and the Expertise and Innovation Centre Inland Waterway (EICB, 2013). The information for the other European inland terminals was collected from the websites of the terminals and other sources. The geographic coordinates of the terminals was obtained by geocoding the addresses of the terminals. Table 4.2 shows a summary of the intermodal services of the terminals. It is certain that there are more terminals in the scope of the present map that provide intermodal transhipment services. In those cases where a group of terminals is clustered in a smaller geographic area, we connected the cluster to the network as a single terminal.

Table 4.2. Summary of the intermodality of the European terminals identified in the model

Modality	Number
Road-Rail	294
Road-IWT	47
Road-Sea	34
Rail-Rail (shunting yard)	16
Rail-IWT	4
Rail-Sea	7
Road-Rail-IWT	98
Road-Rail-Sea	98
Road-IWT-Sea	11
Road-Rail-IWT-Sea	45

Sources: Several non-public sources constructed during the period 2008 to 2012.

4.5.3 Features of Infrastructure network

The transport costs of road, rail, and IWW (for each barge class) were calculated based on the information from the previous research (Black et al., 2003; Decisio, 2002; NEA, 2003, 2004).

The commodity-related time costs per NSTR group (two digits) for Dutch transport were calculated by associating the commodity-related time costs to the trade value of the commodity. The relation between the two was estimated based on the previous research (De Jong et al., 2004a; Kreutzberger, 2008). In order to simplify the assignment process, the commodities are grouped in 5 groups according to the volume-to-value distribution of the containers transported to/from/through the Netherlands. The distribution was estimated from a sample derived from the international trade tables provided by Statistics Netherlands (StatLine, 2006). The sample represents the statistic data of freight exported from the Netherlands in the year 2006 (see Figure 4.4).

The handling costs of the Dutch terminals were estimated at the various scales based on regressing the actual handling prices of these terminals and their throughput. The regression relationship shows strong scale effects in the typical range of operation between 10,000 TEU/year and 500,000 TEU/year. Assuming that a similar regression applies to the other European countries, we estimated the handling costs of the non-Dutch container terminals by deploying this regression function in Figure 4.5.

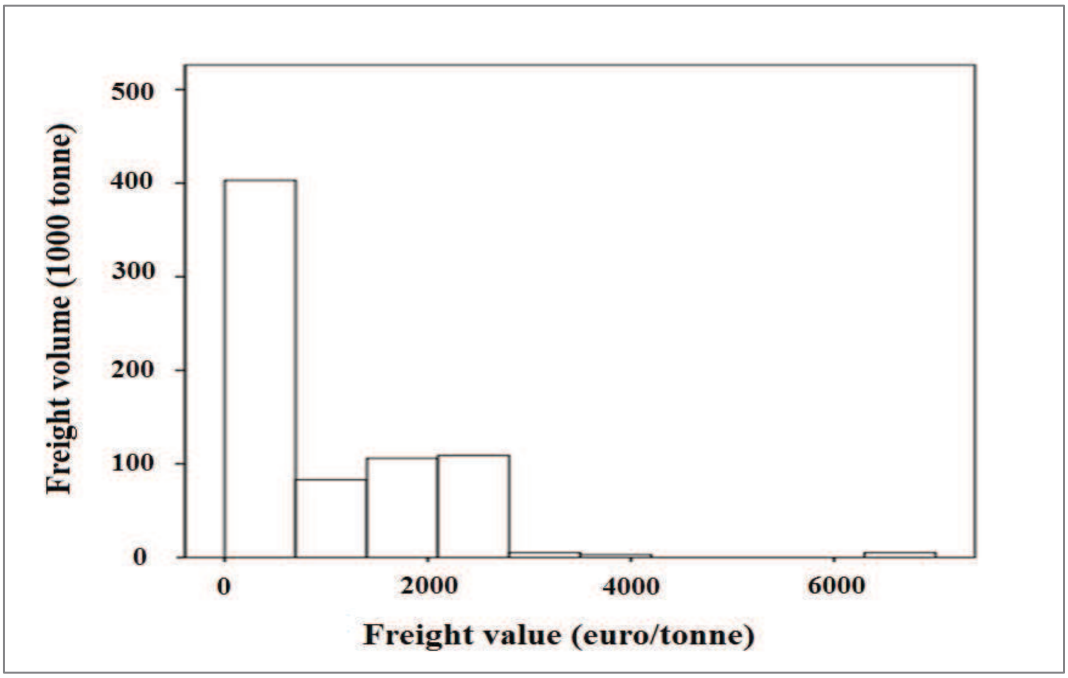


Figure 4.4. Weight to value distribution of Dutch export freight.

Note: A sample representing the statistic data of the freight exported from the Netherlands in the year 2006 calculated from the international trade tables provided by Statistics Netherlands (StatLine, 2006).

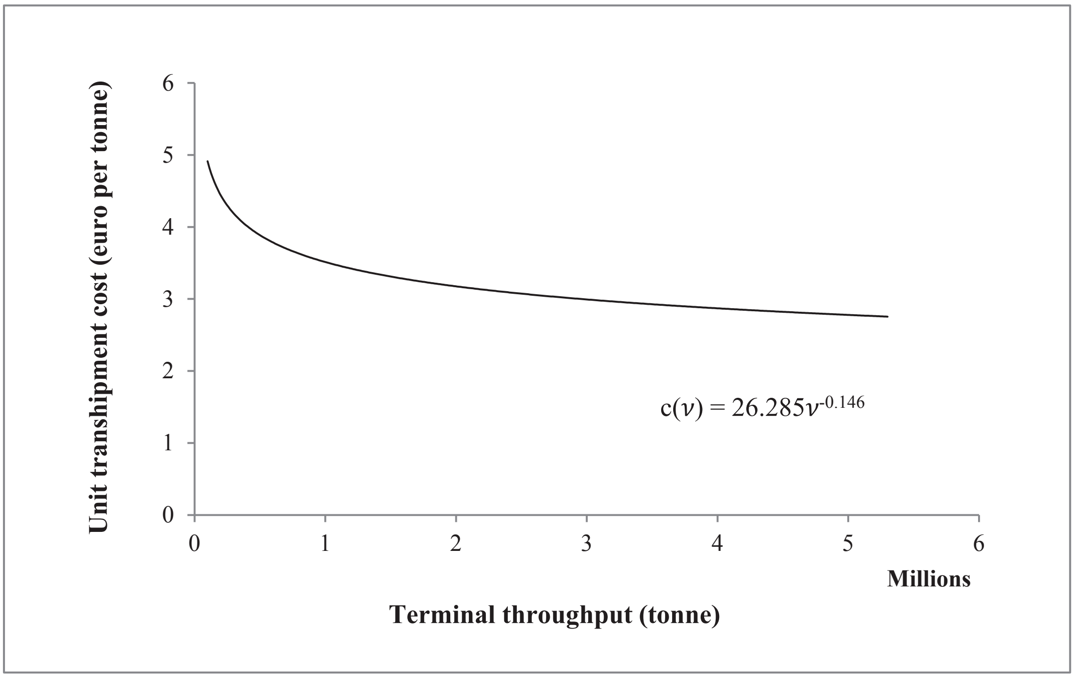


Figure 4.5. Relationship between the average unit transhipment costs and the terminal scale

Emissions of CO_2 from road, rail, inland waterway transport, and transhipment at terminals were calculated based on the reports of previous research (Geerlings and Van Duin, 2011; NEA et al., 2001). Since the emissions from the inland waterway transport depended on the water depth and the navigation speed, the emissions for different classes of barges were calculated in the waterways operating at different speeds and with different drafts based on Holtrop and Mennen's method with a correction for the shallow-water effects (Holtrop and Mennen, 1982). The costs for other externalities, for example, congestion, emissions of other pollutants, accidents, noise, and road damages were adapted from the previous research (Beuthe et al., 2002; Janic, 2007). These externalities are not included in the application presented in Chapter 5, but are available if to be included in other applications.

The capacity of road transport in the basic scenario (year 2006) is estimated on the basis of the Dutch Freeway Infrastructure Capacity Manual according to the lane numbers of the road segments (Centre for Transport and Navigation, 2011). The rail and inland waterways are assumed to have infinite annual capacity. Rail transport may meet capacity shortages in the near future, if large flows shift from road. However, since the model aims at supporting the long-term strategic planning, we assume that the new capacity would be added to the rail network in order to facilitate increase in transport demand. The capacity of Dutch terminals are provided by EICB (EICB, 2013). The capacity of the other terminals is estimated based on the navigating condition of the waterways approaching the terminals. This capacity data is not used in the application be introduced in Chapter 5, but is available for other applications in case that a capacitated network is applicable.

4.5.4 Features of service network

From the base year until now, only shuttle services have operated in the barge shipping market in the Netherlands. No practical information on the barge line service or the hub-based service is available. However, according to previous research (Horner and O'Kelly, 2001; Limbourg and Jourquin, 2009), under conditions of sufficient demand the hub-and-spoke network can achieve better operating costs and can achieve higher load factors than the shuttle barge transport services. Moreover, the hub service network may be more effective for Dutch inland waterway container transport because not all regions are accessible by large barges due to the navigation constraints and because a large amount of transport demand is concentrated in the small number of terminal service areas. Therefore, we designed several potential Dutch barge service networks, and included in the current version of the model. Therefore, based on the service network structures summarized by Woxenius (2007) and the geographic conditions of the Dutch inland waterways, we assumed 3 potential configurations of hub service networks. These hub service networks are initialized by the actual physical network features and information on daily operations.

a. Simple hub-and-spoke network service (*Figure 4.6 a)*

The containers are transported from inland terminals 1, 2, or 3, to the hub (Amsterdam) by small barges, then consolidated and transhipped to larger barges at the hub (Amsterdam), and further transported to the sea terminals.

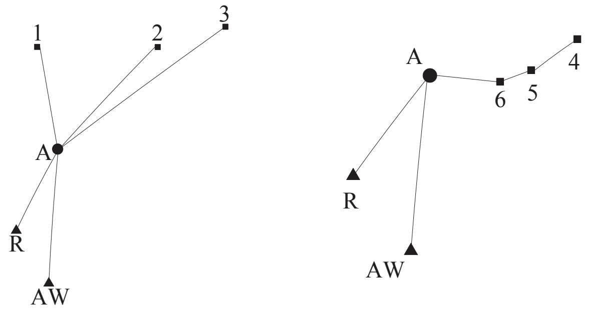
b. Hub-and-spoke network with pickup-and-delivery service (Figure 4.6 b)

The transport services are provided by small barges in the order 4->5->6 to the hub and in the order 6->5->4 from the hub (Amsterdam). Containers are loaded at each inland terminal, consolidated at the hub (Amsterdam), and further transported to the sea terminals by larger barges, and vice versa.

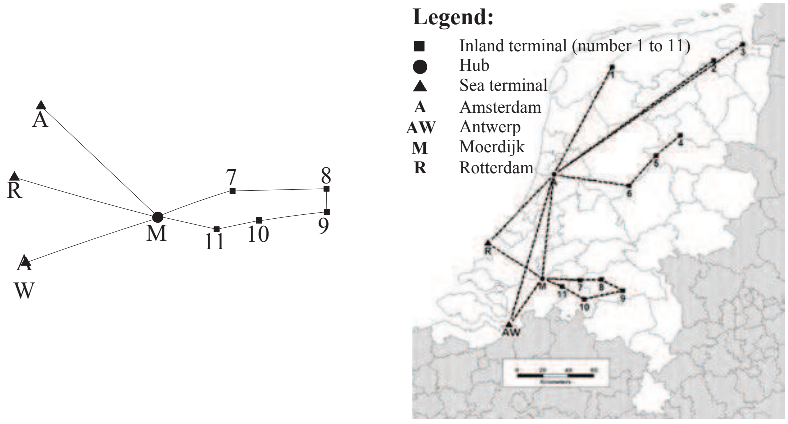
c. Hub-and-spoke network with circular-pickup-and-delivery service (Figure 4.6 c)

The transport services are provided in order of 7->8->9->10->11 both clockwise and counter-clockwise by small barges. Containers are loaded and unloaded at each terminal, consolidated to the larger barges at the hub (Moerdijk), and further transported to the sea terminals.

A diagram of the three integrated hub service networks for the container transport by IWW in the Netherlands is shown in Figure 4.6 d.



(a) Hub-and-spoke **(b) Hub-and-pickup-delivery**



(c) Hub-and-circular-pickup-delivery **(d) Joint hub service network**

Figure 4.6. Scheme of configurations of the hub-based service networks for inland waterway (IWW) container transport in the Netherlands.

The capacities and barge speeds of barges operating in each service route are assumed to be those of the largest barge allowed to navigate along such route. The handling time of each barge's round trip is estimated based on the actual situation in the base year. The information about shipping schedules of different Dutch barge service operators were obtained from the Bureau of Inland Navigation Promotion (Bureau Voorlichting Binnenvaart), based on the actual schedules in the year 2010. The navigating conditions of the inland waterways are embedded into the model according to the CEMT Classification of inland waterways (CEMT, 1992).

4.6 Calibrating the model for the Netherlands container terminal network

The flow assignment sub-model is fundamental for the network design function of this model. We calibrate this sub-model to ensure that the decisions on use of the modelled network present the practice. There are four sets of observations for calibration:

- the freight transport survey of CBS (CBS, 2006), where the volume and transport mode of the freight transported between each OD pair is recorded;
- the ship lock counts for approximately 30 ship locks located in the Netherlands in TEU;
- the border counts of the railway transport crossing the border of the Netherlands in tonne;
- the throughput of the Dutch inland terminals (for both rail terminals and barge terminals) in TEU.

These observations indicate the aggregated results of decisions of the network use made by the transport operators at different levels. The total network modal share shows the mode choices at the network level. The regional modal share shows the mode choices at the regional level. The ship lock counts and the border counts for rail, indicate to some extent the route choice at the corridor level or the link level. The terminal throughput show the terminal choice at the terminal level. When considering a network, all the regional modal shares, the ship lock counts, the border counts for rail, and the terminal throughput can be transformed to in link-level observations. The regional modal share of road or intermodal transport can be represented by the flow ratio of the access/egress link to the sum of the pre-/end-haulage links of the region. The ship lock counts and the border counts for rail can be treated as the flow observations of the corresponding geographic links where the counts are carried out. The terminal throughput can be interpreted as the flows over the corresponding transhipment links.

In the GA-based calibration, we used the minimum CVRMSE for all the resulting link-level flows and the corresponding observations as the objective for optimization. Due to the fact that no observations of the road flow were available, we assigned the demand for road transport to the road network applying the rule of the shortest path. The modelled link flows over the road network gained from this assignment were used as the observations of the route choice for the road transport in the multimodal flow assignments. The $\boldsymbol{\varepsilon}^{\mathbf{1}} \sim \boldsymbol{\varepsilon}^{\mathbf{6}}$ were defined as variables. The GA searches for the ‘best’ combination of the values of $\boldsymbol{\varepsilon^1} \sim \boldsymbol{\varepsilon^6}$ which lead to the minimum CVRMSE for all link flows.

In the feedback-based calibration, we calibrated $\boldsymbol{\varepsilon^1} \sim \boldsymbol{\varepsilon^6}$ as well. The main rules applied to the calibrations were as follows:

- if the total share of mode $\boldsymbol{m}$ is overestimated, then increase the mode-related costs of the mode ($\boldsymbol{\varepsilon^1_m} + \Delta_\mathbf{1}$), and vice versa;
- if the total share of road is overestimated, then increase the mode-related costs of road ($\boldsymbol{\varepsilon^1_{road}} + \Delta_\mathbf{1}$), increase the access/egress costs ($\boldsymbol{\varepsilon^3} + \Delta_\mathbf{3}$), decrease the mode-related costs of rail and IWW ($\boldsymbol{\varepsilon^1_{rail}} - \Delta_\mathbf{1}$, $\boldsymbol{\varepsilon^1_{iww}} - \Delta_\mathbf{1}$), decrease the pre-/end-haulage costs ($\boldsymbol{\varepsilon^4} - \Delta_\mathbf{4}$), decrease the transhipment costs ($\boldsymbol{\varepsilon^2} - \Delta_\mathbf{2}$), and vice versa;
- if the total share of rail or IWW is overestimated while the share of another mode is underestimated, then increase the transhipment costs ($\boldsymbol{\varepsilon^2} + \Delta_\mathbf{2}$) of the overestimated mode, while decreasing the transhipment costs ($\boldsymbol{\varepsilon^2} - \Delta_\mathbf{2}$) of the other mode, and vice versa.
- if the share of road transport for region $\boldsymbol{o}$ is overestimated, then increase the access/egress costs of the region ($\boldsymbol{\varepsilon^3_o} + \Delta_\mathbf{3}$), decrease the pre-/end-haulage costs ($\boldsymbol{\varepsilon^4_o} - \Delta_\mathbf{4}$), and vice versa;
- if the throughput of terminal t is overestimated, then increase the transhipment costs ($\boldsymbol{\varepsilon^2} + \Delta_\mathbf{2}$), and vice versa;
- if the flow of link l, where the ship lock count or the border count for rail is observed, is overestimated, then increase the mode-related costs of the link ($\boldsymbol{\varepsilon^1_l} + \Delta_\mathbf{1}$), and vice versa;
- if the total share of road transport is overestimated, then increase the average of the unit commodity-related time costs for all commodity types ($\varepsilon^5 + \Delta_\mathbf{5}$), or adjust the proportion of different types of commodities in the total volume for all commodities via $\varepsilon(^6_p \pm \Delta_\mathbf{6}$), and vice versa.

We are aware that the combined effects of applying two or more of the above-mentioned rules might result in counteracting adjustments of the certain parameters. Therefore the calibration procedures needed to be designed according to the combination of the overestimated/underestimated terms. Defining the appropriate value for each Δ and the searching range for each ε in combination can reduce the probability of counteracting to a great extent. The values of Δ and the ranges for ε need to be found in prior by extra experiments. Table 4.3 summarizes the range of freight transport-related costs reported in the previous research.

Table 4.3. The freight transport-related costs reported in the previous research

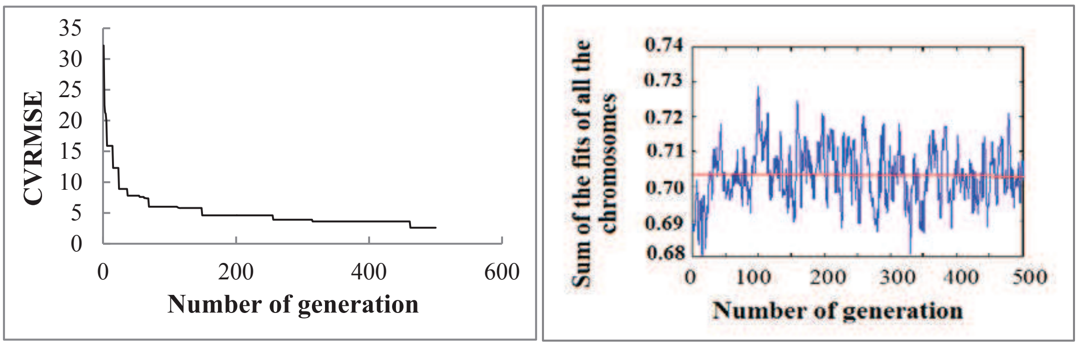
	Min (euro)	Max (euro)
Mode-related costs of main haulage(/tkm):		
Road	0.054	0.186
Rail	0.015	0.05
IWW	0.004	0.01
Transhipment cost (euro/ton-movement)	0.5	3.5
Access/egress costs	0.054	0.2
Pre/End haulage (/tkm)	0.057	0.2
Average of commodity-related time cost (euro/tkm)	0.025	0.045

Note: 1 container (road)=1.7TEU; 1 TEU=6.658 tonne (estimated based on CBS and POR statistics (CBS, 2006; POR, 2007, 2008a, b))

Sources: (Black et al., 2003; CBS, 2006; De Jong et al., 2004a; Decisio, 2002; NEA, 2003, 2004; NEA et al., 2001; NEA et al., 2013).

4.6.1 Results of GA calibration

Figure 4.7 (a) shows the converging process of the CVRMSE of link flows during the GA-base calibration. When this is compared with the 'null model' where all parameters are set at zero, the CVRMSE is reduced by 92% after 500 generations. The quality of the flow assignment model is highly improved. Figure 4.7 (b) illustrates that the total fits of all the chromosomes of each generation deviate in a large range in the first 500 generations. This means that the searching spaces (the range of possible solutions) of each generation of GA do not stay the same, thus the likelihood of arriving at a local minimum or jumping between two local minimums within the first 500 generations is low.



(a) (b)

Figure 4.7. (a). The convergence of the CVRMSE of the link flows in GA-based calibration; (b). Variation of the searching spaces of each generation in GA

The goodness-of-fit between the modelled results and the observations in terms of link flows, throughput of terminals, and regional modal shares are shown in Figure 4.8, Figure 4.9, and

Figure 4.10. Figure 4.8 shows a rather high value of R^2, which means that the global fit of the link flows is good. However, the figure also shows that overestimation and underestimation exist in the range of 0~2.5 million tons in terms of link flows. One reason for this mis-estimation is the imbalanced flows between an OD pair in the two directions. The imbalanced flows take approximately 7% of the total flow (measured in tonnes) in the OD data of the base year. It is not possible to remove the mis-estimation, because the current version of the model does not specify the link directions.

The result of the fit of regional demand for road transport in Figure 4.9 is even better with an R^2 of 0.9. The mis-estimations centre in the range of 0.2~0.6 million tons in terms of link flow. The plots in the figure show both under-estimation and over-estimation of links with the small flow. These indications, in combination, suggest that some route choices between some OD pairs associated with small transport demand were not captured correctly. In practice, the transport services handling the smaller amount of demand and those handling the larger amount of demand are indeed different, especially in terms of the transport mode and price. One solution for this mis-estimation could be differentiating supply of transport service for small and large demand, as well as performing separate flow assignments for each of them.

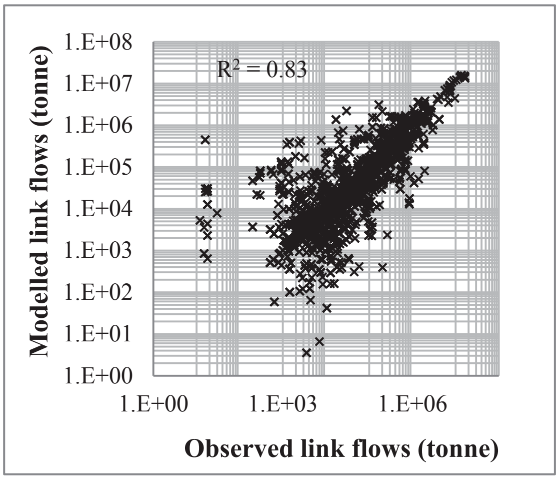


Figure 4.8. GA calibration result at link level

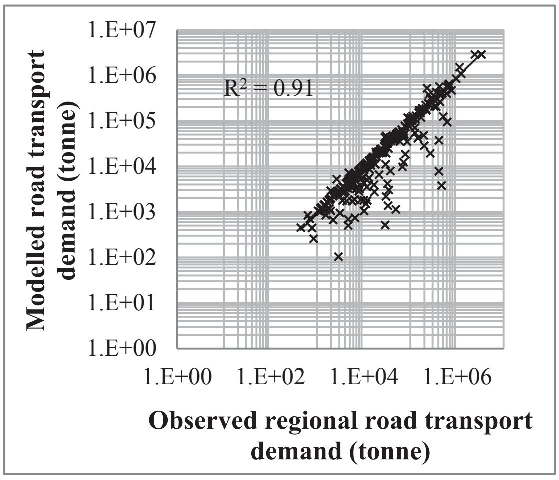


Figure 4.9. GA calibration result at regional level

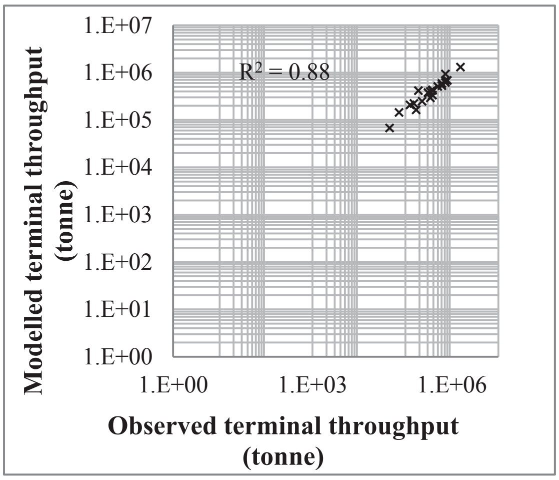


Figure 4.10. GA calibration result at terminal level

4.6.2 Results of feedback-based calibration

Similarly as the GA-based calibration, the feedback-based calibration starts from the 'null model'. After 2000 iterations, the CVRMSE of link flows reduces by 88% as compared to the 'null model' (Figure 4.11 a). Figure 4.11 (b) shows the reduction in the deviations of the modelled modal shares when compared to the observed modal shares. The deviations reduced to less than 5% of the absolute transport volume. Figure 4.12, Figure 4.13, and Figure 4.14 illustrate the comparisons between the modelled results and the observations in terms of the flows over ship locks or the links of cross border rail, the regional shares of road, and the throughput of the Dutch barge terminals. These results as taken together indicate that the quality of this feedback-based calibration is acceptable.

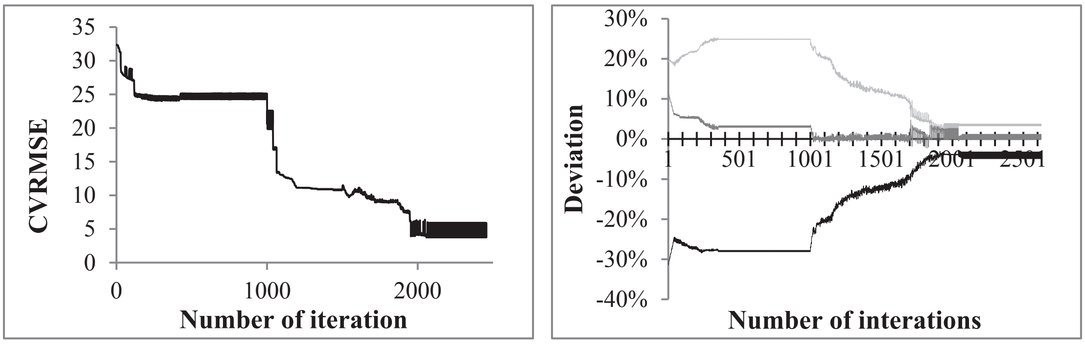


Figure 4.11. (a) The convergence of the CVRMSE of the link flows in feedback-based calibration; (b) Relationship between the number of iterations and the modal share deviations during calibrating process

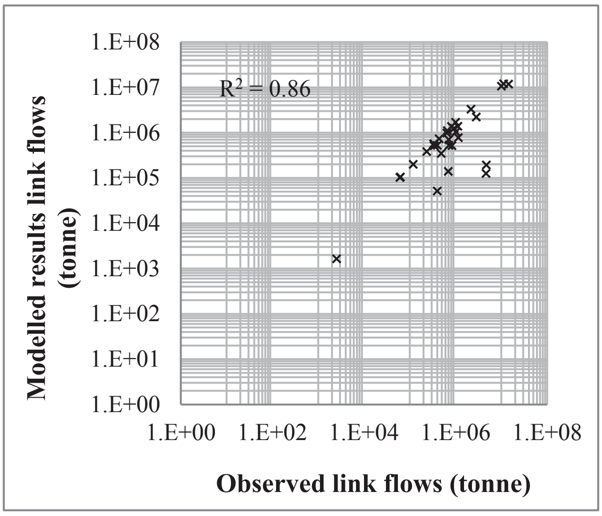


Figure 4.12. Feedback-based calibration result at link level

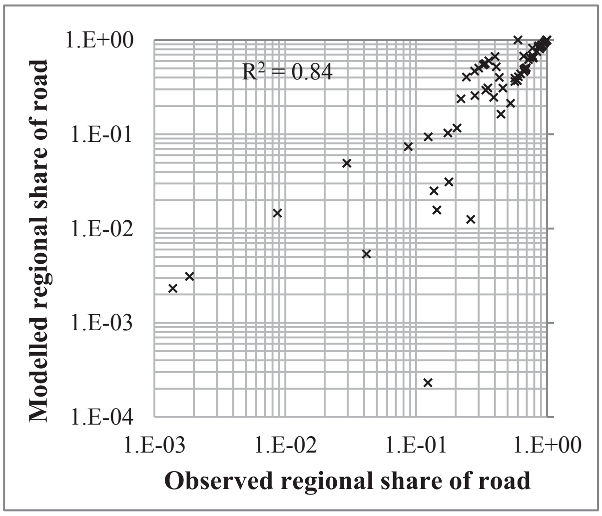


Figure 4.13. Feedback-based calibration result at regional level

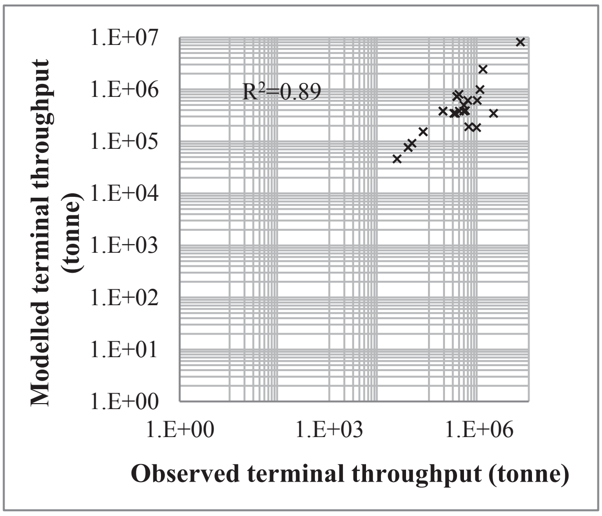


Figure 4.14. Feedback-based calibration result at terminal level

4.6.3 Performances of the two calibration methods

We have run the optimization 5 times, 500 generations with a population of 100 in each run. The average computing time was 153 hours (of which generating log files took 40% of the time) when using a PC with 6 cores (3.47GHz each) and 12.0 GB RAM. The average processor capacity occupation was approximately 20%. The CVRMSE was reduced by 92% when compared to the 'null model' in the best situation of the five runs. The population of a generation, the probability of crossover, and the probability of mutation have strong influence on the performance of GA in terms of efficiency and convergence. The experiential values of the GA parameters have been discussed in general (Goldberg, 1989a; Michalewicz, 1996). There is no unique "best" combination of these GA parameters. It depends on the nature of the optimization problem, and the evolving strategies applied. The strategies that we chose for the calibration were as same as the ones used in the bi-level network optimization (see Subsection 3.4.3). The experience gained from this case is that for the optimization problem with such a large number of variables, a crossover probability between 80% and 90%, and a mutation probability between 1% and 3% lead to more efficient converging process as compared to higher probabilities.

The feedback-based calibration was also carried out 5 times, with the same computing environment, 3000 iterations in each run. Starting from the same setup as with the GA calibration, the CVRMSE converged after 2000 runs in the worst situation of the five runs. It took 10 hours (including the time for generating log files) for the 2000 iterations on average. The CVRMSE was reduced by 89% in the best situation when compared to the 'null model'. The computing efficiency is highly dependent on the setup of the feedback value of each parameter. Preliminary experiments are required in order to find the reasonable feedback values.

The computation time and optimization efficiency of these two types of calibration were evaluated separately. These results could not be are not able to be compared. These two types of calibration were carried out in different phases, and the ship lock counts and the rail border counts were not available when we calibrated the model with the GA-based method.

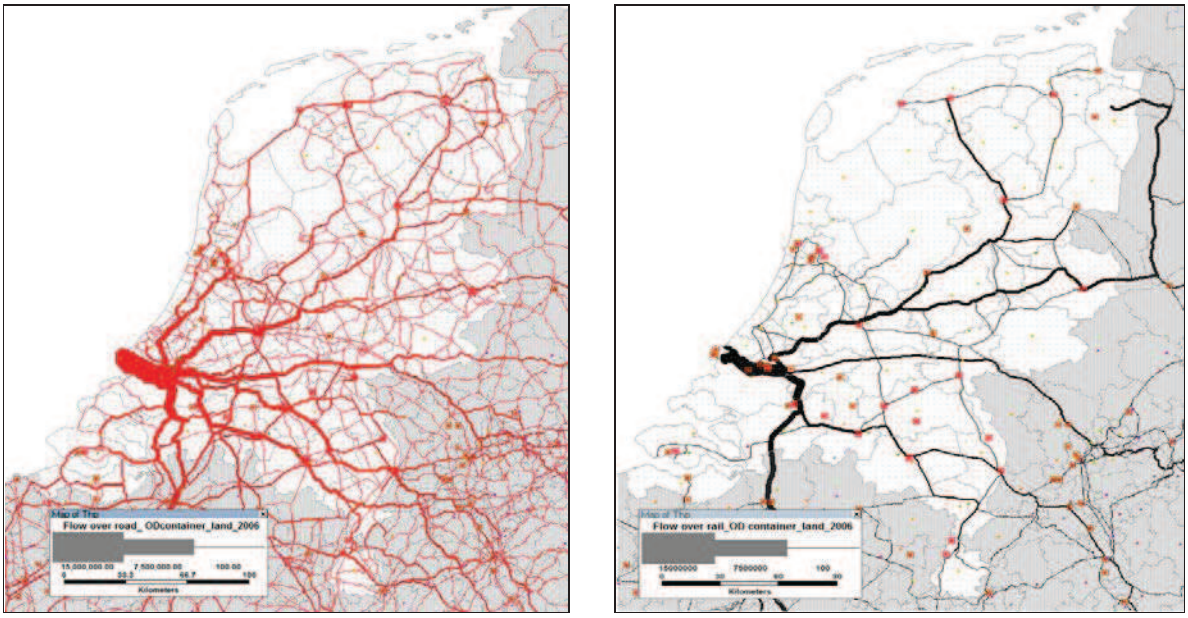
The quality of the model results from both the GA-based calibration and the feedback-based calibration was sufficient to simulate the flow assignment for Dutch container transport. In the next section, we discuss the validation of the model calibrated by applying the feedback-based calibration.

4.7 Validating the model for the Netherlands container terminal network design

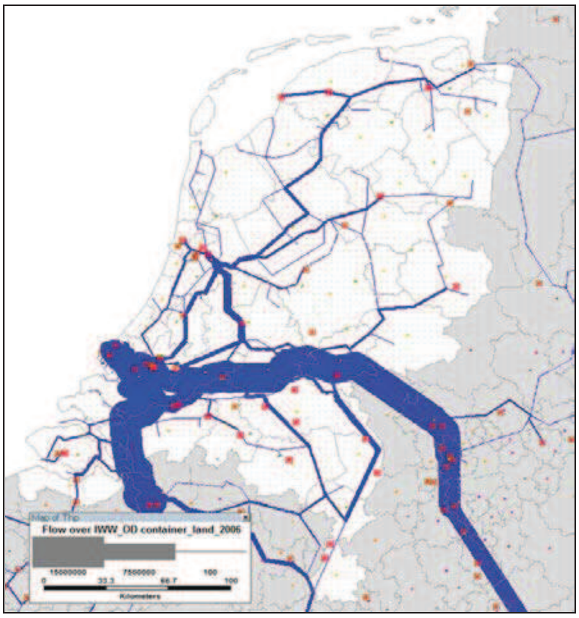
The previous subsection mainly compared two calibration methods. In this section, we validate the model from additional aspects. First, we show the flow map estimated by the calibrated model for the base scenario of year 2006, and qualitatively compared it with the real situation. Second, we test the stability of the calibration to ensure that the values of the parameters are stable if we calibrate the model several times. Third, we test the cross elasticities of mode-related costs to the total network flow of each mode, in order to obtain insight into the sensitivity of the model to the cost changes and estimate the reliability of the model if it would be used in the costs-related scenario analysis or predictions. Last, we compare the catchment area of the terminals with the observed data to estimate the reliability of the terminal choices made by the model.

4.7.1 Flow map in the base scenario

Figure 4.15 shows the modelled flow assignment for the base year 2006 over the road (a), the railway (b), and the inland waterway network (c), respectively. As expected, most of the container flows originate or end at Rotterdam, and mainly are transported to/from Germany and Belgium. The Rhine River has the most barge flows to/from Germany and Switzerland. The Rotterdam-Antwerp Cannel has the most barge flows to/from Belgium. Most of the rail transport is carried out via Rotterdam-Antwerp Rail to the south, or via Utrecht towards the northeast. There are not as many flows as expected on the Betuwe Line since it recently started operation (in 2007). Approximately 500 trains per week (including bulk) operated on the Betuwe Line in 2011 (POR, 2011). Calibration based on the border counts of rail for the year 2006 led to assignment of little flow on the Betuwe Line.



(a) Road **(b) Rail**



(c) IWW

Figure 4.15. Modelled flow assignment of the Dutch container transport over road (a.), rail (b.), and inland waterways (c.) in the base year 2006

4.7.2 Stability analysis of the feedback-based calibration

To calibrate the model, due to the data availability, we fit the modelled results with the link flows, terminal throughput, and regional modal shares. All of them are aggregated results of the flows between OD pairs. Therefore, more than one set of parameter values would give an adequate fit. The different sets of value may lead to different route choices for the flows between an OD pair. In order to estimate this uncertainty in the parameter estimation. We tested the stability of the parameter values in different runs of calibration. Figure 4.16, Figure 4.17, and Figure 4.18 illustrate three runs of calibration, the distribution of the calibrated regional access/egress costs, the calibrated unit transhipment costs, and the calibrated pre-/end-haulage costs, respectively. The similar distributions of the parameter values, in terms of mean and standard deviation, shown in the figures indicate that the composition of the parameters values remains stable in the three calibration runs. In addition, the distributions of the variances of the three groups of parameters in the three calibration runs were evaluated. The results in Figure 4.19 show that most of the parameter values have very small variance among the three runs. This indicates that most individual parameters are stable in the acceptable ranges among the multiple runs of calibration.

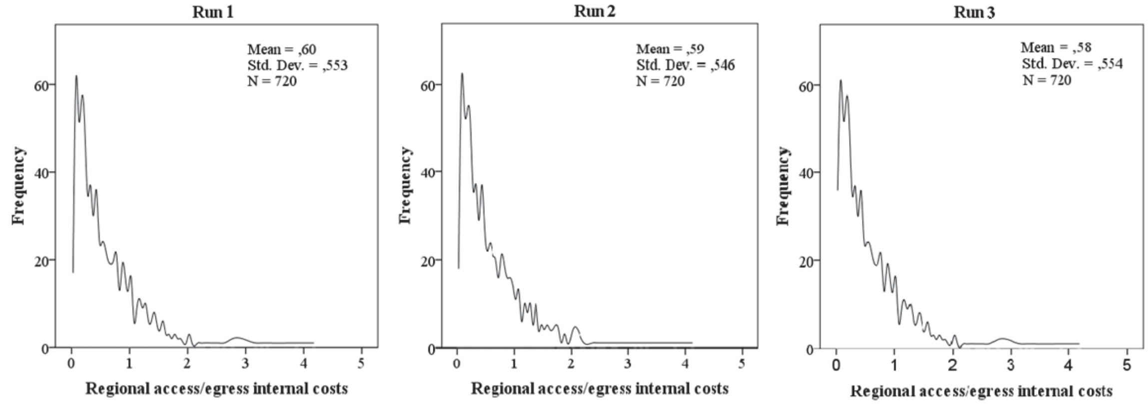


Figure 4.16. Distribution of the calibrated regional access/egress costs

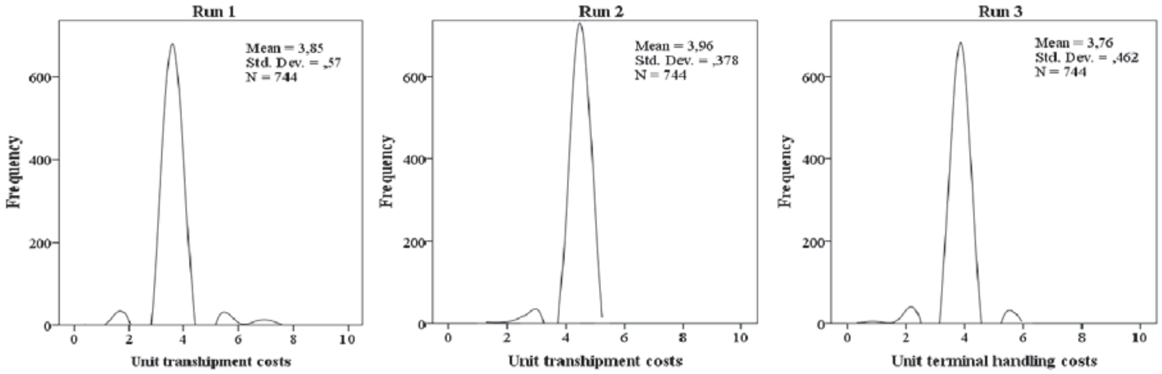


Figure 4.17. Distribution of the calibrated unit transhipment costs

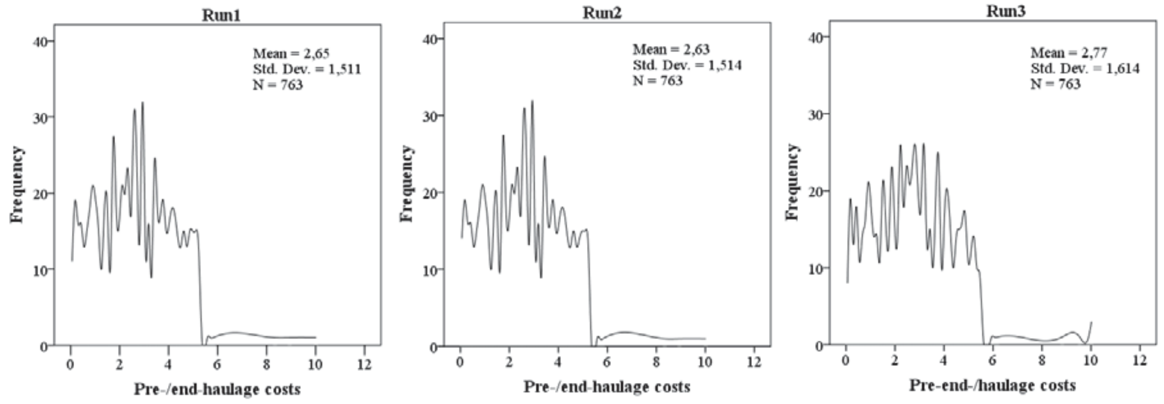


Figure 4.18. The distribution of the calibrated pre-/end-haulage costs

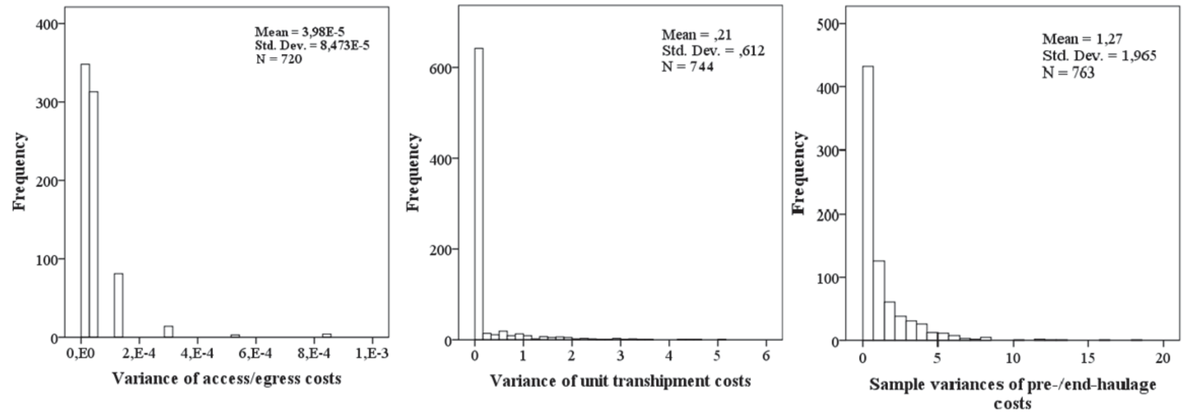


Figure 4.19. Distribution of the variances of the calibrated parameters in multiple calibrating processes

4.7.3 Sensitivity analysis mode-related costs

The sensitivity of the flow assignment sub-model to mode-related costs is tested by the cross elasticities of the mode-related costs to the total network flow of each mode. The mode-related costs of road or rail are increased by 1%, 5%, or 10% when compared separately to the base reference scenario. The elasticity is calculated as the ratio of change in the mode-related costs to change in the total flow measured in tonnes. The changes are expressed in natural logs in order to obtain a constant elasticity model. The following Equation (4-5) represents the cross elasticity of the mode-related costs of mode M_1 to the total network flow of mode M_2 .

$$\boldsymbol{E_{M_1,M_2} = \frac{\Delta ln(q^{M_1})}{\Delta ln(c^{M_2})}, M = \{road, rail, IWW\}} \qquad \textbf{(4-5)}$$

The results are shown in Table 4.4.

Table 4.4. Cross elasticity of mode-related costs to total network flow of each mode (measured in tonnes)

Cost increase		**Cost elasticity of transport demand**		
		Road	Rail	IWW
1%	Road	-2.11	5.47	2.25
	Rail	0.44	-2.17	0.75
	IWW	-0.16	1.49	-1.45
5%	Road	-0.78	2.94	0.38
	Rail	0.25	-1.00	0.27
	IWW	0.01	0.88	-1.19
10%	Road	-0.81	2.22	0.70
	Rail	0.13	-0.94	0.40
	IWW	-0.01	0.76	-0.93

The elasticities with respect to road costs at the level of 1% are larger than the others. This indicates that the model is relatively less stable for a small costs change of 1% comparing with a larger change. At the level of 5% or 10% of costs change, the elasticities are in a range of -0.01 to 2.94. The cross elasticity of the transport demand with respect to the road costs is highest for rail transport due to that the rail transport takes a much smaller share (8.9%) in the total transport demand as compared to road or IWW transport. Therefore, a flow shift taking small proportion in the road transport demand may take a large proportion in rail transport. In addition, the cross elasticity of road with respect to IWW costs at the level of 1% and 10% are negative. This means that the increase in the costs of IWW transport will reduce the demand for road transport. One reason could be that the reduced demand for the IWW transport was taken over by the rail transport. The increased demand for rail transport led to economies of scale, and thus resulted in lower handling costs. Consequently, some transport demand for road transport were taken by rail as well.

As compared to an earlier elasticity analysis of the multimodal transport in Europe (Beuthe et al., 2001), the elasticities of the model are of the same order of magnitude (Table 4.5). The largest difference is found in the cost elasticity of rail transport demand when the road costs change by 5%. The increase in road costs results in a much larger influence on the demand for rail transport in this model than the Beuthe's model. The main reason seems to be that the two analyses are based on different geographic regions. Rail transport takes different shares in the two regions. The share of rail (measured in tkm) in the freight transported to/from/through the Netherlands is 8.9% (measured in tkm) in the base year (2006) of the model, while the rail share of Europe is 21.5% (measured in tkm) in the base year of 1995 in Beuthe's analysis. In addition, IWW cost reduction shows less influence on the demand for road transport in the present case. This seems to be due to the geographic conditions as well. A large portion of flows transported by IWW in the Netherlands are transported on a distance less than 300 km. The IWW is not very competitive when compared to the road transport for short distances.

Table 4.5. Aggregate elasticities for 5% total cost reduction (flow measured in tonnes) (Beuthe et al., 2001)

Cost reduction		**Cost elasticity of transport demand**		
		Road	Rail	IWW
5%	Road	-0.59	2.19	3.59
	Rail	0.09	-1.77	0.47
	IWW	0.11	1.75	-2.13

4.7.4 Catchment area of the terminals

Estimating the terminal choices is a new feature added to the flow assignment in this model. It captures the behaviour that transport demand generated in one region can be assigned to the intermodal transport, but via terminals located in other regions. To the best knowledge, there is no data available describing the terminal choices in the container transport. Therefore, the pre-/end-haulage distance and the catchment area of terminals to approximate the results of terminal choice are used.

Figure 4.20 shows distribution of the freight volumes over different pre-/end-haulage distances. The reference data was the aggraded result of the Transportation Survey of the Netherlands 2011 (CBS, 2011). Since the pattern of the Dutch container transport market did not change significantly, we assume that the survey for the year 2011 is assumed to represent the situation for the year 2006. The modelled results show that more than half of the pre-/end-haulage (in terms of tonne) are shorter than 20 km. Less than 10% of them are between 20 km to 40 km. To some extent this indicates that the modelled results reflect the actual situation.

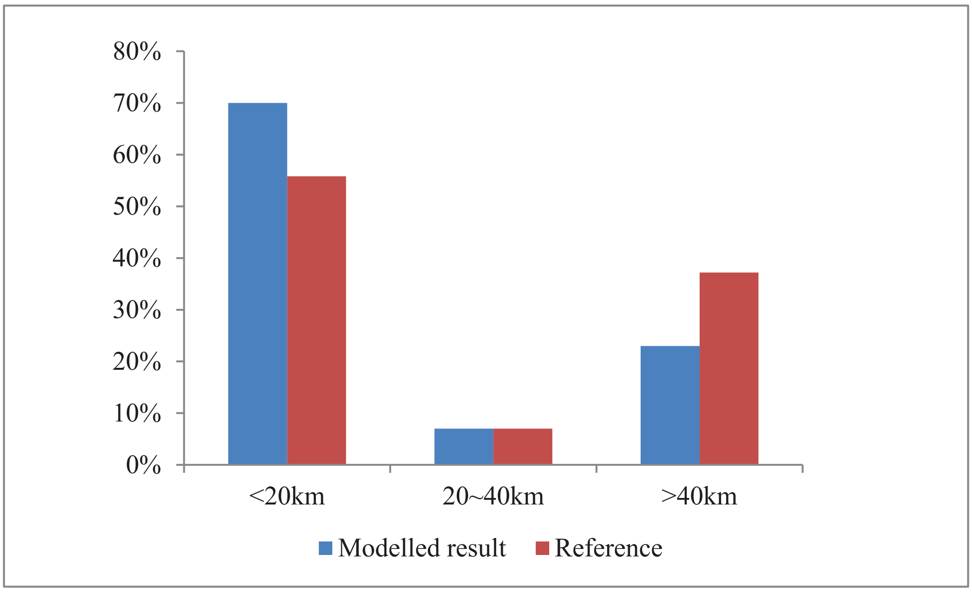


Figure 4.20. Pre-/end-haulage: comparing the modelled and reference results for the Dutch terminals' catchment distances

Figure 4.21 illustrates the modelled catchment areas of the Dutch IWW terminals. The catchment area of each Dutch IWW terminal is coloured in light pink. The overlapped shades show the overlapping catchment areas of multiple terminals. The darker shades indicate that the regions served by more terminals. The intensiveness of competition in each area given the number of terminals operating actively in the regional market can be expected. This map presents an adequate picture of IWW transport in the Netherlands in 2006. The competition was intense in West-Brabant to the Rotterdam area and the Amsterdam area, while there was not as much competition near Zeeland or Venlo despite the very large flows over these two areas.

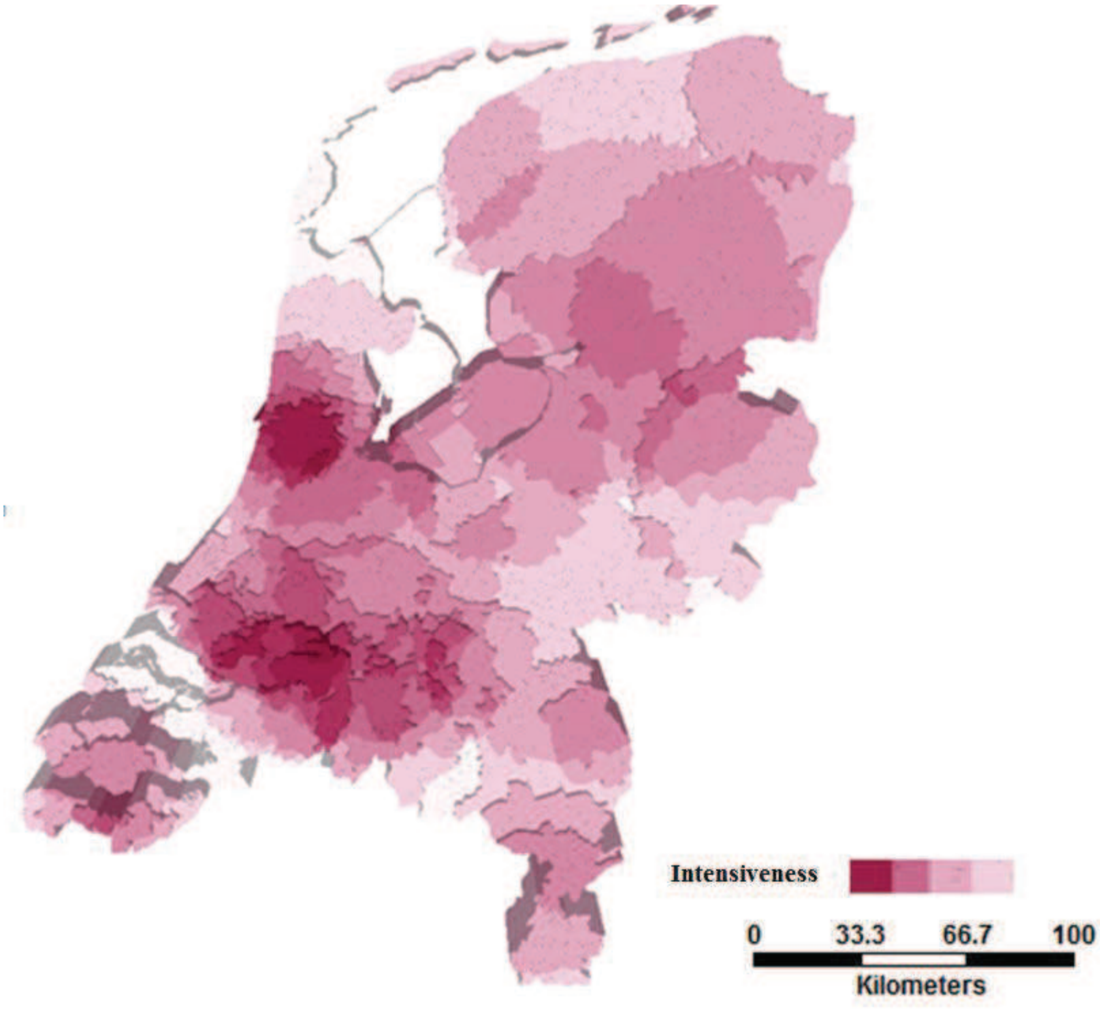


Figure 4.21. Estimated catchment areas of the Dutch IWW terminals in 2006

4.8 Summary and discussion

In the previous chapter, the formulation, architecture, and the functions of the newly developed model were explained. In the current chapter, the methods and the procedures used to calibrate and validate the model have been elaborated.

It has shown difficult to calibrate a large-scale multimodal multicommodity flow assignment model due to the large number of variables, the fact that each variable consists of many elements, and having high requirements for reference data availability.

The calibration of this model have been formulated as a parameter estimation problem. Among a larger number of parameterizable variables that influence the modelled results, the alternative specific constants of terminal handling costs, the average regional pre-/end-haulage costs, the average regional access/egress costs, the average mode-related transport costs of geographic links, and the average commodity-related time costs, have been chosen as the calibrating parameters.

Two calibration methods have been examined: the GA-based method and the feedback-based method. The GA-based method has advantages in searching for satisfactory solutions when each solution is composed of a large number of variables, and each variable has a specified range. Furthermore, GA has fewer restrictions on searching paths. The feedback-based approach often produced good results in these cases where the influence of each element is to some extent predictable. The calibration results for the case of Dutch container transport has shown that both methods can achieve satisfactory results. The feedback-based method has shown much better efficiency in terms of the computation time. However, this computing efficiency is highly dependent on the setup of the feedback value of each parameter. Preliminary experiments are required in order to find the reasonable feedback values.

The model has been validated by comparing a part of the modelled link flows with the observations, testing the cross elasticities of the costs to demand, and comparing the catchment area of the Dutch terminals with the data obtained in practice. The results of calibration indicate that the model has captured well the aggregated results of decisions of the network use.

However, the results have also shown some mis-estimations. One of the main reasons seemed to be ignorance of the link directions since transport demand are imbalanced in two directions. The errors can be removed by carrying out the network specification with double directions. But as a consequence, the topology and the orientation of the network can become a new challenge for the network specification. In addition, the quality of calibration can be improved. Due to the data availability, only calibration and validation of the model by using the reference data from the same year of the demand data have been possible. It would be very helpful to improve the reliability of the model further by validating the model with panel data. Without the panel data based validation, the predictions of future scenarios will depend upon the assumption that transport operators will behave similarly even under conditions of changing the infrastructure supply and/or the transport demand.

Chapter 5

Freight Transport Infrastructure Network Design: An application to the Dutch Container Transport Network

5.1 Introduction

The goal of this thesis is to design a model for the strategic planning of an infrastructure network in a large-scale network. New requirements for a FTIND model were identified in Chapter 2, and a new integrated model was developed. This model incorporates the new requirements of multimodality, multicommodity, and multiactor in the large-scale freight transport network.

The new model is implemented for the strategic planning of the Dutch container transport network, which is described in Section 5.2. The objective of the design is defined in Section 5.3. The calibration and validation of the model for Dutch container transport was carried out in Chapter 4. In this chapter, the CO_2 pricing scheme, IWW terminal network configurations, and the potential hub-service-networks as the design measures are used to optimize the Dutch container transport infrastructure network. The reasons for choosing these measures are explained in Section 5.4, followed by the introduction of the application setup in Section 5.5. In Section 5.6, the impact of each of the instruments and their combinations on Dutch container transport, regarding reduction of CO_2 emissions, and total network costs are analysed. An overall discussion of this application and concluding remarks are provided in Section 5.7.

5.2 Problem statement

Currently, port development in the Netherlands relies increasingly on rail and waterway systems for hinterland access. In this context, intermodal transhipment is required for the regions that are not directly accessible by rail and waterways. The interaction between different modes takes place at intermodal terminals where the transhipment of the containerized freight is conducted.

In addition to problems of accessibility, increasing demands for transport can also cause environmental problems. The most discussed topic that has attracted the most public attention is transport emissions. Intermodal freight transport may contribute to reducing road congestion and also directly diminishing the emissions of Green House Gases (GHG). Developing an intermodal freight transport network is an important strategy of the European Commission to achieve a sustainable transport system (see Section 1.1).

Container transport in the Netherlands is characterized by intensive transport between the port of Rotterdam and its hinterland. For example, around 4.0 million containers in terms of TEUs (Twenty Foot Equivalent Unit(s)) were transported in the Netherlands, of which 87% were to/from the port in 2010. The modal split of container transport to, from, and transiting the Netherlands was 47% by road, 15% by rail, and 38% by inland waterways (NEA et al., 2013).

The network of multimodal hinterland terminals in the Netherlands is very dense. In 2010, around 30 inland barge terminals provided handling services for containers. About half of the terminals had an annual throughput greater than 50,000 TEUs. Most of the inland terminal operators also play a role as transport operators. They also provide transport services by their own or chartered fleets. At present, almost all services provided by these operators are shuttle barge transport services between one inland terminal and multiple sea terminals in the port of Rotterdam, Amsterdam, or Antwerp. Most of their customers are located close to these terminals causing more than half of the shipments to have a pre-/end- haulage distance of less than 30 km (CBS, 2011).

The accessibility to the inland waterway network varies across the regions. More than half of the land area of the Netherlands is accessible to barge terminals within a distance of 20 km. 20% of this area is served via barge terminals accessible by class IV barges (capacity of 90 -120 TEUs). The other part is served by the terminals accessible by class II and class III barges (capacity of 24 - 32 TEUs). This indicates that there may be potential benefits from economies of barge size by setting up hub services with larger barges moving between the hubs.

Currently, intermodal container transport in the Netherlands has difficulties in competing with road transport. The main reasons are the extra handling costs at the inland terminals, and the less flexible schedules of the intermodal services. In addition, the rather weak demand in the service area of particular terminals prevents them from benefiting from scale economies. If the new services could attract enough flows to intermodal transport, both the terminals and the transport services providers would benefit from the economies of scale and the consolidation effects. This may result in a reduction in unit door-to-door transport costs which could increase competitiveness with road transport. Consequently, inland waterway transport might attract even more flows from other modes, and thus achieve a higher utilization of the infrastructure and services. This means that the inland waterway transport would be able to charge lower transport costs to the shippers compared with road transport. Based on the growth of maritime container transport, the total demand for container transport is estimated to increase by 150% by 2020 compared with 2010 (De Langen et al., 2012). In addition, the port of Rotterdam Authority aims to boost the share of inland shipping to 45% for the freight handled at the new terminals at Maasvlakte II (POR, 2009). Such growth in combination with public support for the development of sustainable transport provides a good opportunity for reshaping the intermodal terminal network and developing the new hub service network.

Much effort has been put into developing intermodal container transport. In order to promote intermodal container transport, the Dutch government has subsidized public intermodal terminals by providing investment for starting up new terminals or for expanding the existing terminals (Ministry of Infrastructure and the Environment, 2002). It was clear that these subsidies were provided for the purpose of helping terminals to achieve sufficient capacity to operate without additional investment for a five year period, but not to compete with other terminals by providing a lower handling price. This subsidized program was implemented from 2002 to 2012.

Terminal operators have been looking for alternative ways of accessing the sea terminals around the main container terminals in the port of Rotterdam. The sea terminal operators are developing inland barge service networks in order to extend gate services and enhance their competitiveness in the hinterland distribution (Notteboom, 2007). To meet the anticipated increase in demand for transporting maritime containers (De Langen et al., 2012) via inland waterways (due to the capacity expansion of sea container terminals), some Dutch barge terminal operators have planned to expand their handling capacity in order to benefit from scale economies.

The hinterland transport operators have initiated plans to cooperate within new service networks. These include hub-and-spoke service and circular pickup-and-delivery service, in addition to the current shuttle barge transport services. The aim is to increase competitiveness in the market by increasing service frequency and load factor (Brabant Intermodal, 2012; Visser et al., 2012).

All of these measures may contribute to solving the dilemma between the accommodation of an increased freight flow and the demand for a sustainable living environment. What is needed is to know which measures, can lead to better network performance in terms of total network costs, environmental impact, and network utilization, especially for Dutch container transport.

5.3 Objective of the application

In this chapter, we will use the calibrated model to evaluate the potential policies, and search for the optimal integrated solutions leading to optimizing performances of the container transport network. The "network performance" is evaluated in three aspects.

- The total network costs, consisting of internal costs and external costs. The former is the generalized costs borne by the transport operators and the shippers. The latter is particularly the CO_2 emission charges incurred due to CO_2 pricing.
- The network use, which is indicated by the modal shift from road to rail/IWW transport, and is presented by the proportion of the shifted flow in the total flow measured in tonnes or tonne-kms.
- The impact on the environment which is quantified by the total network CO_2 emissions.

Studies have been done with costs minimization as the optimization objective. Some of them also have included the environmental aspects. Li et al. (2008) have optimized distribution centre locations taking into consideration transport costs and transport/production carbon emissions. Hoen et al. (2012) have studied mode choices under several types of emission caps. Bauer et al. (2010) have identified and addressed environmental considerations in the context of intermodal freight transport and introduced the costs of greenhouse gas emissions into a scheduled service network design problem. Dekker et al. (2012) has reviewed the present and possible developments in operations research from the perspective of integrating the environmental considerations into logistics with focuses on design, planning and control in a supply chain for transport. He has argued that hub-and-spoke transport and combining transports from different suppliers are concepts related to the reduction of emissions, but papers incorporating both have been lacking.

We choose CO_2 pricing, the terminal network configuration, and the hub-service-network as the alternative design measures for optimizing the network performance. The service-based measures are not applied to all freight flows on the network, but to where the cooperation between the transport operators are possible. The reasons for choosing these measures and their potential impacts in the network performance will be elaborated further in the following section.

5.4 Design measures for optimization

CO_2 pricing

The CO_2 pricing policy is assumed to be a charge on the CO_2 emissions incurred during transport and transhipment, borne by the transport operators, measured in euro per tCO_2 emissions. Recognized as a negative externality of freight transport, these CO_2 emissions have not been directly paid by the transport operators (Janic, 2007).

CO_2 pricing policy defined in this application internalizes the costs of CO_2 emissions to the transport costs borne by all the transport operators and applied to all modes of transport. As a result, rail and IWW would be more preferable than road given their lower tkm CO_2 emission costs, and an appropriate pre-/end-haulage distance. Some freight flows would move from road to rail or IWW. This could also contribute to reducing CO_2 emissions for the total network since rail or IWW transport generate less CO_2 emissions as compared to road transport given the condition of moving the same volume of freight over the same distance, and if the transport means are utilized efficiently. The higher CO_2 emissions charges, the more preferable rail and/or inland waterway transport become, thereby reducing the total network emissions. Assuming that the inland terminals can benefit from the cost efficiencies of handling larger volumes of freight, CO_2 pricing would also contribute to reducing the average costs at the terminals. The total network costs may decrease if the benefit from handling cost efficiencies is able to compensate for the extra costs of CO_2 emission charges.

Terminal network configuration

A terminal network configuration includes the number of terminals in an infrastructure network and their location. Each configuration of terminal network presents a specific scenario of the accessibility to intermodal transport. Assigning fixed OD demand over the various candidate configurations of terminal network may lead to different flow assignments over the network. Abandoning certain terminals or expanding certain terminals may change the average costs of inland waterway transport by (de)centralizing the transhipments and rerouting the flows. If transhipment costs decrease then more flows may shift from road to inland waterway transport, and thus bring the lower total network costs and CO_2 emissions.

Hub-service-networks

Intermodal container transport faces challenges of competing with road transport since most containers are moved over short distances. The costs saved by benefiting from lower cost per tkm in the main haulage often does not compensate for the extra expenses caused by the pre-/end-haulage and transhipment, given the current terminal network layout and the current situation of service operation. Previous research has found that the hub-and-spoke networks may have more advantageous in terms of operating costs when compared to the shuttle barge transport services under conditions of sufficient demand (Horner and O'Kelly, 2001; Limbourg and Jourquin, 2009). The geographic and infrastructural conditions of the Dutch IWW are feasible for operating the hub-and-spoke based transport networks (see Figure 4.6). In these networks, the hub-based services have the potential of benefiting from the more economic hub-hub transport if the demand for these services is large enough to achieve more efficient utilization of the transport capacity.

In the remaining part of this chapter, for the purpose of explaining more clearly the concept of service network, we adopt the term ‘hub-service-networks’ to represent the service networks where the hub-hub transport is involved. The services provided in the ‘hub-service-networks’ are called ‘hub-network-services’.

If the inland waterway transport operators in the Netherlands operated new hub-network-services in a collaborative way, the service frequency and the load factor of

IWW transport would increase. The intermodal transport may be able to provide a more flexible shipping schedule at lower prices, and thus be more competitive to the road transport or the shuttle barge transport services. Intermodal transport might attract more flows with a flexible schedule and competitive costs. The total costs of the entire multimodal network might decrease due to economies of scale at terminals, economies of barge size, and higher utilization of the current terminal and fleet capacities. The ratio of empty containers is not specified in this application. An average load factor is applied to each container based on the total volumes transported and the total number of containers.

Combinations of policies

Combination of two or three of the above-mentioned design measures may result in the combined effects. A higher price for CO_2 emissions given a fixed OD transport demand may direct more flows from road to rail or IWW and thus bring more transport demand to the hub-service-network. Meanwhile, more flows might be attracted to the terminals where the hub-network-services are available. The flow concentration might make these terminals benefiting from economies of density or economies of scale resulting in lower transhipment costs. Such costs may attract more flows to this hub-network-service which consequently results in higher utilization of the current terminal and barge capacities.

On the other hand, a non-well configured terminal network may result in higher total network internal costs when a higher price for $CO_{2,}$ as compared to the same terminal network configuration with lower CO_2 price. The extra transhipment costs incurred during the intermodal transport increase the total network internal costs. When the CO_2 emission costs are charged at very high rate, the dominant component of the total costs because the CO_2 emission costs. Then the flows will be directed to lower emission modes instead of the lower internal cost modes. In this case, the low-emission mode is not necessarily the low-cost mode to be chosen by the transport operators.

5.5 Application setup

The model proposes and evaluates alternatives by using a scenario-based approach. Each scenario consists of a certain terminal network configuration with (or without) feasible new hub-service-networks and a certain CO_2 price.

In order to quantify the criteria for ‘network performance’ the total network costs, the modal-share (in tkm) of rail and IWW transport, and total network CO_2 emissions are chosen. The total network costs mean the total costs of all the flows accommodated by the super network with internalization of the CO_2 emissions charges. The scope of the ‘total network’ is defined as the super network (visualized in Figure 4.3), which is relevant to Dutch container transport. Both domestic and intra-European containerized freight flows were taken into account in the flow assignment.

In the pool of the potential design measures, which are used as input for the model, we defined 42 locations within the Netherlands as elements of the alternative terminal networks.

The CO_2 price is given in a range of 0 to 1000 euros per tCO_2 with an increment of 10 euros per tCO_2. The generator of combination of design measures generates packages consisting of one terminal network configuration, optional for each of the 42 operating terminals, single CO_2 price, and a binary variable indicating if the hub-service-networks are available or not.

The results presented in the next section are reached after several runs of the model. Each run aims to evaluate the network performances under the condition of one or a combination of the design measures. Table 5.1 summarizes the setup of optimization processes for these networks. Due to the computation ability, 30,000 scenarios for the design measure of terminal network configuration; and scenarios for the combination of terminal network configuration and CO_2 pricing; and 50,000 scenarios for the combination of the three design measures are calculated. The combination of terminal network configuration and hub-service-networks are not evaluated due to the model's constraints. A hub-service-network is available only if all of the involved terminals are in operation. Therefore, the results about the efficiency or effectiveness of this combination of design measures are not comparable to the other design measures.

Table 5.1. Summary of the network optimization setup

Run	Design measures	No. of scenarios	No. of variables
1	CO_2 pricing	100	1
2	Terminal network configuration	30,000	42
3	Hub-service-networks	2	1
4	CO_2 pricing and terminal network configuration	30,000	43
5	CO_2 pricing and hub-service-networks	200	2
6	All of the three instruments	50,000	44

5.6 Interpretation of Results

In this section, we present the main findings from all six network optimization processes in the same order as shown in Table 5.1.

5.6.1 CO_2 pricing

This subsection focuses on investigating the impact of the price for CO_2 emissions on network performance. We analyse 100 scenarios in which the CO_2 emissions are priced at the rates of 0 ~ 1000 euros per tCO_2 with an increment of 10 euros per tCO_2, while the transport infrastructure supply and services are assumed to be the same as in the base scenario. This implies that the configuration of terminal network is the same as in the base scenario without availability of the new hub-service-networks.

A brief summary of the main findings of this scenario analysis is as follows:

- Reduction in CO_2 emissions when CO_2 price increases (Figure 5.1);
- Reduction of the internal costs cannot compensate the increase in the total costs due to internalizing the external costs (Figure 5.2);
- Dominant contribution to the decrease of the internal costs is modal shift from road to intermodal transport (Figure 5.3);
- Flows move more intensively from road to rail or IWW when CO_2 price increases (Figure 5.4);
- Global economies of scale at terminals are observable (Figure 5.5).

Impact of CO_2 price on CO_2 emissions

Figure 5.1 shows that increasing of the price for CO_2 emissions from 0 to 1000 euros per tCO_2 leads to a decrease in the total network CO_2 emissions gradually. If higher CO_2 prices are internalized, the rail and inland waterways are expected to attract more flows due to their lower rates of CO_2 emissions. The total network emissions do not change significantly until CO_2 is charged at higher rates. Based on the assumptions made for this case, the critical rate appears to be 400 euros per tCO_2. The CO_2 emissions decrease more sharply when the CO_2 price is charged at a rate higher than 400 euros per tCO_2. One reason for this is that only when a high enough price is charged for CO_2, the cost difference between the road and intermodal transport becomes sufficiently large to cause shifting significant amount of flows to intermodal transport. As well, the total network emissions could decrease up to 50% when the CO_2 is charged for 1000 euros per tCO_2.

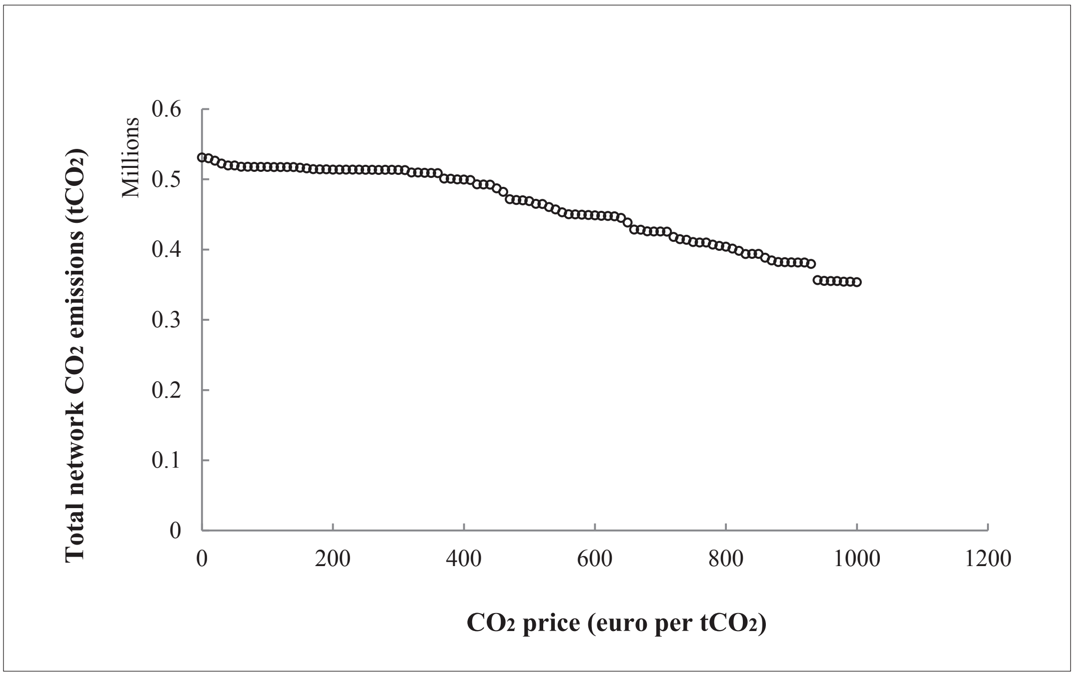


Figure 5.1. Relationship between the total network CO_2 emissions and CO_2 prices in given example

Impacts of CO_2 price on internal and external costs

Figure 5.2 shows that internalizing the emission costs of CO_2 also results in the lower total network internal costs. The reason is that with the extra costs for CO_2 emissions, some of the flows are transported by rail or IWW with lower CO_2 emission costs despite their extra handling costs for intermodal transhipments. The monotonically decreasing curve of the total network intermodal costs indicates that the costs saved by using rail or IWW transport, instead of road transport, can cover the extra transhipment costs (see also Figure 5.3 for more details).

However, the increasing curve of the total network costs shows that the gain from the modal shift cannot compensate for the internalized costs for CO_2 emissions. The increase in the total network costs of CO_2 emissions is dominant in the change of the total network costs. Therefore, CO_2 pricing could contribute to reducing the CO_2 emissions, but it would not be easily accepted by the transport operators because there would be a limited amount of reduction in the CO_2 emissions for such high extra costs.

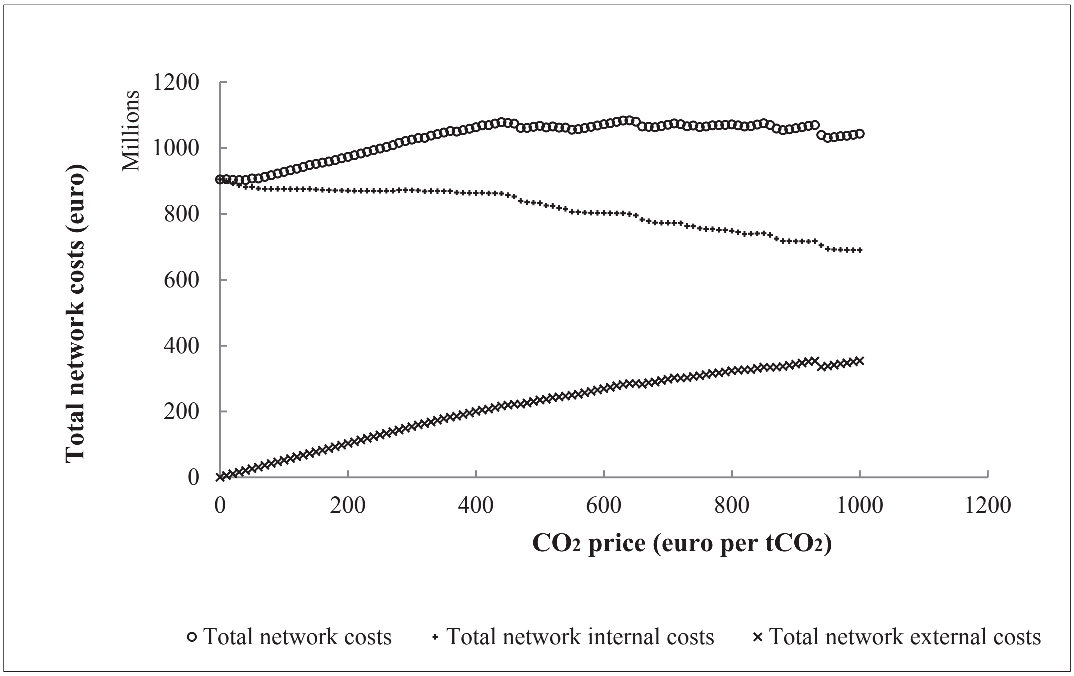


Figure 5.2. Relationship between the total network costs and CO_2 prices in given example

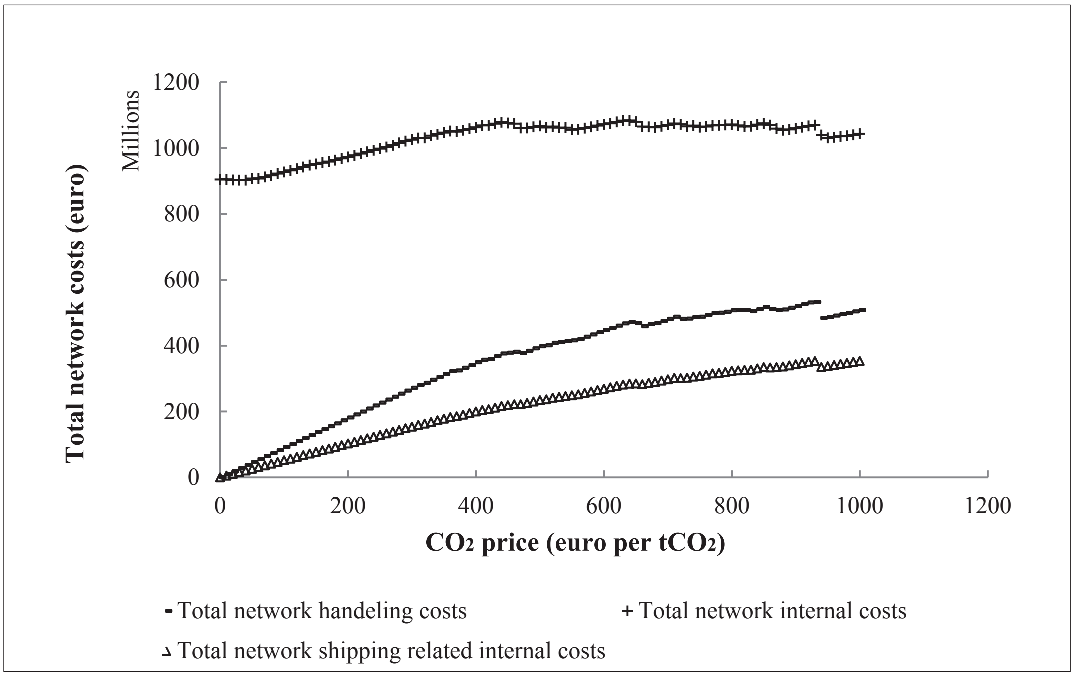


Figure 5.3. Relationship between particular constructs of internal costs and CO_2 prices in given example

Impact of CO_2 price on Modal shift

Figure 5.4 shows the impact of CO_2 pricing policy on the total network modal shift. The share of road transport decreases from 60% to 20%, while CO_2 emissions are charged from 0 to 1000 euros per tCO_2. These percentages are measured in tkm transported in the NL. The share of road is 40% if measured in tonne, loaded or/and unloaded in the NL, in the base scenario. As illustrated in the figure, the flows shift first from road to IWW, later from both road and IWW to rail. This indicates that the IWW transport can receive flows only to a point and after the rail transport takes over.

Such a pattern could not be exactly explained. Additional analyses of costs for particular scenarios are necessary in future research. At this moment, we presume three factors may play a role in such modal shift pattern. First, the model assumes that most of the locomotives are powered by electricity so no direct CO_2 emissions are counted for rail transport. We assume that the emissions already counted in the energy sector are not relevant to transport emissions. Therefore, no extra CO_2 emission costs are charged for rail transport. This becomes an overwhelming advantage when compared to the road and IWW transport, when CO_2 is charged at a high rate (around 600 euros per tCO_2 in this case). Second, the accessibility of the IWW might also limit its competitiveness in contrast to the road or rail transport.

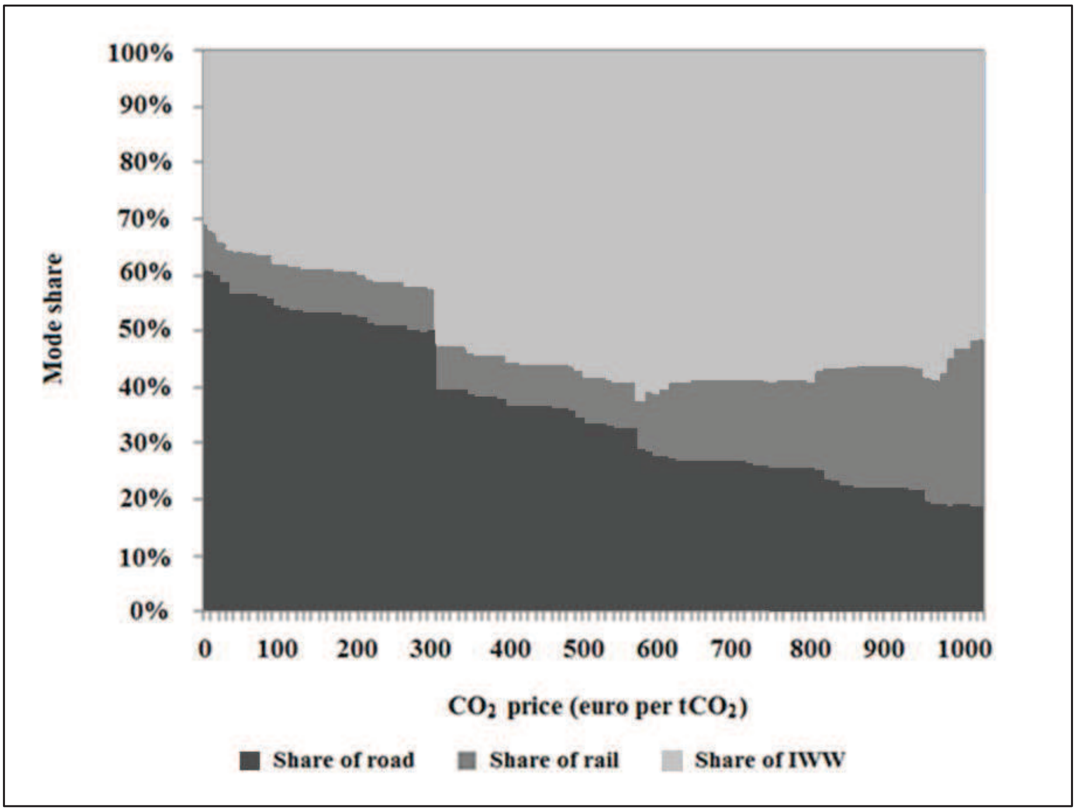


Figure 5.4. Share of road, rail, and IWW in the Netherlands measured in tkm

Economies of scale at terminals

It is clear that more flows shift from road to rail or IWW when CO_2 is charged (see Figure 5.4). However, the former results do not indicate whether the flows tend to consolidate in several terminals or to be distributed to more terminals in smaller volume. The network would benefit from the former situation more due to the scale economies at terminals. Figure 5.5 shows that the Dutch container transport could benefit from the global scale economies at terminals. The curve in addition to economies shows that diseconomies may happen as well when the total through exceeds the break-even point. This might be due to the fact that a larger number of containers are handled at the small-scale terminals as compared to the scenario at the break-even point. In addition, the average handling costs vary from 3 to 4.5 euros per tCO_2. This indicates that the average handling costs could reduce by 30% on the basis of the highest handling costs. It is important to note that these numbers based on the assumptions defined for this case study, which also includes the relation between average terminal handling costs and the assumed throughput of the terminal based on the actual price of the Dutch inland IWW terminals.

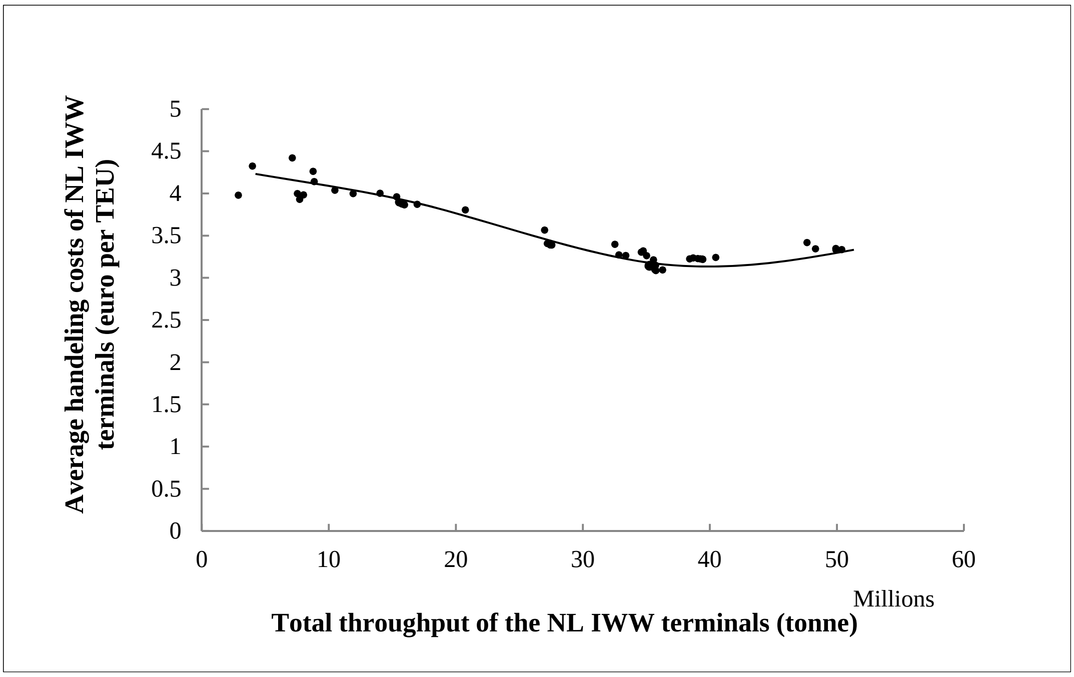


Figure 5.5. Relationship between the total IWW throughput and the average handling costs of the Dutch IWW terminals

Short summary

CO_2 pricing policy can lead to a modal shift and consequently a reduction in the total network CO_2 emissions. It can also result in the lower total network internal costs, although extra handling costs are incurred in the intermodal transhipments. However, the costs saved from using intermodal transport cannot compensate the internalized costs of CO_2 emissions. When the CO_2 emissions are charged of higher prices, IWW transport takes more flows from road transport, and after a certain point rail transport takes the modal shares from both IWW and road.

5.6.2 Terminal network configuration

The findings presented in the previous subsection indicate that the costs saved from using intermodal transport cannot compensate for the internalized CO_2 emission costs. In this subsection, contribution of reconfiguring the terminal network to improving the network performance is analysed. There is no charge for CO_2 emissions, and the new hub-service-networks are assumed not to be available. Each scenario is based on the terminal network, where 42 terminals in the NL are assumed to be the candidate locations for container transhipment. The total costs in these scenarios are equal to the internal costs because of not charging CO_2 emissions.

The brief summary of the main findings of this scenario analysis is as follows:

- Scenarios are found with better network performance compared to the base scenario in both costs and emissions (Figure 5.6);
- An obvious characteristic shared by the scenarios with better network performance is that they benefit more from global economies of scale (Figure 5.7);
- Closing terminals not able to attract an appropriate flow contributes to improving the network performance (Figure 5.6 to Figure 5.7).

Network performance

Different terminal configurations result in very different network performances. Figure 5.6 shows the performances of 30,000 terminal network configurations without the charge for the CO_2 emissions. The points spread in a large range in both dimensions of the total network costs and CO_2 emissions. Within the scenarios evaluated in this figure, the total network costs ascent from 80% to 150% of the costs of base scenario. The total network CO_2 emissions vary from 50% to 150% of the total emissions in the base scenario. This shows a substantial potential for improvements.

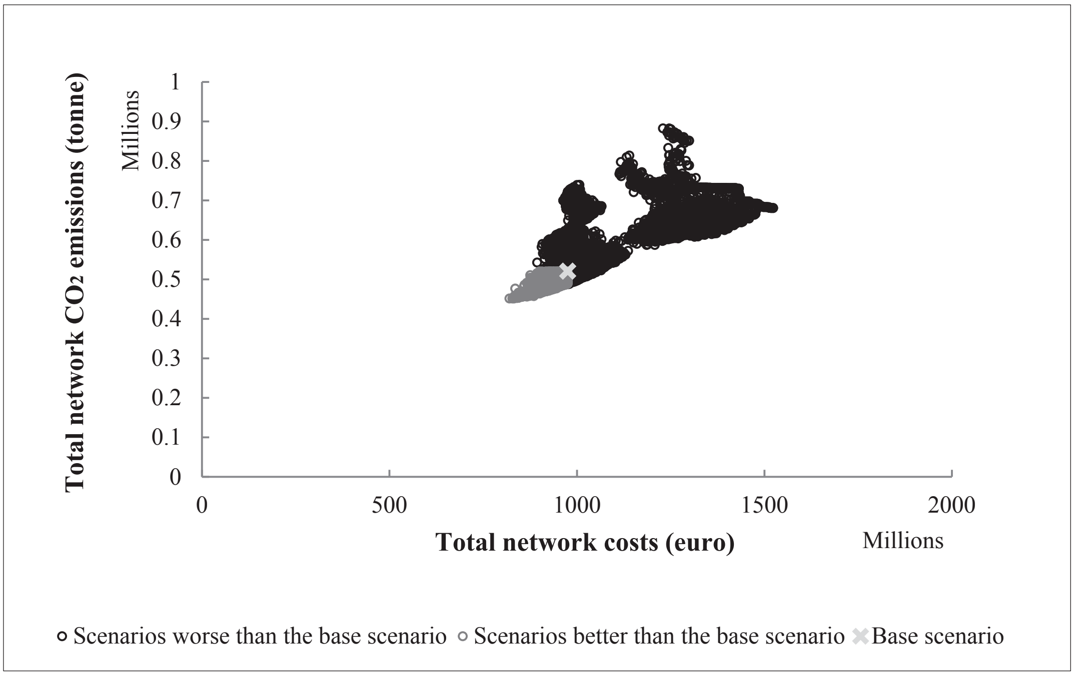


Figure 5.6. Relationship between the total network costs and CO_2 emissions

Characteristics of the better scenarios

Better alternatives with lower CO_2 emissions and lower total network costs, as compared to the base scenario, are shown by the black dot in Figure 5.6. The average throughput of these terminals are higher than that number in the base scenario (see Figure 5.7). This appears to be in line with tendency of the total network costs to decrease with an increase in the average terminal throughput. This indicates that closing terminals not able to attract appropriate volumes of flows can contribute to improving the network performance.

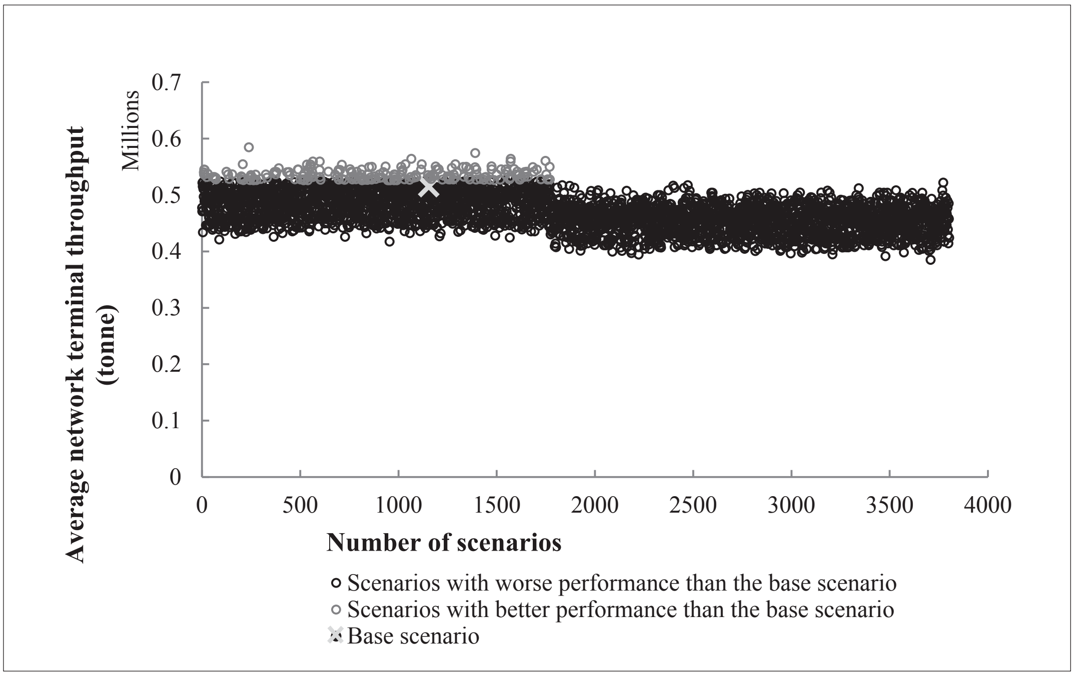


Figure 5.7. Average throughput of all terminals in the network for different terminal network configurations

Note: for the purpose of better illustration, this figure shows the results of a random sample of 3,000 scenarios.

Short summary

Therefore, we can conclude from the previous analyses of the two design measures. The CO_2 pricing policy may contribute to the reduction of the CO_2 emissions, especially when CO_2 is charged at a high rate. But the extra costs would result in a significant increase in the operational costs, which would be directly borne by transport operators. The optimal terminal network configurations with lower total network costs and lower CO_2 emissions are those where the handling capacity of the terminals are efficiently utilized. But regarding different interests of local governments or terminal operators, an optimal terminal network configuration is not likely to be achieved in the short term.

5.6.3 Collaborative hub-network-services

This subsection discusses whether new collaborative hub-network-services could contribute to a better network performance by benefiting from consolidation effects.

In this scenario analysis, the CO_2 price is assumed to be zero, the terminal network configuration is given as the same as the base scenario, and the hub-network-services are available. The costs of each leg of the hub-network-services depend on the flow transported by these services.

A summary of the main findings of this scenario analysis is as follows:

- No hub-network-service is feasible in the base scenario, due to extra transhipment costs, low load factor on the barging legs, and low transport demand.

No hub-network-service is feasible in the base scenario

The results obtained from the flow assignment in the scenario as described at the beginning of this subsection show that none of the hub-network-services is feasible for competing with road transport or with the shuttle barge transport services, given the terminal network configuration in the base scenario. It can be expected that different services are infeasible due to different reasons, since the costs of a service depend on many factors. Some of these include transport demand, navigating condition, barge size, and service frequency. Each service presents different case given these various aspects. However, we noticed that all services show a common characteristic in the simulation: a low load factor in the barging legs. The load factors on the links between the inland terminals and hubs resulting from the model were 0 ~ 0.75, given the barge service frequencies in the year 2006. The shuttle barge transport services between the inland terminals and the sea terminals have load factors of 0.6 ~ 0.9, based on the practice in 2006.

Example of moving a container from Rotterdam to Tilburg

In order to gain more insight into this issue, we take the example of moving one container (1TEU in this case) from the port of Rotterdam to a customer located in Tilburg, where road, shuttle barge, and the hub-network-based barge transport service are available. The assumptions for the road and shuttle barge transport are made respecting the practice.

The road mode is assumed to be a full truck departing from the port of Rotterdam and heading to the customer in Tilburg, with an average speed of 40 km per hour.

The shuttle barge mode is assumed to transport the container from the port of Rotterdam to the terminal in Tilburg with a load capacity of 32 TEU. The container is transhipped to a truck at the terminal in Tilburg for the end-haulage between the terminal and the customer. The load factor of the barge is assumed to be 0.85, which was the average capacity for barges of this size operating between Tilburg and the port of Rotterdam in the year 2006.

The hub-based service mode assumes as that the container is transported by a barge with loading capacity of 200 TEU from the port of Rotterdam to the hub terminal located at Moerdijk, and then transhipped to a barge with a load capacity of 32 TEU, which is navigable in the waterway approaching the terminal in Tilburg. The container is transported at the terminal of Tilburg from the barge to a truck for the end-haulage. The load factor of both legs of service is the result of the simulation calculated by the model based on the base scenario.

The waiting time and handling time at the port of Rotterdam and at the inland terminals is factored into the distance-related, and the time-related transport costs. The loading and unloading time of trucks is also taken into account. All calculations are executed in a single-trip.

A brief summary of the shipment between Rotterdam and Tilburg is provided in Table 5.2.

Table 5.2. Input for the simulated single-trip shipment of a container between Rotterdam and Tilburg

	Uni-modal-truck	**Shuttle barge**	**Hub-network-based barge**
Size of the transport mean	1 TEU	32 TEU	200 TEU (hub-hub), 32 TEU (pickup-and-delivery)
Origin and destination	The port of Rotterdam – the customer	The port of Rotterdam – the customer	The port of Rotterdam – the customer
Pre-haulage	Not applicable	0 km (shipment starts in a terminal of the port of Rotterdam)	0 km (shipment starts in a terminal of the port of Rotterdam)
Main haulage	120 km, the port of Rotterdam – the customer	120 km, the port of Rotterdam – the terminal of Tilburg	120 km, the port of Rotterdam – the terminal of Moerdijk – the terminal of Oosterhout - the terminal of Tilburg
Load factor	1.0	0.85	0.75 (hub-hub), 0.5 (pickup-and-delivery)
Handling	Not applicable	10 hours in sea port and 2 hour in each inland terminal	10 hours in sea port and 2 hour in each inland terminal
End-haulage	Not applicable	20 km, the terminal of Tilburg – the customer	20 km, the terminal of Tilburg – the customer

Figure 5.8 compares the total transport costs of three types of service (including distance related, mode-related time, and transhipment costs, but excluding the commodity-related time costs). It shows that under the assumed conditions (Table 5.2), the hub-network-service has the highest costs.

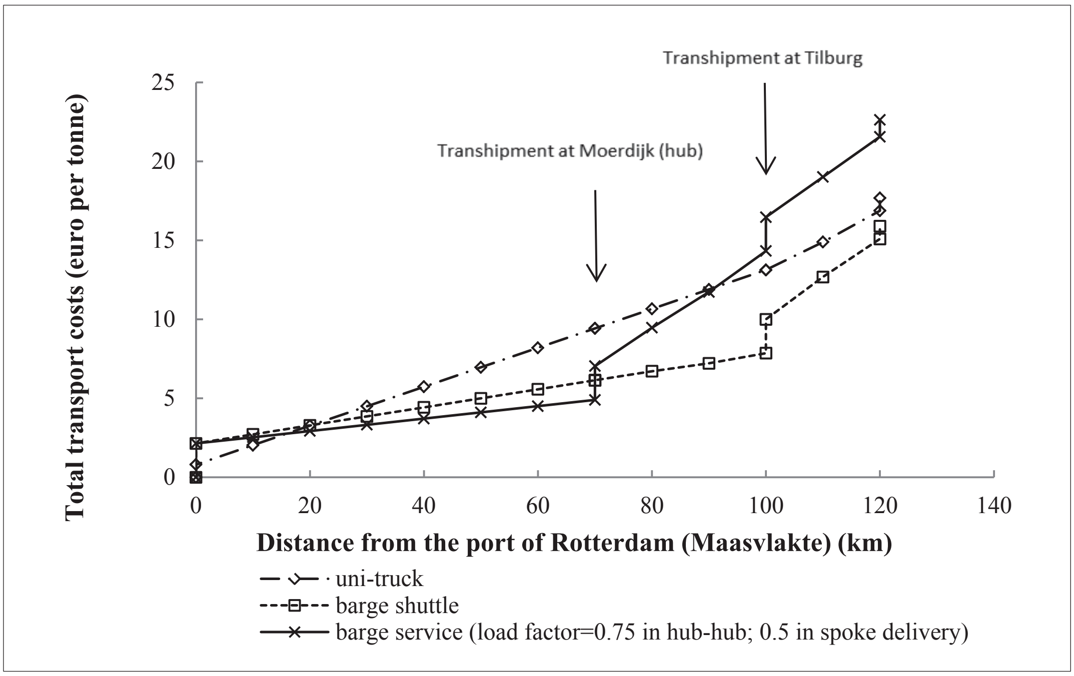


Figure 5.8. Relationship between the average total transport costs of a container and distance: cast of the route Rotterdam to Tilburg

One reason for this is the extra transhipment costs. When compared to the road shipment, the costs saved in IWW transport cannot compensate costs of the two extra transhipments at the inland hub (Moerdijk) and at the destination (Tilburg). When compared to the shuttle barge service shipment, the costs saved by better utilizing of the fleet capacity of the hub-hub transport cannot compensate the transhipment costs at the inland hub.

Another reason for the higher cost of hub-network-service is low load factor of the hub-based barge services, particularly between the hub (Moerdijk) and the destination terminal (Tilburg). This makes the transport costs between the hub and the terminal more expensive than the shuttle barges serving the same origin and destination and using the same type of barge (32 TEU). This is shown in Figure 5.8. The cost of the hub-network-based barge service has a sharper slope between 70 km and 100 km (the leg between Moerdijk and Tilburg) as compared to the costs of the shuttle barge service. In this case, due to low load factors, the unit transport costs of the hub-based barge service are higher than those of either shuttle barge service or road trucking.

In order to find the threshold of the load factor which would lead to a competitive hub-based barge service, the load factor has been increased incrementally. We find that when the load factors of both hub-hub and hub-inland terminal are as high as 0.85, the hub-based barge service becomes more competitive as compared to the other two modes (Figure 5.9). Although the hub-based barge service is still the most expensive among the three options, the very close costs show its potential competitiveness, and opportunity to be used in some specific circumstances. However, it is still not competitive in terms of transport time mainly due to the extra transhipment time.

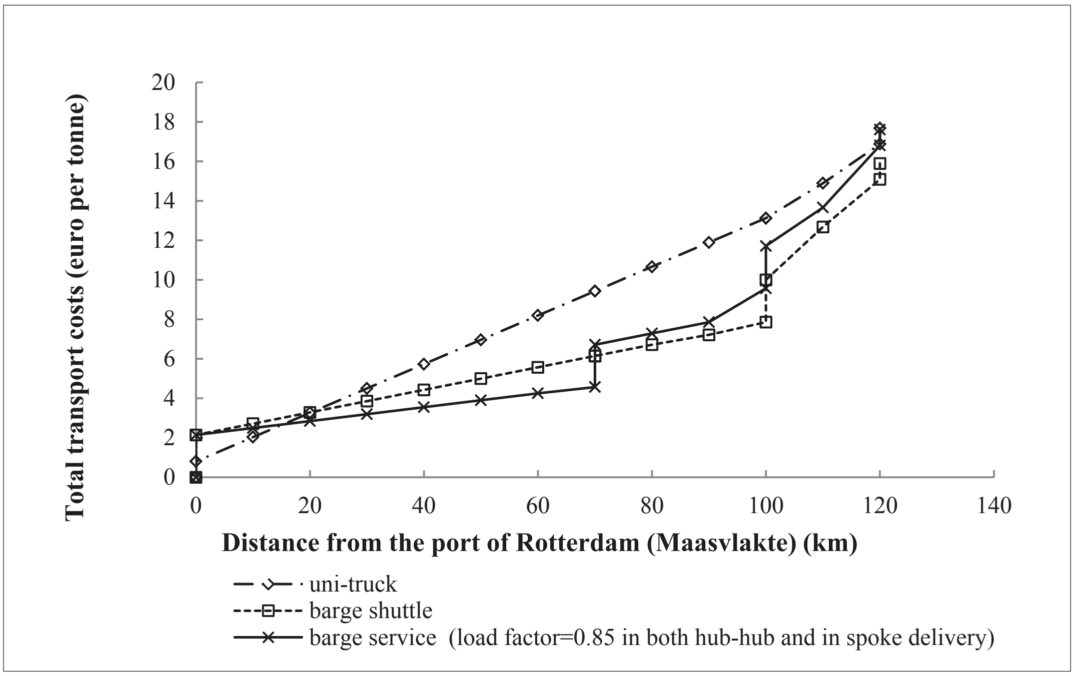


Figure 5.9. Relationship between the average total transport costs of a container and distance: case of the route Rotterdam to Tilburg (assumed high load factor)

Rather low transport demand could also be another reason for infeasibility and the lack of competitiveness of the hub-based barge transport.

In order to estimate feasibility of these hub-network-services when the demand for IWW transport would increase dramatically, we apply a demand projection for the year 2040. As estimated according to the global growth in the maritime container transport, the demand for hinterland transport of the port of Rotterdam could grow by a factor of 4.5 ~ 5.3 in 2040 as compared to the demand in 2006 (De Langen et al., 2012).With such transport demand in 2040 and the terminal configuration in the base scenario, the results indicate that the simple hub-and-spoke service between the northern part of the Netherlands and the sea terminals of Rotterdam and Antwerp would be more economical than the shuttle barge transport services. The pickup and delivery services (as shown in Figure 4.6, b and c) serving the middle and southern parts of the Netherlands would not be feasible due to still low load factor where conditions of providing the service level as the shuttle barge transport.

Short summary

The results obtained from the flow assignment in the scenario described at the beginning of this subsection show that none of the hub-network-services is feasible in competing with road or shuttle barge transport services, given the terminal network configuration in the base scenario. Extra transhipment costs, low load factor, and low transport demand are the main reasons. However, when a shipment between the port of Rotterdam and a customer located in Tilburg is considered as an example, the hub-based services could become more competitive if the average load factor was up to about 0.85. Given this condition, the simple hub-and-spoke service between the northern part of the Netherlands and the sea terminals of Rotterdam and Antwerp would be feasible if the demand for IWW transport were to increase dramatically.

5.6.4 CO_2 pricing and terminal network configuration

As discussed in previous subsections, CO_2 pricing has an effect on increasing the share of intermodal transport. In addition, appropriate terminal network configurations have the advantage of benefiting from economies of scale at terminals. Scale economies could result in decrease in the unit transhipment costs, thereby promoting the competitiveness of intermodal transport in terms of costs. As a result, increased volumes transported by intermodal transport would influence the demand for terminals. What would be the combined effect of implementing both policy measures? In this subsection, we assume that the CO_2 emissions are charged at prices between 0 and 1000 euros per tCO_2; the terminal network configuration, as a variable, has the same setup as in the subsection 5.5; and the hub-network-services are assumed not to be available. The network performances of 30,000 scenarios are evaluated.

A summary of the main findings of the analysis for this scenario is as follows:

- For the optimal terminal network configurations, the total costs (including the charge for CO_2 emissions) decreases when the CO_2 price increases, assuming existence of scale economies at terminals (Figure 5.10 and Figure 5.11);
- Combination of the two measures is more effective than only single measure of CO_2 pricing, especially when CO_2 emissions are charged at a lower rate (Figure 5.12);
- Terminal network configurations broaden the range of efficient networks, with a frontier of total network costs and total network CO_2 emissions (Figure 5.13).

The combined measure creates new efficiencies

Figure 5.10 shows relationship between the costs of the optimal terminal network configuration and CO_2 price. Comparing with the network costs in Figure 5.2, the total network costs of the “optimal” terminal network configuration without the charge of CO_2 (intercept point of the total network costs in Figure 5.10) is lower than in the base scenario (intercept point of the total network costs in Figure 5.2).

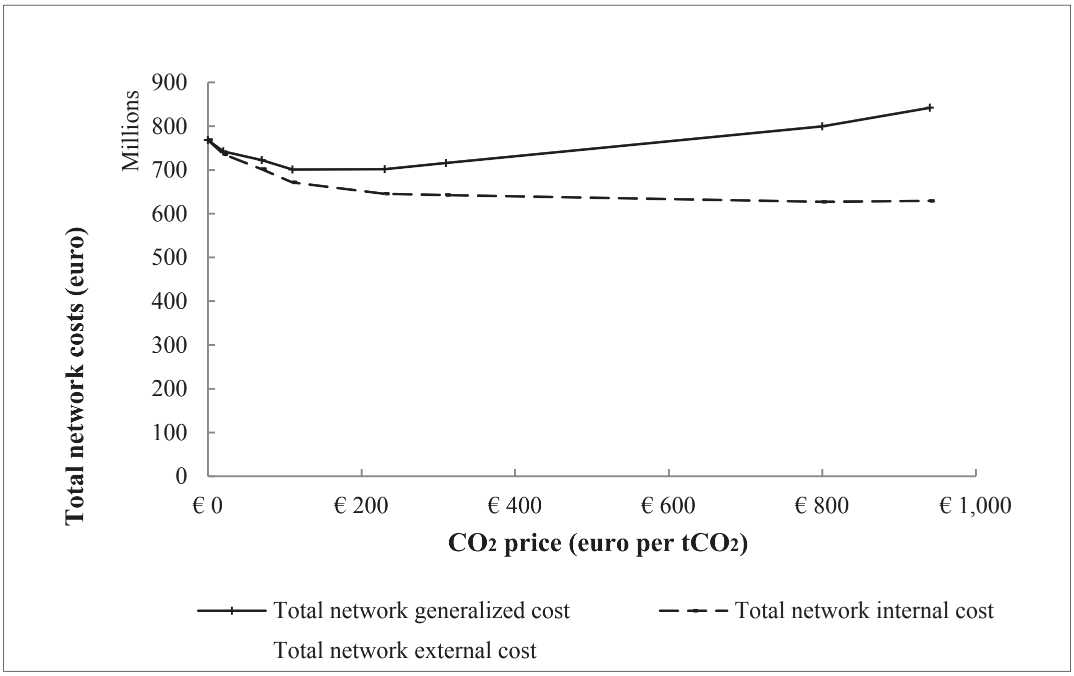


Figure 5.10. Relationship between the total network costs of optimized terminal network configurations and price of CO_2 emissions (with the effect of economies of scale at terminals).

As shown in Figure 5.10, the total costs of the optimal network configuration decrease at the beginning and reach the inflection point when CO_2 emissions is priced at around 100 euros per tCO_2. This is due to the combined effect of modal shift and economies of scale at terminals. If CO_2 emissions is charged at a higher price as compared to the price at the inflection point, the cost-savings obtained from the modal shift and the economies of scale at terminals cannot compensate the increase in the total network costs due to the extra charges on CO_2 emissions.

A comparison with another test, where we assumed that the economies of scale do not exist, confirmed that the economies of scale are the dominant factor leading to the decrease in the total network costs (Figure 5.11). This indicates that theoretically, by benefiting from the economies of scale, the total network costs may decrease when internalizing the costs of CO_2 emissions given certain terminal network configurations. Relationship between the throughput of a terminal and its unit handling costs in this analysis is estimated using the market prices of the Dutch inland terminals. The subsidies granted to the terminal operators, and influences of the changes in them are not included in the total network costs. Therefore, in practice, the decrease in the total network costs may not happen, if the subsidies to help the terminals to achieve efficient scale are taken into account as a part of the total network costs.

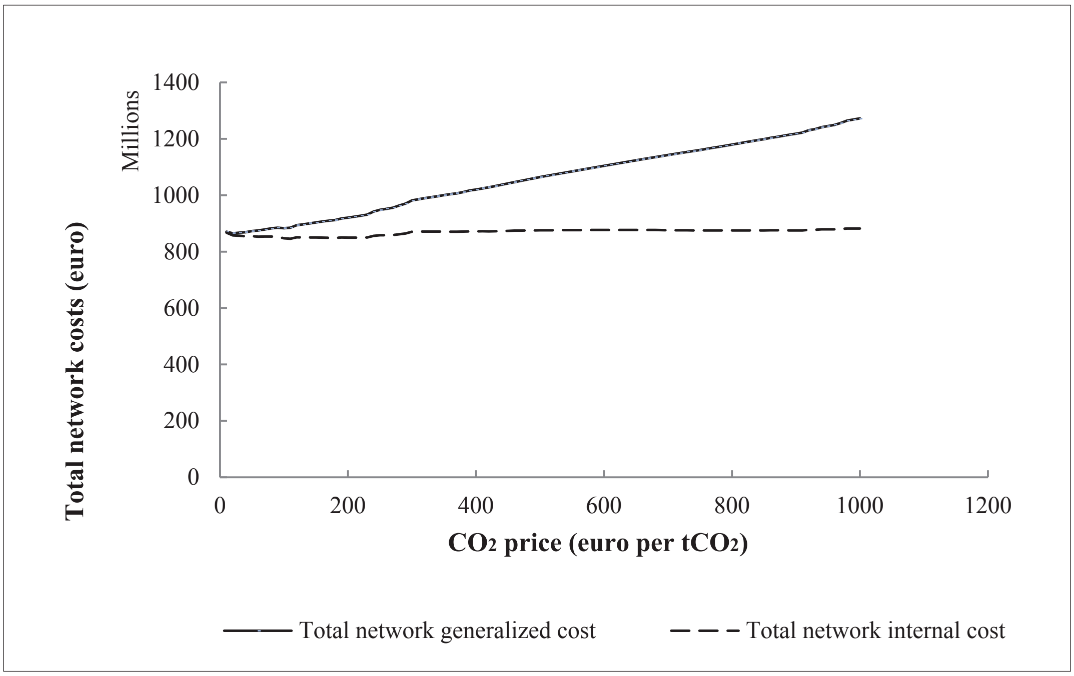


Figure 5.11. Relationship between the total network costs of optimized terminal network configurations and price of CO_2 emissions (without the effect of economies of scale at terminals).

Combined impacts of terminal network configuration and CO_2 price on emissions

The relationship between total network CO_2 emissions of various terminal network configurations and the CO_2 price is shown in Figure 5.12. Each dot represents the result of one scenario, which is composed of the combination of a specific terminal network configuration and CO_2 price. As can be seen, the dots are widely spread on the vertical axis, which indicates the rather strong impact of the terminal network configuration on the total network CO_2 emissions.

We can observe that two series of dots form two lines. The one series lining the top part of the figure shows the scenarios where no terminal was available in the network, so all containers were transported by road. In these cases, CO_2 price has no impact on the mode-choice, or on the total network CO_2 emissions. The other series of dots, in the middle of the figure, shows the scenarios where the terminal network configurations remain the same as in the base scenario, shown in Figure 5.1. It clearly shows that the terminal network configuration in the base scenario with intermodal transport has much lower emissions as compared to the scenario where no intermodal transport is available.

We also added a trend line for the optimal scenario of each CO_2 price by a heavy line. This line illustrates the frontier of the minimal total network CO_2 emissions that are able to be achieved by pricing CO_2 at certain rates. The frontier declines with increase in the CO_2 price. When compared with the scenarios where only CO_2 pricing is deployed (shown by the series of dots in the middle of the figure), more optimal terminal network configurations can lead to the lower total network CO_2 emissions. The slope of the line illustrating the scenarios with only CO_2 pricing and the slope of the frontier suggests the effectiveness of each design measure in terms of reducing the total network CO_2 emissions. The combination of two measures is more effective than only a single measure of CO_2 pricing, especially when CO_2 emissions are charged at a lower rate.

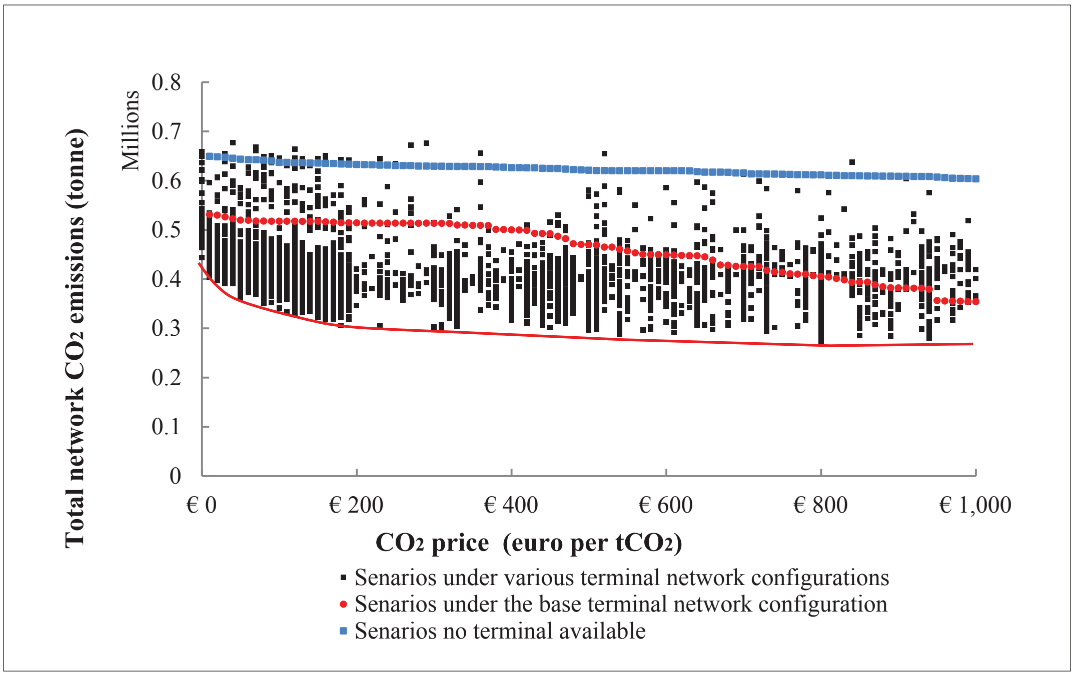


Figure 5.12. Relationship between the total network CO_2 emissions and prices of CO_2 emissions

Terminal network configurations broaden the range of efficient networks

Figure 5.13 shows the total costs and CO_2 emissions for a large number of different terminal network configurations with different CO_2 prices. The curve shown in the figure illustrates the frontier of the optimal scenarios, consisting of the optimal terminal network configurations for CO_2 prices ranging 0 to 1000 euros per tCO_2. Each point in the figure represents the network performance for one scenario. The one series lined up on the top part of the figure shows the scenarios where no terminal is available in the network. The preferred terminal network configuration depends on the CO_2 price. In order to achieve different objectives, for example, minimum total network costs or minimum total network emissions for different network configurations are required. It will be very valuable and helpful to the decision makers to analyse the large amount of terminal network configurations, and find out the features of the configurations leading to various network performances, in the future research.

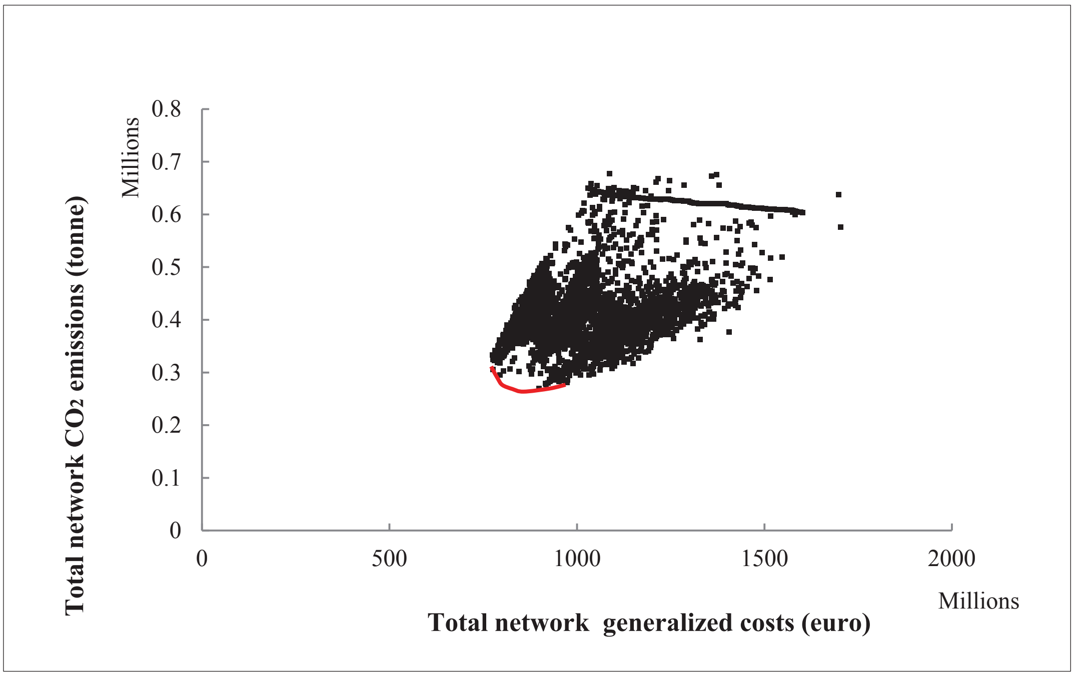


Figure 5.13. Relationship between the total network costs and the total network CO_2 emissions for different terminal network configurations

Note: the results are obtained by using GA; groups of dots clustering and expanding towards the origin of the quadrant illustrate the clustering and evolving of the solutions.

Short summary

The terminal network configuration in the base scenario with intermodal transport has much lower emissions as compared to the scenario where no intermodal transport is available. The CO_2 pricing policy can lead to a reduction in the total network CO_2 emissions. The optimization of terminal network configurations without CO_2 pricing can also lead to a reduction in the total network CO_2 emissions. However, the combination of the two measures is more effective than only implementing CO_2 pricing, especially when CO_2 emissions are charged at a lower rate. The terminal network configurations broaden the range of efficient networks, consequently, instead of one optimal solution, we found a frontier consisting of optimal solutions for minimized total network costs or minimized total network CO_2 emissions. The frontier provides more options in optimization of the terminal network, in terms of the target network performance.

5.6.5 CO_2 pricing and collaborative hub-network-services

The collaborative hub-network-services in IWW are not competitive to the road or shuttle barge transport services in the base scenario (Figure 5.8). One of the main reasons for this is insufficient demand to make collaborative hub-network-services operationally and economically unfeasible. However, Figure 5.9 shows that the costs of the hub-network-services are closely related to the load factor. Therefore, higher CO_2 prices may make inland waterway transport more advantageous due to its lower CO_2 emissions per tkm. The increase in demand for inland waterway transport may lead to more feasible hub-network-services. Furthermore, the hub-network-services may benefit more from an increase in transport demand than the shuttle barge transport services, due to the advantage in economies of scale or economies of density. This subsection presents the possible contribution of the collaborative hub-network-services to the improvement of network performance with increased CO_2 prices. The CO_2 prices are assumed to vary from 0 to 1000 euros per tCO_2 . The hub-network-services are assumed to be available.

A summary of the main findings of this scenario analysis are as follows:

- The flows transported by the hub-network-services increase when CO_2 is charged at a rate lower than 250 euros per tCO_2 and decreases when CO_2 is charged at a higher rate (Figure 5.14); the reasons for this non-monotonic relationship are transhipment costs and the efficiency of the utilization of the fleet capacity.

The flow transported by hub-network-services changes with the variation of CO_2 price

In Figure 5.14, it can be seen that no flow is transported by the hub-network-services in the base scenario where CO_2 price is zero. The hub-network-services start to gain share of flows when the CO_2 price is around 100 euro per tCO_2. The total flow transported by the hub-network-services shows the tendency to increase with increasing of the CO_2 prices from zero to around 250 euros per tCO_2, but also to decrease after this turning point. This indicates that with a lower than 1000-euros price per tCO_2 and with the fixed demand, the share of hub-network-services will be limited within a certain range.

The continued trend of total throughput for Dutch IWW terminals (Figure 5.15) shows that with an increase in the CO_2 price, IWW transport will continue to gain market share. The results shown in Figure 5.14 and Figure 5.15 suggest in combination that if the CO_2 price is higher than 250 euros per tCO_2, the shuttle barge transport services gain modal share from the hub-network-services. The shuttle barge transport services gain the market share from other modes of transport as well. This breakeven point can be observed by comparing the increase in the total IWW flow and the total throughput of the Dutch IWW terminals. The large increase in the total throughput of the Dutch IWW terminal, despite the extra transhipment throughput resulting from the hub-network-services, implies that the increase in total IWW flow is much higher than the drop in flow of the hub-network-services. In addition, by comparing these two figures, it can be observed that with a CO_2 price of zero to 1000 euro per tCO_2, the given hubs in total take about 10% to 20% of the total Dutch IWW container throughput.

In Figure 5.4, the rail transport takes over share from IWW transport (measured in tkm) when CO_2 is charged higher than 600 euros per tCO_2 with the terminal network configuration in the base scenario. This indicates that with hub-network-services, IWW transport would become more competitive as compared to the rail transport if CO_2 is charged at a high rate.

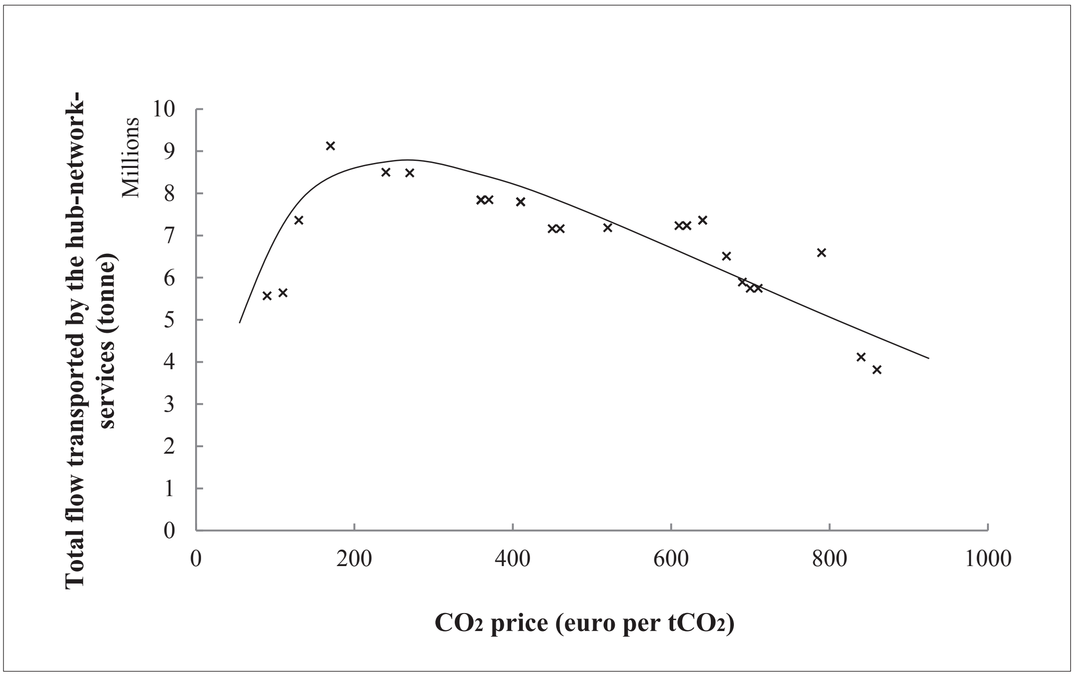


Figure 5.14. Relationship between the total flow transported by the hub-network-services and different CO_2 prices

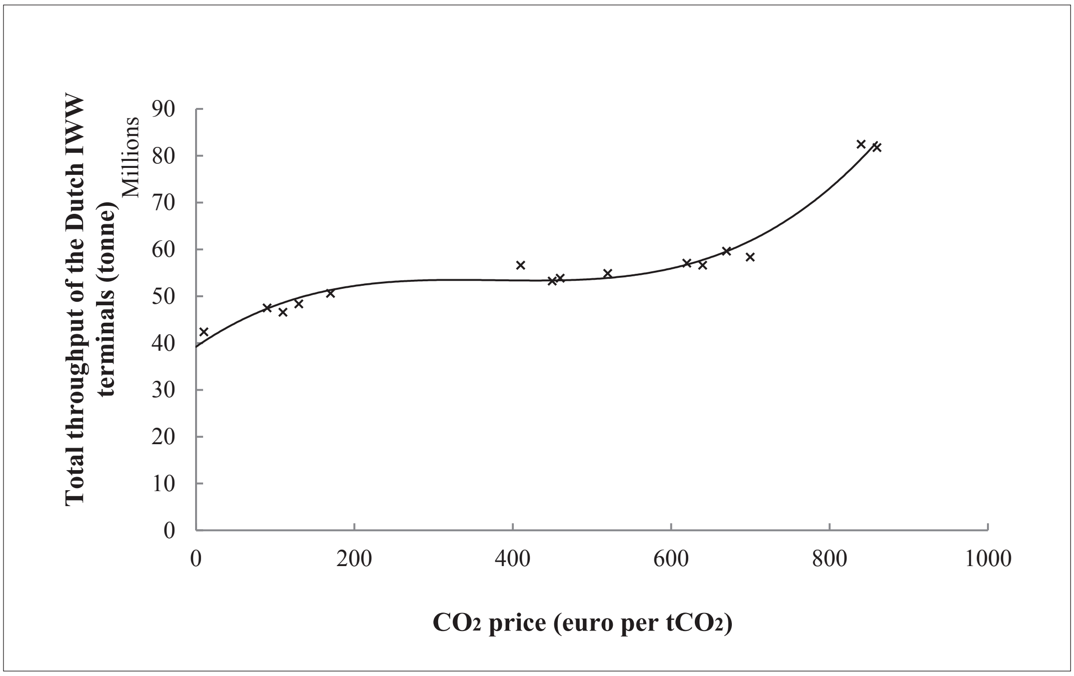


Figure 5.15. Relationship between the total throughput of the Dutch IWW terminals and different CO_2 prices with different possible hub-network-services

Transhipment costs and fleet capacity utilization of the services

Figure 5.14 shows that the hub-network-services lose their competitiveness when compared with the shuttle barge transport services. Two assumptions of the model explain this result.

One could be the unit transhipment costs. Transhipment in the hub-network-services are assumed to be charged for a fixed fee (the same as the transhipment costs for the shuttle services in the base scenario) with a fixed discount. The hub-network-services benefit from the higher efficiency of fleet capacity utilization, but do not benefit from the economies of terminal scale. On the contrary, the shuttle barge transport services are assumed to benefit from the economies of terminal scale, but not from the efficiency of fleet capacity utilization. Therefore, when the terminal throughput increases, the unit transhipment costs of shuttle services decrease, and results in the higher competitiveness in terms of costs.

Another reason could be efficiencies of fleet utilization for both types of services while demand for IWW transport increases. When CO_2 is charged at lower rates, demand for IWW transport increases. At this stage, the shuttle barge transport services for certain ODs may require additional fleet capacity, but the extra capacity would not be fully used. The hub-network-services assumed to be collaborative services, will probably achieve a higher utilization of the shared fleet capacity. Therefore, the costs of the hub-network-services are lower than that of the shuttle services for certain OD pairs. When CO_2 is charged at higher rates, the demand for IWW transport continuously increases. Since additional shuttle barge transport services would be able to operate with a higher load factor, some hub-network-services could lose their competitiveness against the shuttle services. Consequently, the total flow transported by the hub-network-services decrease, while the total throughput of the IWW terminals increases.

Short summary

The flow transported by the hub-network-services increases when CO_2 is charged at a rate lower than 250 euros per tCO_2. When CO_2 is charged at a higher rate (Figure 5.14), the shuttle barge transport services take over a part of the flows from hub-network-services, due to lower transhipment costs and higher utilization of the fleet capacity. Moreover, along with hub-network-services, the IWW transport could become more competitive as compared to the rail transport if CO_2 is charged at a higher rate.

5.6.6 CO_2 pricing, terminal network configuration, and collaborative hub-network-services

Finally, we implemented the three design measures to the Dutch container transport network simultaneously aiming at evaluating the network performances for different combined measures. Each dot in Figure 5.16 represents one scenario. In each scenario some or all of the 42 Dutch inland waterway terminals are assumed to be in operation; CO_2 emissions are assumed to be free of charge or be charged for a certain rate not higher than 1000 euros per tCO_2; each collaborative hub-network-service is assumed to be available if all of the terminals involved in the service are operational.

The results in Figure 5.16 are obtained by using GA. We can observe that several clusters of dots show trends of approaching to the origin of the quadrant. These trends show the evolving process of the network optimization, following the rules of GA. The dots lined up in the top part of the figure represent the same scenarios shown by the dots lined up in the top part of Figure 5.13, thus showing the network performances resulted from the scenarios where no terminal is available.

When compared with the results of network optimization in Figure 5.13, where the hub-network-services are not available, the frontier shown in Figure 5.16 is closer to the origin of the quadrant in both dimensions of costs (X-axis) and emissions (Y-axis). This indicates that the combined effect of the three design measures is more effective in reducing CO_2 emissions than otherwise. Moreover, if the terminal network achieved an optimal configuration, the transport operators would collaboratively provide appropriate hub-network-services to reduce CO_2 emissions by pricing CO_2 , but these may not result in an increase in total network costs.

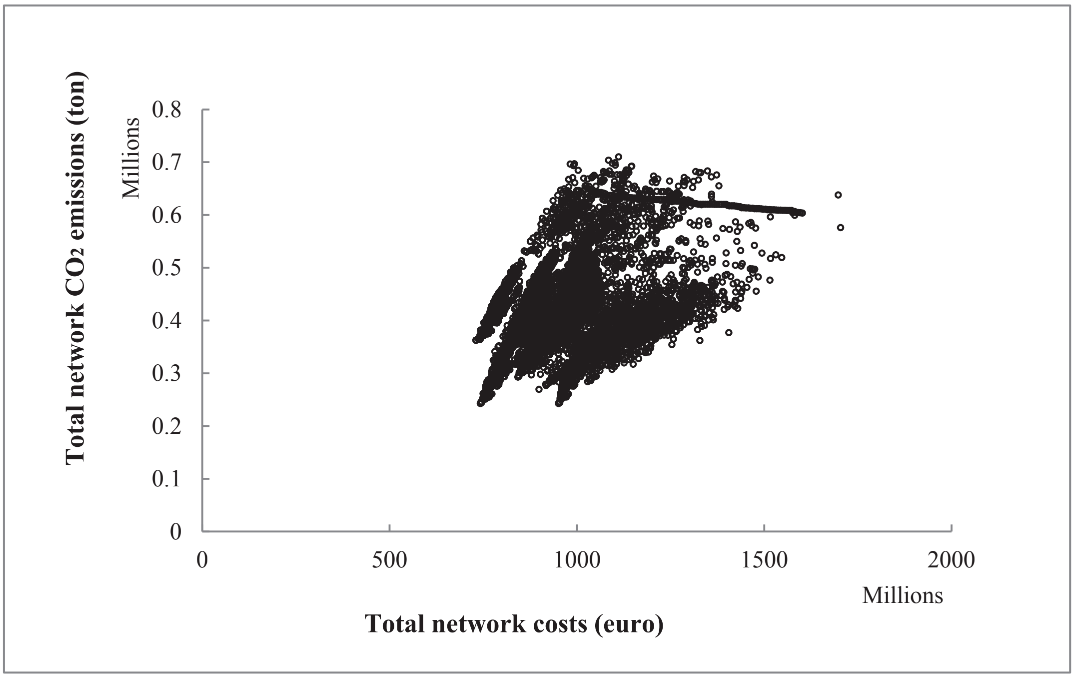


Figure 5.16. Relationship between the total network costs and the total network CO_2 emissions for different terminal network configurations and possible hub-network-services

Note: the results are obtained by using GA; the dots clustering and expanding towards the origin of the quadrant illustrate the clustering and evolving of the solutions.

5.7 Summary and discussion

In this chapter, the model to optimize the performance of the Dutch container transport in terms of total network costs and CO_2 emissions is applied. This is carried out by implementing three design measures: (1) CO_2 pricing, (2) terminal network configuration, and (3) collaborative hub-network-services. The focus lied on the inland waterway transport, aiming at understanding how pricing policy, terminal networks, and collaborative services should be designed in order to accommodate a specific container transport demand, in terms of the total volumes and commodity composition.

The findings indicate that the increase in the CO_2 emission price leads to a reduction in the total network CO_2 emissions, but also results in an increase in the total network costs. The benefits gained from using intermodal transport do not compensate the extra costs of CO_2 emission charges.

The optimal terminal network configurations may yield a network with the lower total network costs and lower CO_2 emissions. Closing terminals not being able to attract sufficient volumes of demand can increase the network efficiency. However, due to the different interests of local governments and terminal operators, an optimal terminal network configuration is not likely to be achieved in the short term.

Combination of the CO_2 pricing and terminal network configuration is more effective than only CO_2 pricing, especially when CO_2 emissions are charged at lower rates. The terminal network configurations broaden the range of efficient networks. It has been found a frontier of the minimal total network costs and the total network CO_2 emissions, instead of one single optimal solution. The frontier provides more options in optimization of the terminal network in terms of the target network performance.

The third design measure is implementation of the hub-network-services. The results show that those the hub-network-services assumed and tested in this study cannot compete with road transport or the shuttle barge transport services in the base scenario due to the extra transhipment costs, low load factor, and low demand for IWW container transport. However, for higher levels of demand than assumed in the base scenario, and changing CO_2 emissions at a sufficiently high price, the hub-based services would become more competitive. Extra transhipment costs, low load factor, and low transport demand are the main reasons for such change.

If CO_2 pricing was implemented, certain hub-network-services would receive flows already if CO_2 is charged at a low rate. When prices for CO_2 increase further, the shuttle barge transport services would become more competitive than the hub-network-services. However, concluding from the results, the hub-network-services with CO_2 pricing policies would improve the competitiveness of IWW against the rail transport. If the hub-network-services are not provided, the rail transport takes over the modal shares from both IWW and road, if the CO_2 emissions are charged at a high rate. In the scenarios where the hub-network-services are optional, that is, when CO_2 prices are high, the IWW becomes more competitive as compared to the rail transport despite the fact that the hub-network-services lose their share from the shuttle barge transport services.

The evaluation analyses show that the combined effect of the three measures is more effective in reducing CO_2 emissions than the combination of CO_2 pricing and the terminal network configuration. In addition, if the terminal network could achieve an optimal configuration and the transport operators would collaboratively provide appropriate hub-network-services, to reduce CO_2 emissions by CO_2 pricing, the total network costs may not be increased.

Chapter 6

Freight Transport Infrastructure Network Design: Findings, Implementation, and Recommendations Conclusions

6.1 Main findings from modelling

After reviewing the literature in the field of freight transport infrastructure network design (FTIND). The involvement of public concerns, represented by the governmental perspective, bringing additional complexity into infrastructure network design was found. From the governmental perspective FTIND requires strategic planning with an extension of the spatial scale and time span in order to incorporate the increasing public awareness of the environmental problems and quality of life issues, and provide a convincing vision of the future infrastructure network to the public. These new requirements from FTIND lead to the first research question of this thesis: *what are the challenges in design of freight transport infrastructure network for the large-scale network.*

The enlargement of spatial scale, for example up to a national or an international scale, creates additional complexity in the network design in three ways. First, there are more transport modes involved in (inter)national freight transport, thus multimodality is needed to be taken into account. The multimodality of the network poses a challenge for FTIND due to additional heterogeneous choices of the network use, non-linear cost-volume relation caused by economies of density and economies of scale benefiting from the terminal scale, service capacity density, fleet, vehicle, and barge size, etc. Second, multiple commodities characterized by different value densities and different appearances need to be taken into account and these may require, among other things, different types of transport networks. Multicommodity brings heterogeneous criteria in choices of the network use. Third, with enlargement of the spatial scale, more actors with various objectives are involved in planning. These actors would design their network from different perspectives, at different levels, and considering different choice criteria, thus bringing heterogeneous design objectives into the FTIND. Forth, the enlarged networks with multicommodity and multiactor bring more possibilities for the service networks. Decisions made in the service network and the infrastructure network design are significantly influenced by each other. Enhancing the interaction between the service network and the infrastructure network design in freight transport modelling faces challenges of dealing with heterogeneous decisions with short- or long-term decisions and in macro- or micro- scopes. To sum up, the large-scale, multimodality, multicommodity, multiactor, and service networks are the main challenges for the network design from a government perspective, especially when being simultaneously addressed.

Identification of these challenges gives direction to the state of the art in the FTIND modelling and leads to the answer to research question 2: *What methods are available to deal with the(se) challenges?* Based on the literature review on the implications for freight transport infrastructure network design and in modelling, the following was found. The super network representation is found suitable to contribute to dealing with multimodality and multicommodity. The mathematical methods dealing with consolidation effects are helpful for presenting multimodality and multiactor. The methods for commodity-related costs' measurement and valuation contribute to identifying multicommodity. The multi-objective programming and heuristic solving techniques provide possibilities for dealing with multiactor and an enlarged spatial scale of the network.

However, none of the existing models could deal with all of these challenges simultaneously. Southworth and Peterson have presented a large-scale multimodal network for the United States model based on a geographic information system (Middendorf, 1998; Southworth and Peterson, 2000; Southworth et al., 1997). The model designed for freight flow routing simulation captures the appearance of the commodities, and the difference in transport costs. Jourquin et al. have developed another GIS-based FTIND model (Jourquin and Beuthe, 1996; Jourquin et al., 1999) that focused on the European. This model conducted mode-choice, mean choice, and route choice. This model realized multimodal multicommodity by generating virtual links for each possible transport mean on each physical link for each type of commodity. Economies of barge service scale were integrated into the model by establishing a discount for the hub-hub links in the form of a percentage of the total link cost. Economies of terminal scale were also modelled in a later version of the model which captured an objective of terminal operators: achieving lower transhipment costs to attract more flows. Yamada et al. have introduced another multimodal FTIND model in a geographic scope of south-eastern Asia (Yamada et al., 2009). The model dealt with both freight and passengers by defining them as multiclass users. Congestion was modelled by a cost-and-delay function which correlated the time costs and the transport volumes over a link.

The decisions of shippers and government are simulated through multi-level programming. Groothedde et al. have developed a model for multimodal service network design (Groothedde et al., 2005). This model, to some extent, integrated the infrastructure network design (hub allocation) and the service network design (fleet design). It simulated the choices of the shipper who operated the transport service collaboratively.

Concluding from the above-mentioned state of the art of FTIND modelling, there is a lack of models able to simultaneously incorporate large-scale, multimodal, multicommodity, multiactor, and service networks. Therefore, a new model is formulated specifically aimed at fulfilling these new requirements, thus going beyond the existing models and answering the research question 3: *what freight transport network optimization model is needed to deal with all of the challenges following from Question 2 in an integrative approach.* The model supports design of infrastructure network while taking into account the objectives of multiple actors in freight transport. It optimizes the network performance from the governmental perspective aiming at minimizing the total network emissions and the total network costs. The cost economies which would be beneficial to the terminal operators and transport operators are taken into account as optimizing the economies of scale and economies of density for both terminals and hub-based barge services. Multiple types of commodities can be assigned over the European multimodal transport network including road, rail, and inland waterway. The pre-/end-haulage and hub-network-based networks are specified in the network particularly aiming to capture the features of relevant services better than the existing models. The optimization problem is solved by bi-level optimization, where the upper level searches for the optimal combinations of design measures, while the lower level performs multicommodity flow assignment over the large-scale multimodal network. The lower level optimization integrates the design of the infrastructure network and the service network in an iterative manner. The optimal fleet, frequency, and choice of the terminal use for each service in the service networks are determined based on the flows transported by the services, while the optimal flow routing are determined based on the minimized generalized costs of using the services.

Improvements in FTIND modelling, as mentioned above, facilitates combinations of design of the freight transport infrastructure networks with respect to pricing policies, terminal network configuration, and collaborative hub-based services. The model thereby enables integrated infrastructure, service, and policy design.

With an objective to make the FTIND contribute to the practice, the research question 4 is set up about H*ow to calibrate and validate the model for practical applications?* Both genetic-algorithm-based (GA-based) and feedback-based approaches are used to calibrate the multimodal flow assignment model. Calibrating the large-scale multimodal multicommodity flow assignment model is particularly difficult due to the large number of variables and the fact that each variable consists of many elements, in combination with the high requirements for availability of the reference data. The terminal handling costs, the average regional pre-/end-haulage costs, the average regional access/egress costs, the average mode-related transport costs of geographic links, and the commodity-related time costs, as calibration parameters, among a larger number of parameterizable variables influencing the model results.

It is found that both methods can achieve satisfactory results. The feedback-based method shows much better efficiency in computation time conditional to the reasonable feedback values (for example, set through preliminary experiments). The good fit between the modelled results and the observations of link flows, the stability test of the calibrated parameters, a sensitivity analysis, and a catchment area analysis show that the model was well calibrated for container transport in the Netherlands.

6.2 Implications for policy makers

The model developed in this thesis can be used to an integrated policy design, infrastructure design, and service design. The objectives of the design can be defined by the model users, for example to design a system with minimal emissions, or a system with minimal costs. The databases for transport demand, features of infrastructure network, information about selective services, and information about transport and transhipment costs, emissions and external costs, are embedded in the model. The data and results can be visualized per mode and per commodity value group on a Geographic Information System (GIS) at a segmental, terminal, corridor, regional, national, and network level.

In order to answer the last research question: H*ow can the newly developed model be applied in practice to the strategic planning of infrastructure networks,* it is implemented in the Dutch container transport network design problem. The CO_2 pricing, inland waterway terminal network configurations, the potential hub-service-networks, and their combinations are used, as the design measures to optimize the Dutch container transport infrastructure network respecting the objectives of reducing CO_2 emissions, and the total network costs. Supported by the new model, the goals of public authorities, transport/terminal operators, and shippers were taken into account. It optimized the infrastructure network performance which representing the goal of the government; optimized the terminal operators’ benefit gained from efficient use of terminal capacity; optimized the fleet use and service frequency for the transport operators; and searched for the optimal door-to-door routes for the shippers, in an integrated way. The results provided new insights into the interrelationships among the infrastructure network, service network, and regulatory policies, as well as the interaction among the different actors.

The results indicate that if CO_2 pricing policy is implemented to the Dutch container transport, a higher CO_2 price results in the lower total network internal costs, although the extra handling costs in intermodal transhipments. The reason is that rail and inland waterway transport generate lower CO_2 emissions per volume of freight over the same distance. The unit costs, taking into account the CO_2 emission costs, can be even lower than that for road transport. Under such conditions, some flows, which are currently transported by road, may be transported by rail or inland waterway, if CO_2 emissions are charged for a certain price. The unit handling costs decrease when inland terminals are better utilized when more flows are transhipped. However, even under these conditions, the costs saved from using intermodal transport cannot fully compensate the internalized CO_2 emission costs. The operational costs borne by transport operators have to increase if CO_2 emission reduction is going to be achieved by implementing the CO_2 pricing policy.

Therefore, as an alternative to charging CO_2 emissions, reconfiguring the terminal networks is analysed aiming at contributing to improving the overall network performance. It is found that the optimal terminal networks enable both lower total network costs and lower total network CO_2 emissions. The common characteristics of these optimized terminal networks indicate that the network efficiency can be increased by closing terminals not being able to attract sufficient volumes of demand. In practice, different interests of local governments or private terminal operators will however play a role. An optimal terminal network configuration is therefore not likely to be achieved in a short term.

Furthermore, the feasibility of several new hub-network-services is evaluated. The aim is to obtain insights into whether collaborative hub-network-services can contribute to achieving better network performance through a better utilization of terminal handling and transport fleet capacities. The results show that these hub-network-services assumed and tested cannot compete with road transport or the shuttle barge transport services in the base scenario due to the extra transhipment costs, low load factor, and low demand for IWW. The average load factor of the hub-network-services is vital for the hub utilization. Under the conditions assumed for implementing the model for Dutch container transport, the simple hub-and-spoke service between the northern part of the Netherlands and the sea terminals of Rotterdam and Antwerp would be feasible if the demand of IWW transport was increased dramatically.

The combinations of these design measures are further evaluated. This is also one of the main advantages of the new model. Implementing the combination of CO_2 pricing and terminal network configuration is more effective than solely implementing CO_2 pricing, especially in the scenarios where CO_2 emissions are charged at a low rate with regard to total network CO_2 emissions. The terminal network configurations broaden the range of efficient networks. A frontier of minimal total network costs and total network CO_2 emissions, instead of one single optimal solution is found. The frontier provides more options in optimization of the terminal network in terms of the target performance.

The results obtained from the evaluation of the hub-service-networks in combination with CO_2 pricing policies show that certain hub-network-services would receive flows, even when CO_2 is charged at a low rate. When prices for CO_2 increase further, the shuttle barge transport services become more competitive than the hub-network-services. However, from the results, follows that the hub-network-services under CO_2 pricing policies could improve the competitiveness of IWW transport against the rail transport. If the hub-network-services are not provided, the rail transport takes the modal shares from both IWW and road, under conditions of charging CO_2 emissions at a high rate. In the scenarios where the hub-network-services are optional, that is, when CO_2 prices are high, the IWW transport becomes more competitive as compared to the rail transport despite the fact that the hub-network-services lose their share to the shuttle barge transport services.

The evaluation analyses show that the combined effect of the three measures is more effective in reducing CO_2 emissions than the combination of CO_2 pricing and the terminal network configuration. In addition, if an optimal configuration of the terminal network could be achieved, and the transport operators would collaboratively provide appropriate hub-network-services to reduce CO_2 emissions through CO_2 pricing, an increase in total network costs may not happen.

There is not one single optimal future infrastructure network. Instead, a good infrastructure network design mainly depends on the future demand, transport price, and development of new transport technology. Intermodal transport networks can take advantage of this recent strong growth of maritime freight transport. However, the demand for intermodal transport capacity depends not only on the growth of the economy. Also, the configuration of the terminal networks will have an impact on the way in which the demand is going to be distributed in the multimodal transport network. Meanwhile, the terminal networks will also have to adapt to changes in the flow patterns in terms of geography and commodity type. The appropriate terminal network configurations, technological innovations in handling equipment and information technology may result in the new network services and consequently translate into that improvements in the intermodal service quality able to attract additional transport demand.

6.3 Recommendations for future research directions

In this thesis, on the basis of the literature on freight transport network design, the research objective was to: Develop *a model that supports intermodal freight network design, while taking into account design measures concerning transport infrastructure and services.* This objective was realized by developing a new model, which optimized the freight transport network performance by using a scenario-based approach. It assigned multicommodity flows to the multimodal network by simulating the decisions of multiple actors involved in the freight transport activities. During the development, validation, and application of the model, new research directions were identified as follows.

6.3.1 Further applications of the model

The model is generically applicable to freight transport infrastructure network design in terms of architecture, methods, and algorithms. In this thesis, the model dealt with optimization of the transport costs and CO_2 emissions by using the design measures of terminal network configuration, CO_2 price, and specific service networks. However, the model is not limited to these three design measures. Similarly it can evaluate alternatives to CO_2 pricing, fuel taxation, tolls, and tkm haulage tax. In addition, taxation, subsidization, alternative fuel, or electric vehicles, can also be considered as design measures. The measurement of externalities is not limited to CO_2. The model is also applicable to NO_x, noise, and traffic incidents/accidents with supplementary data. As mentioned earlier, the model users can set the design objectives in accordance with the model application. Evaluation of the network performance can be carried out at the link, terminal, regional, and/or network level, per mode, per commodity type, and/or a combination of the former. As a result, another not highlighted functionality of the model is the assessment of effectiveness and efficiency of different design measures. For example, the effect of different taxation schemes with similar internalized costs on CO_2 emissions can be compared.

In addition to the alternative design measures and objectives, new implementations can be carried out by different measures on commodity categorization. In the presented application, the commodities (containers) were categorized by their trade values in order to capture the impact of freight value on the decisions of the network use. The model also supports other methods of commodity categorization. Taking containers as an example, when containers as being empty or loaded, the model can be used for container balance optimization by repositioning the empty containers. Another example is to categorize the containers by size, for cases when mode choice is strongly dependent on the size of a container. In practice, intermodal transport is more competitive in the market of transporting 20-feet containers, while the operators prefer road transport for 40-feet containers. The main reason is that the rates for transporting 40-feet and 20-feet containers by road are comparable, while the rate for shipping a 40-feet container by barge is almost twice as expensive as for 20-feet container due to the number of slots occupying the barge. Furthermore, the implementation of the model can be broadened to design of the multimodal transport network for mixed flow of the maritime and continental containers. This can be achieved by categorizing the commodity types by maritime and continental containers, and specifying their specific requirements for transport network use, and specifying these two types of containers in the transport demand database. Including the continental containers into the existing maritime container transport network broadens the scope of network use. By deploying the modified model, the network can be analysed and optimized taking into account economies of scope. This may bring new benefits to the transport system.

6.3.2 Potential improvement of the model

In addition to extending the model to other applications, the potential for improving the model in terms of the quality of evaluation, reliability of prediction, and computation capability exist.

Reliable data and information are crucial for the large-scale simulations. Currently, there are a lot of data collected by new methods in addition to more traditional methods, such as, trade statistics, loop data, and border counts. Data collected by weight-in-motion devices provide the vehicles’ wheelbase and gross weights. By using these data, the passenger and freight flows on the road can be distinguished, and thus enabling obtaining the observations of freight flows, and the road capacity occupied by passenger transport over time. This data would be very useful in calibrating the road flows and quantifying the road capacity for freight transport.

In addition, the data collected via tracking and tracing devices would provide OD demand-based information. Currently, trade statistics only provide information about the amount of freight moved from origin to destination, without information on the route or any possible transhipment. Tracking and tracing data identify the transport route. Although it is not possible to track all freight, a sample of tracking and tracing data already enables validating specific assumptions on the mode, terminal, and/or route choice in the various situations and for different types of commodities.

Computing time is a challenge for all large-scale simulation models. Models can be infeasible due to long computing time. This is not the case for this model with the presented application. However, computing time does become a challenge in the context of network optimization where a large number of scenarios are initiated and evaluated iteratively. Based on the architecture of the model, it is possible to compute multiple scenarios simultaneously (i.e., in parallel), as well as simultaneously process different procedures such as scenario initiation and evaluation. Therefore, multithreading and distributed computing procedures can be utilized. Reconstructing the computation process of this model in batch mode would shorten the computation time substantially.

6.3.3 Extension of the model

During the development and implementation of the model, a vision on the future freight transport network design models is also obtained.

This model is a static model having advantages in the macroscopic analyses. However, some features of freight transport have to be ignored due to the fact that the static models are not able to capture the real-time dynamics in transport networks. A potential research direction is to incorporate time into the model. As a result, one would be able to capture dynamic demand (e.g., the transport demand variations throughout a day) and dynamic network supply (e.g., capacity limitations due to ship locks, rail capacity drop caused by prioritizing passenger trains, and limits on handling capacity due to time windows). Multiple actors would benefit from such model extension if the attributes of network dynamics are well captured. The shippers and transport operators would be able to use the model for tactical and operational planning. In case of shippers, this would, for instance, enable delivery planning incorporating inventory management. Another good example of the benefits from applying dynamic version of the model is the ability of transport operators to assess the scheduling of synchronized intermodal transport services. The terminal operators could predict the future demand, and the number of calls with estimation of the deviations of the actual time of arrival/departure from the scheduled time. Based on these accurate estimations at the operational level, a more realistic prediction would be possible at the system level for the strategic network design. A dynamic version of the model would furthermore enable more realistic estimations of transport emissions, and enable analyses of the network and/or service robustness.

References

Bai, R., Kendall, G., Qu, R., Atkin, J.A.D. (2012) 'Tabu assisted guided local search approaches for freight service network design', *Information Sciences*, 189(0), pp. 266-281.

Ballis, A., Golias, J. (2002) 'Comparative evaluation of existing and innovative rail-road freight transport terminals', *Transportation Research Part a - Policy and Practice*, 36(7), pp. 593-611.

Bauer, J., Bektas, T., Crainic, T.G. (2010) 'Minimizing greenhouse gas emissions in intermodal freight transport: An application to rail service design', *Journal of the Operational Research Society*, (61), pp. 530-542.

Beuthe, M., Bouffioux, C. (2008) 'Analysing Qualitative Attributes of Freight Transport from Stated Orders of Preference Experiment', *Journal of Transport Economics and Policy*, 42(1), pp. 105-128.

Beuthe, M., Degrandsart, F., Geerts, J.F., Jourquin, B. (2002) 'External costs of the Belgian interurban freight traffic: a network analysis of their internalisation', *Transportation Research Part D-Transport and Environment*, 7(4), pp. 285-301.

Beuthe, M., Jourquin, B., Geerts, J.F., Ha, C.K.A.N. (2001) 'Freight transportation demand elasticities: a geographic multimodal transportation network analysis', *Transportation Research Part E-Logistics and Transportation Review*, 37(4), pp. 253-266.

Black, I., Seaton, R., Ricci, A., Enei, R. (2003) 'Final Report for RECORDIT: Actions to Promote Intermodal transport'.

Borg, J. (1991) *Makrologistiska Studier*. Linkoping Institute of Technology, Sweden.

Brabant Intermodal (2012), Retrieved April 2013, from http://www.brabantintermodal.com/

Cargo, R. (2011) 'European Map of Intermodal Rail Terminals', Rail Cargo.

Caris, A., Macharis, C., Janssens, G.K. (2008) 'Planning problems in intermodal freight transport: Accomplishments and prospects', *Transportation Planning and Technology*, 31(3), pp. 277-302.

CBS (2006) 'Geharmoniseerde Databestanden 2006', Centraal Bureau voor de Statistiek Nederland, Heerlen.

CBS (2011) 'Transportation Survey', Centraal Bureau voor de Statistiek Nederland, Heerlen..

CEC (1995) 'COMMUNICATION FROM THE COMMISSION: The Common Transport Policy Action Programme 1995-2000', Commission of the European Communities, Brussels.

CEC (1997a) 'COMMUNICATION FROM THE COMMISSION: Intermodality and intermodal freight transport in the European Union. A system approach to freight transport. Strategies and actions to enhance efficiency, services and sustainability', Commission of the European Communities, Brussels.

CEC (1997b) 'GREEN PAPER: on Sea Ports and Maritime Infrastructure', Commission of the European Communities, Brussels.

CEC (1998) 'COM:MUNICATION FROM THE COM: The Common Transport Policy Sustainable Mobility: Perspectives for the Future', Commission of the European Communities, Brussels.

CEC (2003) 'DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures', Commission of the European Communities, Brussels.

CEC (2006a) 'COMMUNICATION FROM THE COMMISSION: Keep Europe moving – Sustainable mobility for our continent. Mid-term review of the European Commission’s 2001 Transport White Paper', Commission of the European Communities, Brussels.

CEC (2006b) 'COMMUNICATION FROM THE COMMISSION: on the Promotion of Inland Waterway Transport “NAIADES” An Integrated European Action Programme for Inland Waterway Transport', Commission of the European Communities, Brussels.

CEC (2006c) 'Keep Europe Moving - Sustainable Mobility for our Continent. Mid-term review of the European Commission’s 2001 Transport White Paper', Commission of the European Communities, Brussels.

CEC (2007) 'COMMUNICATION FROM THE COMMISSION: Freight Transport Logistics Action Plan ', Commission of the European Communities, Brussels.

CEC (2009) 'COMMUNICATION FROM THE COMMISSION: A sustainable future for transport: Towards an integrated, technology-led and user friendly system ', Commission of the European Communities, Brussels.

CEMT (1992) 'CEMT Classification of inland waterways', European Conference of Ministers of Transport, Retrieved March, 2010, from www.cemt.org

Centre for Transport and Navigation (2011) 'Freeway Infrastructure Capacity Manual (Handboek Capaciteitswaarden Infrastructuur Autosnelwegen)'.

Christopher, R.H., Jeffery, A.J., Michael, G.K. (1995) 'A Genetic Algorithm for Function Optimization: A Matlab Implementation', North Carolina State University.

Costa, L., Oliveira, P. (2004) 'An Elitist Genetic Algorithm for Multiobjective Optimization', *Metaheuristics*, Kluwer Academic Publishers.

Crainic, T.G. (2000) 'Service network design in freight transportation', *European Journal of Operational Research*, 122(2), pp. 272-288.

Crainic, T.G., Kim, K.H. (2007) 'Chapter 8 Intermodal Transportation', in Cynthia, B., Gilbert, L., *Handbooks in Operations Research and Management Science*, Elsevier.

Crainic, T.G., Laporte, G. (1997) 'Planning models for freight transportation', *European Journal of Operational Research*, 97(3), pp. 409-438.

Crainic, T.G., Rousseau, J.M. (1986) 'Multicommodity, Multimode Freight Transportation - a General Modeling and Algorithmic Framework for the Service Network Design Problem', *Transportation Research Part B-Methodological*, 20(3), pp. 225-242.

De Jong, G., Bakker, S., Pieters, M. (2004a) 'Hoofdonderzoek naar de Reistijdwaardering in het Vervoer van Goederen over de Weg', RAND Corporation, Pittsburgh.

De Jong, G., Bakker, S., Pieters, M., Wortelboer, P. (2004b) 'New values of time and reliability in freight transport in the Neterlands', *European Transport Conference*.

De Langen, P.W., Van Meijeren, J., Tavasszy, L.A. (2012) 'Combining Models and Commodity Chain Research for Making Long-Term Projections of Port Throughput: an Application to the Hamburg-Le Havre Range', *European Journal of Transport and Infrastructure Research*, 12(3), pp. 310-331.

Decisio (2002) 'Tussenevaluatie Subsidieregeling Openbare Inland Terminals, Eindrapportage', Amsterdam.

Dekker, R., Bloemhof, J., Mallidis, I. (2012) 'Operations Research for green logistics - An overview of aspects, issues, contributions and challenges', *European Journal of Operational Research*, 219(3), pp. 671-679.

Dijkstra, E.W. (1959) 'A note on two problems in connexion with graphs', *Numerische Mathematik*, 1(1), pp. 269-271.

EC (1992) 'WHITE PAPER: The Future Development of the Common Transport Policy: A Global Approach to the Construction of a Community Framework for Sustainable Mobility', European Communities, Luxembourg.

EC (1999a) 'COMMUNICATION FROM THE COMMISSION: The Development of Short Sea Shipping in Europe: A Dynamic Alternative in a Sustainable Transport Chain Second Two-yearly Progress Report', European Communities, Brussels.

EC (1999b) 'DIRECTIVE 1999/62/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 June 1999 on the charging of heavy goods vehicles for the use of certain infrastructures', *Official Journal of the European Communities*, (L 187), pp. 42-50.

EC (2001) 'WHITW PAPER: European transport policy for 2010: time to decide', European Commission, Luxembourg.

EC (2002) 'EU Intermodal Freight Transport Key Statistical Data 1992-1999', European Commission, Luxembourg.

EC (2006) 'DIRECTIVE 2006/38/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures', *Official Journal of the European Union*, L 157, pp. 8-23.

EC (2008) 'DECISION No 70/2008/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 January 2008 on a paperless environment for customs and trade', *Official Journal of the European Union*, (L 23), pp. 21-26.

EC JRC IPTS (2005) 'Transtools', IPTS, E.J., © 2008 EC JRC IPTS.

Edwards, J.D., Engineers, I.o.T. (1999) *Transportation planning handbook*. Institute of Transportation Engineers.

EEA (2012) *Greenhouse gas emission trends and projections in Europe 2012: Tracking progress towards Kyoto and 2020 targets*, Luxembourg.

EICB (2013) 'Dutch Container Terminal Database', Expertise and Innovation Centre Inland Waterway.

Ernst, A.T., Krishnamoorthy, M. (1998) 'Exact and heuristic algorithms for the uncapacitated multiple allocation p-hub median problem', *European Journal of Operational Research*, 104(1), pp. 100-112.

Escudero, A., Raicu, R., Muñuzuri, J., Delgado, M.d.C. (2010) 'Dynamic optimisation of urban intermodal freight transport with random transit times, flexible tasks and time windows', *Procedia - Social and Behavioral Sciences*, 2(3), pp. 6109-6117.

Eurostat (2006) 'Euro Geographics for the administrative boundaries', http://epp.eurostat.ec.europa.eu/.

Eurostat (2011) 'Glossary: Country Codes', Retrieved December, from http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:Country_codes
Eurostat, JRC, EFGS, REGIO-GIS (2010) 'NUTS Classification'.

Friesz, T.L., Gottfried, J.A., Morlok, E.K. (1986) 'A SEQUENTIAL SHIPPER-CARRIER NETWORK MODEL FOR PREDICTING FREIGHT FLOWS', *Transportation Science*, 20(2), pp. 80-91.

Geerlings, H., Van Duin, R. (2011) 'A new method for assessing CO2-emissions from container terminals: a promising approach applied in Rotterdam', *Journal of Cleaner Production*, 19(6-7), pp. 657-666.

Geerts, J.-F., Jourquin, B. (2001) 'Freigth Transportation Planning on the European Multimodal Network: the case of the Walloon Region', *European Journal of Transport and Infrastructure Reseach*, 1(1), pp. 91 - 106.

Giorgi, L., Schmidt, M. (2002) 'European transport policy--a historical and forward looking perspective', *German Policy Studies*, 2(4).

Goldberg, D.E. (1989a) *Genetic Algorithms in Search, Optimization and Machine Learning*, 1st ed. Addison-Wesley Professional.

Goldberg, D.E. (1989b) 'Genetic Algorithms in Search, Optimization, and Machine Learning', Addison-Wesley Professional.

Gorman, M.F. (2008) 'Evaluating the public investment mix in US freight transportation infrastructure', *Transportation Research Part A: Policy and Practice*, 42(1), pp. 1-14.

Groothedde, B., Ruijgrok, C., Tavasszy, L. (2005) 'Towards collaborative, intermodal hub networks - A case study in the fast moving consumer goods market', *Transportation Research Part E-Logistics and Transportation Review*, 41(6), pp. 567-583.

Guelat, J., Florian, M., Crainic, T.G. (1990) 'A multimode muliproduct network assignment model for strategic-planning of freight flows', *Transportation Science*, 24(1), pp. 25-39.

Harker, P.T., Friesz, T.L. (1986a) 'Prediction of intercity freight flows, I: Theory', *Transportation Research Part B: Methodological*, 20(2), pp. 139-153.

Harker, P.T., Friesz, T.L. (1986b) 'Prediction of intercity freight flows, II: Mathematical formulations', *Transportation Research Part B: Methodological*, 20(2), pp. 155-174.

Helmreich, S., Keller, H. (2011) *FreightVision - Sustainable European Freight Transport 2050*. Springer.

Hoen, K.M.R., Tan, T., Fransoo, J.C., Houtum, G.J. (2012) 'Effect of carbon emission regulations on transport mode selection under stochastic demand', *Flexible Services and Manufacturing Journal*, pp. 1-26.

Holtrop, J., Mennen, G.G.J. (1982) 'An Approximate power prediction method,' *International Shipbuilding Progress*, 7, pp. 1660-170.

Horner, M.W., O'Kelly, M.E. (2001) 'Embedding economies of scale concepts for hub network design', *Journal of Transport Geography*, 9(4), pp. 255-265.

Janic, M. (2006) 'Sustainable Transport in the European Union: A Review of the Past Research and Future Ideas', *Transport Reviews*, 26, pp. 81-104.

Janic, M. (2007) 'Modelling the full costs of an intermodal and road freight transport network', *Transportation Research Part D-Transport and Environment*, 12(1), pp. 33-44.

Jonkeren, O., Jourquin, B., Rietveld, P. (2011) 'Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area', *Transportation Research Part a-Policy and Practice*, 45(10), pp. 1007-1019.

Jourquin, B. (1995) 'Un outil d'analyse economique des transports de marchandises sur des reseaux multimodaux et multi-produits: le reseau virtuel, concepts, mtthodes et applications', Universitaires Catholiques de Mons, Mons, Belgium.

Jourquin, B. (2005) 'A multi-flow multi-modal assignment procedure on large freight transportation networks', *Studies in Regional Science*, 35(4), pp. 929-946.

Jourquin, B., Beuthe, M. (1996) 'Transportation policy analysis with a geographic information system: The virtual network of freight transportation in Europe', *Transportation Research Part C-Emerging Technologies*, 4(6), pp. 359-371.

Jourquin, B., Beuthe, M., Demilie, C.L. (1999) 'Freight bundling network models: Methodology and application', *Transportation Planning and Technology*, 23(2), pp. 157-177.

Jourquin, B., Iassinovskaia, G., Lechien, J., Pinna, J., Usai, F. (2009a) 'Lines and services in a regional multi-modal transport model: the case of the regional express network around Brussels', *Bivec-Gibet Transport Research Day*, Brussels.

Jourquin, B., Iassinovskaia, G., Usai, F. (2009b) 'TranslogisTIC : Délivrable WP6.2'.

Kim, B.J., Kim, W. (2006) 'An equilibrium network design model with a social cost function for multimodal networks', *Annals of Regional Science*, 40(3), pp. 473-491.

Kim, N.S., Van Wee, B. (2009) 'Assessment of CO2 emissions for truck-only and rail-based intermodal freight systems in Europe', *Transportation Planning and Technology*, 32(4), pp. 313-333.

Konings, R., Priemus, H., Nijkamp, P. (2008) *The Future of Intermodal Freight Transport: operations, design and policy*. Edward Elgar, Cheltenham.

Kreutzberger, E.D. (2008) 'Distance and time in intermodal goods transport networks in Europe: A generic approach', *Transportation Research Part a - Policy and Practice*, 42(7), pp. 973-993.

Li, F., Liu, T., Zhang, H., Cao, R., Ding, W., Fasano, J.P. (2008) 'Distribution center location for green supply chain', *Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on*.

Limbourg, S., Jourquin, B. (2009) 'Optimal rail-road container terminal locations on the European network', *Transportation Research Part E: Logistics and Transportation Review*, 45(4), pp. 551-563.

Magnanti, T.L., Wong, R.T. (1984) 'Network Design and Transportation-Planning - Models and Algorithms', *Transportation Science*, 18(1), pp. 1-55.

Manheim, M.L. (1979) *Fundamentals of Transport Systems Analysis*. MIT Press, Cambridge.

Meng, Q., Wang, X. (2011) 'Intermodal hub-and-spoke network design: Incorporating multiple stakeholders and multi-type containers', *Transportation Research Part B: Methodological*, 45(4), pp. 724-742.

Michalewicz, Z. (1996) *Genetic Algorithms + Data Structures = Evolution Programs*. Springer, USA.

Middendorf, D. (1998) 'Intermodal Terminals Database: Concepts, Design, Implementation, and Maintenance. Prepared for Bureau of Transportation Statistics U.S. Department of Transportation', in Center for Transportation Analysis, E.D., Oak Ridge National Laboratory (ed), Oak Ridge.

Middendorf, D., Bronzini, M.S., Peterson, B.E., Liu, C., Chin, S.-M. (1995) 'Estimation and validation of mode distances for the 1993 Commodity Flow Survey', *the 37th Annual Transportation Research Forum*, Reston.

Ministry of Infrastructure and the Environment (2002) 'Subsidieregeling openbare inland terminals', in Environment, M.o.I.a.t. (ed), Ministry of Infrastructure and the Environment, Den Haag.

Morton O'Kelly, Darko Skorin-Kapov , Jadranka Skorin-Kapov (1995) 'Lower Bounds for the Hub Location Problem', *Management Science*, 41(4), pp. 713-721.

Nash, C., with contributions from partner (1999) 'UNITE (UNIfication of accounts and marginal costs for Transport Efficiency) Final Report for Publication ', Programme, t.F.R.

NEA (2003) 'Onderzoek Kosten per uur in de Binnenvaart', NEA, Rijswijk.

NEA (2004) 'Factorkosten van het Goederenvervoer: Een Analyse van de Ontwikkeling in de Tijd', NEA, Rijswijk.

NEA, Sterc, Transcare (2001) 'Vergelijkingskader modaliteiten', Rijswijk.

NEA, TNO, TUDelft (2013) 'Multimodaal Internationaal container netwerk (IDVV Spoor 3, Cluster 3, WP3.2) ', the Netherlands.

Notteboom, T. (2007) 'Inland waterway transport of containerised cargo', *Journal of Maritime Research*, 4(2), pp. 63-80.

O'Kelly, M.E., Bryan, D.L. (1998) 'Hub location with flow economies of scale', *Transportation Research Part B: Methodological*, 32(8), pp. 605-616.

Ortuzar, J.d.D., Willumsen, L.G. (2011) *Modelling Transport, Chapter 11: Equilibrium and Dynamic Assignment*, 4th ed. John Wiley & Sons, Ltd.

Oum, T.H., Waters, W.G. (1996) 'A survey of recent developments in transportation cost function research', *Logistics and Transportation Review*, 32(4), pp. 423-463.

Panzar, J.C., Willig, R.D. (1977) 'Economies of Scale in Multi-Output Production', *The Quarterly Journal of Economics*, 91(3), pp. 481-493.

POR (2007) 'Port ROT container by region by incoming outgoing 2007'.

POR (2008a) 'Port ROT modal split container thp_2004-2008'.

POR (2008b) 'Port Statistics 2004-2007'.

POR (2009) 'Steering the Feeders', *Port Special*, Port of Rotterdam, Rotterdam.

POR (2011) '50% more trains on the Betuwe Route', from http://www.portofrotterdam.com/en

/News/pressreleases-news/Pages/50-trains-betuwe-route.aspx

Powell, W.B., Sheffi, Y. (1983) 'The Load Planning Problem of Motor Carriers - Problem Description and a Proposed Solution Approach', *Transportation Research Part a-Policy and Practice*, 17(6), pp. 471-480.

Powell, W.B., Sheffi, Y. (1989) 'Design and Implementation of an Interactive Optimization System for Network Design in the Motor Carrier Industry', *Operations Research*, 37(1), pp. 12-29.

Racunica, I., Wynter, L. (2005) 'Optimal location of intermodal freight hubs', *Transportation Research Part B: Methodological*, 39(5), pp. 453-477.

Sharma, S., Ukkusuri, S.V., Mathew, T.V. (2009) 'Pareto Optimal Multiobjective Optimization for Robust Transportation Network Design Problem', *Transportation Research Record*, (2090), pp. 95-104.

Sheffi (1985) *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice-Hall, New Jersey.

Site, P.D., Salucci, M.V. (2009) 'Thematic Research Summary Freight Transport'.

Skorin-Kapov, D., Skorin-Kapov, J., O'Kelly, M. (1996) 'Tight linear programming relaxations of uncapacitated p-hub median problems', *European Journal of Operational Research*, 94(3), pp. 582-593.

Southworth, F., Peterson, B.E. (2000) 'Intermodal and international freight network modeling', *Transportation Research Part C: Emerging Technologies*, 8(1-6), pp. 147-166.

Southworth, F., Xiong, D., Middendorf, D. (1997) ' Development of analytic intermodal freight networks for use within a GIS', *Grographic Information Systems for Transportation Symposium*, American Association of State Highway and Transportation Officials, Washington, DC.

Spears, W.M., De Jong, K.A. (1991) 'On the Virtues of Parameterized Uniform Crossover', *The Fourth International Conference on Genetic Algorithms*, Morgan Kaufman.

Stada, J., Hauwert, S. (1992) 'Informatiesysteem Goederenstromen Europa (ISG)', Delft University of Technology, Faculty Civil Engineering and Geosciences.

StatLine (2006) 'International Trade ', Centraal Bureau voor de Statistiek, from statline.cbs.nl

Tavasszy, L. (1996) 'Modeling European Freight Transport Flows', *Faculty of Civil Engineering*, Delft University of Technology, Delft.

Tavasszy, L.A., Bruzelius, N. (2005a) 'The value of freight transport time: a logistics perspective - state of the art and research challenges', *ECMT Round Table 127: Time and Transport*, ECMT, Brussels.

Tavasszy, L.A., Bruzelius, N. (2005b) 'The value of freight transport time: a logistics perspective - state of the art and research challenges', *ECMT Round Table 127: Time and Transport*, Brussels.

TE (2010) 'CO2 emissions from transport in the EU27: An analysis of 2008 data submitted to the UNFCCC', European Federation for Transport and Environment, Brussels.

Visser, J., Francke, J., Gordijn, H. (2012) 'Multimodale Achterlandknooppunten in Nederland: Een Studie naar Containeroverslagterminals in het Achterland van Nederlandse Zeehavens', Ministerie van Infrastructuur en Milieu.

Wandel, S. (1992) 'Towards a theoretical framework for analyzing interrelations between shifts in logistics, transport, informatics and infrastructure', *6th World Conference of Transport Research*, Lyon.

Wardlaw, R., Sharif, M. (1999) 'Evaluation of genetic algorithms for optimal reservoir system operation', *Journal of Water Resources Planning and Management-Asce*, 125(1), pp. 25-33.

Wieberneit, N. (2008) 'Service network design for freight transportation: a review', *Or Spectrum*, 30(1), pp. 77-112.

Woxenius, J. (2007) 'Generic framework for transport network designs: Applications and treatment in intermodal freight transport literature', *Transport Reviews*, 27(6), pp. 733-749.

Woxenius, J., Persson, J.A., Davidsson, P. (2013) 'Utilising more of the loading space in intermodal line trains - Measures and decision support', *Computers in Industry*, 64(2), pp. 146-154.

Yamada, T., Russ, B.F., Castro, J., Taniguchi, E. (2009) 'Designing Multimodal Freight Transport Networks: A Heuristic Approach and Applications', *Transportation Science*, 43(2), pp. 129-143.

Zamparini, L., Reggiani, A. (2007) 'Freight Transport and the Value of Travel Time Savings: A Meta-analysis of Empirical Studies', *Transport Reviews: A Transnational Transdisciplinary Journal*, 27(5), pp. 621 - 636.

Appendix I.

Examples of visualized information in geographic information system

(see next page)

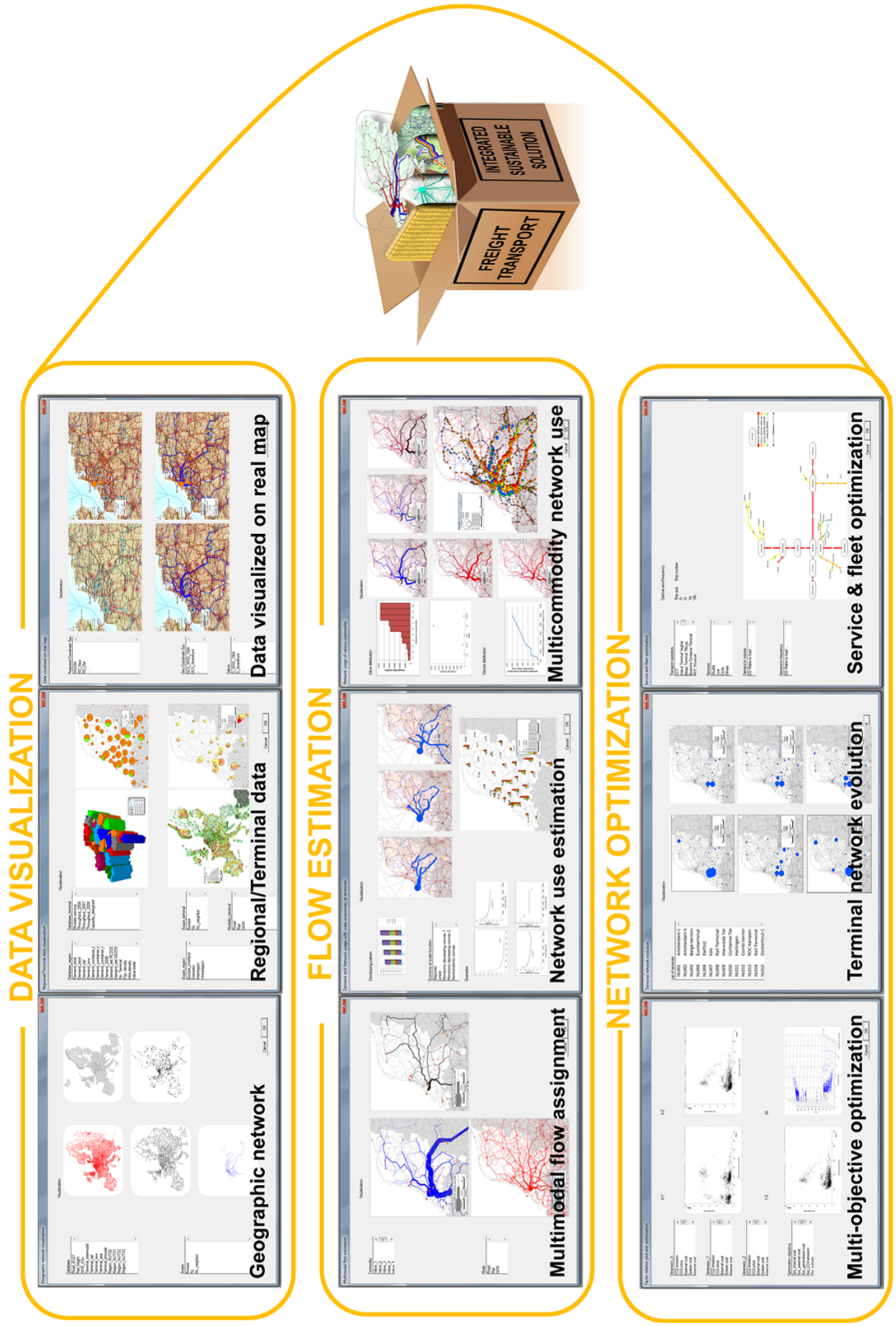


Figure I.1 Examples of visualized information in GIS

Appendix II.

Node attributes and link attributes defined in the network specification

Table II.1. Node attributes defined in the network specification of the model

Node attributes	Geo nodes	Terminals	Centroids
Node ID	x	x	x
Longitude	x	x	x
Latitude	x	x	x
Node type	x	x	x
Modalities served		x	
Terminal ID		x	
Centroid ID			x
Terminal Name*		x	

Note: * Only available where relevant information is available

Table II.2. Link attributes defined in the network specification of the model

Link attributes	Geo road	Geo rail	Geo IWW	Tranship-ment	Pre-/ end-haulage	Access/ egress	Service IWW*
Link ID	x	x	x	x	x	x	x
Length	x	x	x	x	x	x	x
Modality	x	x	x	x	x	x	x
Modalities served				x	x		
ID of the terminal connecting				x	x		
ID of the centroid connecting					x	x	
Unit internal costs	x	x	x	x	x	x	x
Unit CO_2 costs	x	x	x	x	x	x	x
Unit CO_2 emissions	x	x	x	x	x	x	x
Unit external costs	x	x	x	x	x	x	x
Total internal costs	x	x	x	x	x	x	x
Total costs	x	x	x	x	x	x	x
Capacity	x	x	x	x	x	x	x
Speed	x	x	x	x	x	x	x
Average VOT	x	x	x	x	x	x	x
Total costs	x	x	x	x	x	x	x
CO_2 price	x	x	x	x	x	x	x
Terminal throughput				x			
National name	x						
European name	x						
Road class	x						
Cross border*		x	x				x
Country	x	x	x	x	x	x	x
Border counts*		x					
Ship lock counts*			x				

Note: * Only available where relevant information are available; IWW = inland waters

Appendix III.

Flow Chart of the Optimization Module

Chapter 3 introduces the mathematical specification, and optimization process of the present freight transport infrastructure network design model. As shown in Figure 3.5, the model is structured by several modules. In this way, the users are able to choose some or all of the modules according to their needs in the decision-making. The following flow chart describes the detailed computing process for the optimization of the terminal network for the Dutch container transport. All-or-nothing and genetic algorithms are used for flow assignment and optimization, respectively. The model provides more algorithms. User equilibrium, stochastic user equilibrium, system optimization are optional for flow assignment. Random search, simulated annealing, and different strategies for genetic algorithm are available for optimization programming.

The model is coded in GISDK in TransCAD®. Four groups of output will be generated during running the programme: (1) the network performance in each scenario; (2) the terminal network configurations in each scenario; (3) the throughput of each terminal resulted from the terminal network configuration; and (4) performance of the optimization programming. Summaries of the possible output are listed in the tables following the flow chart.

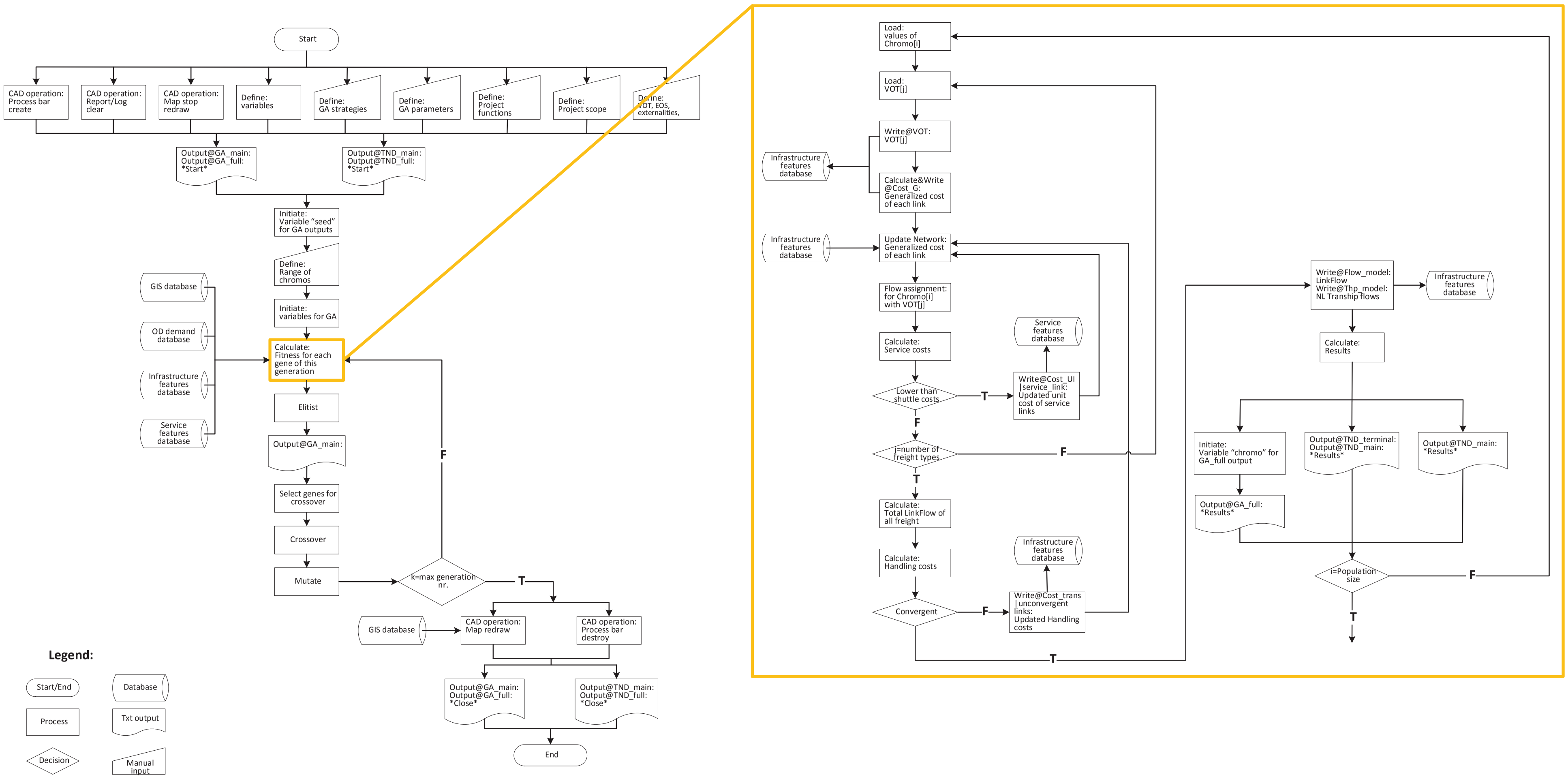


Figure III.1. Flow chart of the optimization module

Table III.1. Summary of the output information of the model

Summary of the network performance of each scenario:
Start
Start date and time
Annotation
Number of variables
Population size
Maximum of generations
Probability of crossover
Probability of mutation
Project scope
VOT
Defined threshold of VOT groups
Freight volume of each VOT group
CO_2 price
About the entire network:
The number of the current generation
CO_2 price
Total network CO_2 emissions
Total network costs
Total network internal costs
Total network external costs
Total network handling costs
Total network rail handling costs
Total network barge handling costs
Total network tkm
Total network tkm over road
Total network tkm over rail
Total network tkm over IWW
total network tkm of uni-modal-road transport
Total network tkm of access/egress
Total network tkm of pre-/end-haulage
Total network tkm share of road transport
Total network tkm share of rail transport
Total network tkm share of IWW transport
Total network tkm share of pre-/end-haulage
Total network tonne throughput of transhipment
Total network tonne throughput of rail transhipment
Total network tonne throughput of IWW transhipment
Total network tonne of uni-modal-road transport
Total network tonne over road

Total network tonne over rail
Total network tonne over IWW
Total network modal-share of road
Total network modal-share of rail
Total network modal-share of IWW
Total network unit cost of transhipment
Total network unit cost of IWW transhipment
About the Dutch network:
NL CO_2 emissions
NL total costs
NL internal costs
NL external costs
NL handling costs
NL rail handling costs
NL barge handling costs
NL tkm
NL tkm over road
NL tkm over rail
NL tkm over IWW
NL tkm of uni-modal-road transport
NL tkm of access/egress
NL tkm of pre-/end-haulage
NL tkm share of road transport
NL tkm share of rail transport
NL tkm share of IWW transport
NL tkm share of pre-/end-haulage
NL tonne throughput of transhipment
NL tonne throughput of rail transhipment
NL tonne throughput of IWW transhipment
Total network tonne of uni-modal-road transport
NL tonne over road
NL tonne over rail
NL tonne over IWW
NL modal-share of road
NL modal-share of rail
NL modal-share of IWW
NL unit cost of transhipment
NL unit cost of IWW transhipment
NL total number of IWW terminals in operation
NL average terminal throughput
NL average IWW terminal throughput
NL unit cost of transhipment

NL unit cost of rail transhipment
NL unit cost of IWW transhipment
NL number of IWW terminals in operation per terminal scale
The terminal network configuration of the current scenario
About service network:
Total service network tkm
The cost multiplier of each service leg comparing to shuttle barge
The cost of each service leg
The load factor of each service leg
The flow over each service leg
The accurate frequency of each service
The minimum number of barges operating for each service
The maximum number of trips of each service
End date and time
End

Terminal network and the throughput of each terminal:

Start
Start date and time
Annotation
Number of variables
Population size
Maximum of generations
Probability of crossover
Probability of mutation
Project scope
VOT
Defined threshold of VOT groups
Freight volume of each VOT group
CO_2 price
The number of the current scenario
The number of the current terminal
The throughput of the current terminal
CO_2 price
The terminal network configuration of the current scenario
End date and time
End

Full report of GA optimization:
Start
Start date and time
Annotation
Number of variables
Population size
Maximum of generations
Probability of crossover
Probability of mutation
The number of the current generation
The number of the current gene
CO_2 price
Value of the objective function of this gene
The chromosomes of this gene
End date and time
End

Summary of the seed of each generation in GA optimization:
Start
Start date and time
Annotation
Number of variables
Population size
Maximum of generations
Probability of crossover
Probability of mutation
The number of the current generation
CO_2 price
Minimum value of the objective function of this generation
The seed of this generation
End date and time
End

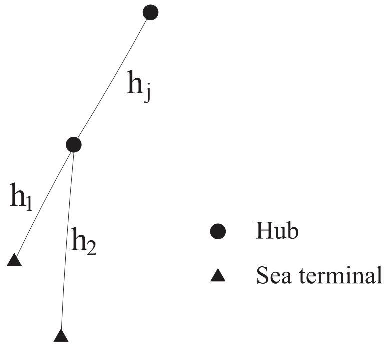
Appendix IV.

Examples of cost functions for service links

The volumes of transport demand and the required frequency of service determine the unit transport cost of a terminal-to-terminal service. Based on the actual situation of the Dutch inland waterway container transport, we assumed that the hub-based services are only provided between inland terminals and sea terminals. No hub-based service is provided to continental flows. In addition, the cost functions for hub-based services are simplified by applying the following assumptions:

- Only the barges with the largest navigable capacity are used on each service leg (the connection between two adjacent terminals);
- The barges deployed are maximally utilized at an annual scale;
- The cost parameters c^F, c^D, t^H are independent from the load factor of a barge.

Hub-hub or hub-sea terminal



Unit cost of a service link connecting hub-hub or hub-sea terminal, measured in euro per tkm, are described as follows.

$$\boldsymbol{c_{h_j}} = \frac{\boldsymbol{c^F_{h_j} \cdot n_{h_j} + [2 \cdot c^D_{h_j} \cdot d_{h_j} + c^T_{h_j} \cdot (t^H_{h_j} + t^S_{h_j})] \cdot k_{h_j}}}{\boldsymbol{v_{h_j} \cdot d_{h_j}}}, \forall \boldsymbol{j} \in \boldsymbol{M} \qquad \textbf{(IV-1)}$$

where

Variables:

h_j: a link connecting two hubs or connecting a hub and a sea terminal;

M: is the set consisting of all the hub-hub and hub-sea terminal links;

$c^F_{h_j}$: annual fixed costs per barge per year of the barges operating over link h_j, $c^F_{h_j} = f(z_{h_j})$;

z_{h_j}: the maximum barge size which is navigable over link h_j;

n_{h_j}: the number of barges needed over link $h_j\ to\ supply\ the\ demand$, $n_{h_j} = f(z_{h_j}, \upsilon_{h_j})$;

$c^D_{h_j}$: transport costs of moving containers over link h_j, measured in euro per tkm, $c^D_{h_j} = f(z_{h_j}, \upsilon_{h_j})$;

υ_{h_j}: average speed of the barges operating over link h_j;

d_{h_j}: length of link h_j;

$c^T_{h_j}$: time costs of moving containers over h_j, measured in euro per t-hour, $c^T_{h_j} = f(z_{h_j})$;

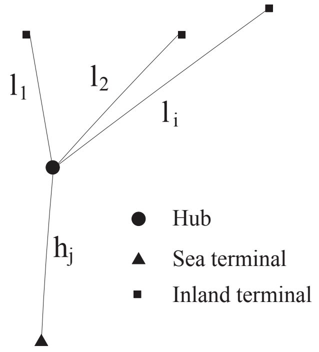
$t^H_{h_j}$: total handling time of a round trip over link h_j;

$t^S_{h_j}$: total shipping time of a round trip over link h_j;

k_{h_j}: total annual transport capacity of the n_{h_j} barges in condition of full load and operating at the maximum number of voyages, measured in tonnes, $k_{h_j} = f(z_{h_j}, \upsilon_{h_j}, d_{h_j})$;

ν_{h_j}: the flow over link h_j.

Simple hub-and-spoke service



Unit cost of a service link as a part of a hub-and-spoke service connecting hub and inland terminal are described as follows.

$$\boldsymbol{c_{l_i} = \frac{c^F_{l_i} \cdot n_{l_i} + \left[2 \cdot c^D_{l_i} \cdot d_{l_i} + c^T_{l_i} \cdot \left(t^H_{l_i} + t^S_{l_i}\right)\right] \cdot k_{l_i} + \sum_{j=1}^{M} (c_{h_j} \cdot \nu_{l_i h_j} \cdot d_{h_j})}{\sum_{j=1}^{M} [\nu_{l_i h_j} \cdot (d_{l_i} + d_{h_j})]}}, \qquad \textbf{(IV-2)}$$

$$\forall\, \boldsymbol{i} \in \boldsymbol{N}, \textbf{ and } \mathbf{j} \in \boldsymbol{M}$$

where

Variables:

l_i: a link connecting an inland terminal with a hub. N is the set consisting of the spokes in this hub-and-spoke network;

$c_{l_i}^F$: annual fixed costs per barge per year of the barges operating over link l_i, $c_{l_i}^F = f(z_{l_i})$;

z_{l_i} : the maximum barge size which is navigable over link l_i;

n_{l_i} : the number of barges needed over link l_i *to supply the demand*, $n_{l_i} = f(z_{l_i}, \upsilon_{l_i})$;

$c_{l_i}^D$: transport costs of moving containers over link l_i, measured in euro per tkm, $c_{l_i}^D = f(z_{l_i}, \upsilon_{l_i})$;

υ_{l_i} : average speed of the barges operating over link l_i;

d_{l_i} : length of link l_i;

$c_{l_i}^T$: time costs of moving containers over l_i, measured in euro per t-hour, $c_{l_i}^T = f(z_{l_i})$;

$t_{l_i}^H$: total handling time of a round trip over link l_i;

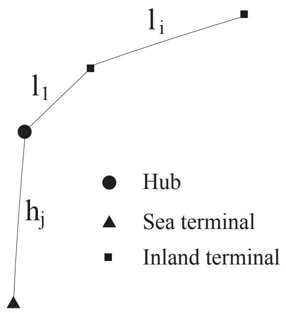
$t_{l_i}^S$: total shipping time of a round trip over link l_i;

k_{l_i} : total annual transport capacity of the n_{l_i} barges in condition of full load and operating at the maximum number of voyages, measured in tonnes, $k_{l_i} = f(z_{l_i}, \upsilon_{l_i}, d_{l_i})$;

ν_{l_i} : the flow over link l_i;

$\nu_{l_i h_j}$: the flow over link l_i and link h_j.

Hub-and-spoke with pickup-and-delivery service



Unit cost of a service link as a part of a pickup-and-delivery service is described as follows.

$$\boldsymbol{c_{l_i}} = \frac{\boldsymbol{c^F_{l_i} \cdot n_{l_i} + \sum_{i=1}^{O}\{[2 \cdot c^D_{l_i} \cdot d_{l_i} + c^T_{l_i} \cdot (t^H_{l_i} + t^S_{l_i})] \cdot k_{l_i}\} + \sum_{j=1}^{M}(c_{h_j} \cdot (\nu_{lh_j} \cdot d_{h_j})}}{\boldsymbol{\sum_{j=1}^{M}[\nu_{lh_j} \cdot (d_{l_i} + d_{h_j})]}}, \qquad \textbf{(IV-3)}$$

$$\forall\, \boldsymbol{i \in O}, \textbf{ and j} \in \boldsymbol{M}$$

where

Variables:

l_i: a link connecting an inland terminal with a hub. N is the set consisting of the spokes in this hub-and-spoke network;

$c^F_{l_i}$: annual fixed costs per barge per year of the barges operating over link l_i, $c^F_{l_i} = f(z_{l_i})$;

z_{l_i} : the maximum barge size which is navigable over link l_i;

n_{l_i} : the number of barges needed over link l_i *to supply the demand*, $n_{l_i} = f(z_{l_i}, \upsilon_{l_i})$;

$c^D_{l_i}$: transport costs of moving containers over link l_i, measured in euro per tkm, $c^D_{l_i} = f(z_{l_i}, \upsilon_{l_i})$;

υ_{l_i} : average speed of the barges operating over link l_i;

d_{l_i} : length of link l_i;

$c^T_{l_i}$: time costs of moving containers over l_i, measured in euro per t-hour, $c^T_{l_i} = f(z_{l_i})$;

$t^H_{l_i}$: total handling time of a round trip over link l_i;

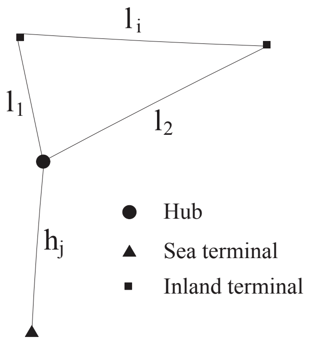
$t^S_{l_i}$: total shipping time of a round trip over link l_i;

k_{l_i} : total annual transport capacity of the n_{l_i} barges in condition of full load and operating at the maximum number of voyages, measured in tonnes, $k_{l_i} = f(z_{l_i}, \upsilon_{l_i}, d_{l_i})$;

ν_{l_i} : the flow over link l_i;

$\nu_{l_i h_j}$: the flow over link l_i and link h_j.

Hub-and-spoke with circular-pickup-and-delivery service



Unit cost of a service link as a part of a circular-pickup-and-delivery service, is described as follows.

$$\mathbf{c_{l_i}} =$$

$$\frac{\mathbf{c^F_{l_i} \cdot n_{l_i} + \sum_{i=1}^{P}\{[2 \cdot c^D_{l_i} \cdot d_{l_i} + c^T_{l_i} \cdot (t^H_{l_i} + t^S_{l_i})] \cdot k_{l_i}\} + \sum_{j=1}^{M}(c_{h_j} \cdot (\nu_{lh_j} \cdot d_{h_j})}}{\mathbf{\sum_{o=1}^{Q}\sum_{d=1}^{R}(\nu_{od} \cdot d_{od})}}, \qquad \textbf{(IV-4)}$$

$$\forall\, \mathbf{i \in P, j \in M, o \in Q, d \in R}$$

where

Variables:

l_i: a link connecting an inland terminal with a hub. P is the set consisting of the links in this hub-and-circle network;

$c^F_{l_i}$: annual fixed costs per barge per year of the barges operating over link l_i, $c^F_{l_i} = f(z_{l_i})$;

z_{l_i} : the maximum barge size which is navigable over link l_i;

n_{l_i} : the number of barges needed over link l_i *to supply the demand*, $n_{l_i} = f(z_{l_i}, v_{l_i})$;

$c^D_{l_i}$: transport costs of moving containers over link l_i, measured in euro per tkm, $c^D_{l_i} = f(z_{l_i}, \upsilon_{l_i})$;

υ_{l_i} : average speed of the barges operating over link l_i;

d_{l_i} : length of link l_i;

$c^T_{l_i}$: time costs of moving containers over l_i, measured in euro per t-hour, $c^T_{l_i} = f(z_{l_i})$;

$t^H_{l_i}$: total handling time of a round trip over link l_i;

$t_{l_i}^S$: total shipping time of a round trip over link l_i;

k_{l_i} : total annual transport capacity of the n_{l_i} barges in condition of full load and operating at the maximum number of voyages, measured in tonne, $k_{l_i} = f(z_{l_i}, \upsilon_{l_i}, d_{l_i})$;

ν_{l_i} : the flow over link l_i;

ν_{lh_j} : the flow over line l and link h_j, $\nu_l = \sum \nu_{l_i}$, $i \in O$;

ν_{od} : the flow between inland terminal o and sea terminal d. Q is the set consisting of the inland terminals in this hub-and-circle network. R is the set consisting of the sea terminals which have flows to/from one of the inland terminals of this hub-and-circle network;

d_{od} : the distance between inland terminal o and sea terminal d.

Summary

"The goal of the European Transport Policy is to establish a sustainable transport system that meets society's economic, social and environmental needs…" (ECE, 2009). This statement indicates the challenges that the European transport policy makers are faced with when facilitating an increasing freight transport demand with limited transport infrastructures. The development of an interconnected intermodal transport system has been recognized by the European Commission as an important, strategic task that will contribute to solving the dilemma between the accommodation of an increased freight flow and the need for a sustainable living environment.

This thesis focuses on model-based, quantitative analysis for infrastructure network design decisions for large scale intermodal transport systems.. The involvement of public concerns, as represented by the governmental objectives on sustainability, brings additional complexity into infrastructure network design. Governments are often concerned with network design on a regional scale or a national scale. The enlargement of the network scale to an international level further increases the level of heterogeneity of the network, among other factors in terms of the number of actors involved, the diversity of transport demand and the variety of transport service supply. These new objectives and dimensions pose new challenges to freight transport infrastructure network design.

This thesis proposes a new model to support policy making for an intermodal freight transport network. The model is able to simultaneously incorporate large scale, multimodal, multi-commodity and multi-actor perspectives. It can be used for integrated policy, infrastructure and service design. Results can be visualized per transport mode and per commodity value group on a geographic information system at segmental level, terminal level, corridor level, regional level, national level, and network level.

Implementation of the model for a realistic scale network design is another contribution of this thesis. To this end, we calibrated the model by using two approaches: a Genetic Algorithm based method and a feedback-based method. The model was validated by comparing the modelled link flows with observations, testing the cross elasticities of the costs to demand and comparing the catchment area of the terminals with areas observed in practice. The calibration results indicate that the model adequately captures the network usage

decisions on an aggregated level. The model was applied to Dutch container transport network design problems. Databases of Dutch container transport demand, features of the European multimodal freight transport infrastructure network, information about selected inland waterway transport services, and information about transport and transhipment costs, emissions and external costs were embedded in the model.

After completing the theoretical and empirical specification the model was applied to policy decisions on the Dutch container transport. The thesis extensively discusses the integrated infrastructure, service, and policy design that may contribute to managing the costs of the freight flows, meanwhile ensuring a sustainable living environment. The main findings from the application are as follows.

- A higher CO_2 price can results in lower total transport costs, despite extra handling costs in intermodal transhipments. The costs saved by bundling freight and using intermodal transport can compensate the additional handling costs. As these cannot compensate for the internalized CO_2 emission costs, the total operational costs borne by transport operators will increase.
- Network efficiency can be increased by closing terminals that are not able to attract sufficient volumes of demand. However, it is not likely to happen in practice, due to the fact that the private terminal operators and the local governments have local interests to protect on those small terminals that may conflict with the objective of minimizing total network costs.
- The hub-network-services assumed and tested in this study cannot compete with road transport or shuttle barge transport services in the base scenario due to the extra transhipment costs, low load factor, and low demand for IWW container transport. In a future scenario, these services are only feasible under very high traffic growth.
- There is not one single optimal future infrastructure network. Instead, a good infrastructure network design mainly depends on the future demand, transport price, and development of new transport technology. Based on the conclusions drawn in this thesis, implementing the combination of CO_2 pricing and terminal network configuration is more effective than solely implementing CO_2 pricing, with regard to total network CO_2 emissions. A range of efficient networks, forming a frontier of minimal total network costs and total network CO_2 emissions, is presented in the thesis, instead of one single optimal solution. The frontier provides more options in terminal network optimization in terms of the target network performance. The question which is the optimal network will depend on the relative value placed on CO_2 emissions.

The thesis ends with a vision on future freight transport network design models. A potential research direction is to incorporate the dimension of time into the model. This extension will enable the model to capture dynamic demand; to be applicable for scheduling synchronized intermodal transport services; to provide more realistic estimations of transport emissions and to analyse network reliability, including network robustness and service robustness.

Reference:

CEC (2009) 'COMMUNICATION FROM THE COMMISSION: A sustainable future for transport: Towards an integrated, technology-led and user friendly system', Commission of the European Communities, Brussels.

Samenvatting

“Doel van het Europese vervoersbeleid is een duurzaam vervoerssysteem tot stand te brengen dat de economische, sociale en ecologische behoeften van de maatschappij vervult…” (CEG, 2009). Deze uitspraak duidt de uitdagingen waarvoor de Europese transportbeleidmakers worden gesteld, wanneer een groeiende vrachtvervoersvraag met beperkte vervoersinfrastructuur moet worden bediend. De Europese Commissie heeft de ontwikkeling van een verbindend, intermodaal transportsysteem aangewezen als een belangrijke, strategische taak die zal bijdragen aan de oplossing voor het dilemma tussen het bedienen van toenemende vrachtstromen en het streven naar een duurzaam, leefbaar milieu.

Dit proefschrift concentreert zich op een model-georiënteerde, kwantitatieve analyse van infrastructuurnetwerken voor grootschalige, intermodale transportsystemen. Publieke belangen, bijvoorbeeld vertegenwoordigd in de duurzaamheidsdoelstellingen, maken de ontwerpopgave van deze netwerken complexer. Ook het vergroten van de netwerkschaal tot een internationaal niveau leidt tot de noodzaak om rekening te houden met de heterogeniteit van het netwerk door het aantal betrokken partijen, de diversiteit van de vervoersvraag en de variëteit van het vervoersaanbod. Deze nieuwe doelstellingen en dimensies stellen nieuwe uitdagingen aan het ontwerp van goederenvervoernetwerken.

Dit proefschrift introduceert een nieuw model ter ondersteuning van beleidsvorming voor een intermodaal goederenvervoernetwerk. Het model kan grootschalige, multimodale netwerken met meerdere goederentypen en voor verschillende stakeholders simultaan beschrijven. Het kan gebruikt worden voor een integrale toetsing van beleidsmaatregelen, infrastructuur en servicenetwerken. Resultaten worden gevisualiseerd via een geografisch informatiesysteem, per vervoerswijze en per goederengroep, op netwerkschakels, overslagterminals, corridors, en ook op regionaal, nationaal, en netwerkniveau.

Een andere bijdrage van dit proefschrift is de implementatie van het model in een netwerkvormgeving van realistische grootte. Wij hebben het model gekalibreerd met behulp van twee technieken: via een Genetisch Algoritme en via een Feedback-gebaseerde methode. Het model is gevalideerd door het vergelijken van de gemodelleerde stromen met geobserveerde stromen, het testen van de prijselasticiteiten van de vraag en het vergelijken van het gemodelleerde bedieningsgebied van de overslagterminals met in de praktijk geobserveerde gebieden. De kalibratieresultaten wijzen erop dat het model het netwerkgebruik op geaggregeerd niveau adequaat nabootst. Het model is toegepast op vraagstukken binnen het Nederlandse containervervoersnetwerk. De nadruk lag op maritieme stromen, maar het model kan ook op continentale stromen worden toegepast. In het model is het volgende geïntegreerd: databases van vraag naar containervervoer in Nederland; kenmerken van het Europese multimodale vervoersnetwerk; informatie over trein- en binnenvaartdiensten, en informatie over vervoers- en overslagkosten, emissiekosten en externe kosten.

Na de ontwikkeling van het model in theoretische en empirische zin is het model toegepast op beleidsmatige besluiten aangaande het Nederlandse containervervoer. Het proefschrift behandelt diverse scenarios voor infrastructuur, vervoersdiensten en beleidsmaatregelen die bijdragen aan de efficiency van goederenstromen en een bijdrage aan een duurzame leefomgeving.. De belangrijkste bevindingen van de cases zijn de volgende.

- Een hogere CO_2 prijs kan leiden tot lagere totale vervoerskosten, ondanks de extra overslagkosten door intermodale overslag. De extra overslagkosten worden gecompenseerd door een kostenbesparing als gevolg van het bundelen van vrachtstromen en intermodaal vervoer. Doordat deze kostenbesparing de geïnternaliseerde CO_2 emissiekosten echter niet kan compenseren, zullen de totale operationele kosten voor vervoerders toenemen.
- Netwerkefficiëntie kan worden vergroot door terminals te sluiten, die niet voldoende vervoersvolume kunnen aantrekken. Het is echter onwaarschijnlijk dat dit in de praktijk zal gebeuren, omdat private (overslag)bedrijven en lokale overheden belangen hebben bij het beschermen van deze kleine terminals; belangen die kunnen conflicteren met de doelstelling om totale netwerkkosten te minimaliseren.
- De hub-netwerkdiensten die zijn getest in onze studie kunnen niet concurreren met wegtransport of shuttlediensten voor de binnenvaart, vanwege extra overslagkosten, een lage beladingsgraad en een te lage vraag. In de toekomst zijn deze diensten alleen op lange termijn haalbaar, bij zeer grote verkeerstoename in het meest extreme vraagscenario.
- Er is niet één enkel optimaal toekomstig vervoersnetwerk. Een goede vormgeving van een infrastructureel netwerk hangt hoofdzakelijk af van de toekomstige vervoersvraag, de vervoersprijs, en de ontwikkeling van nieuwe transporttechnologie. Op basis van de conclusies uit dit proefschrift kan worden gesteld, dat het toepassen van een combinatie van CO_2 beprijzing en een goede configuratie van terminals in het netwerk, effectiever is dan alleen het toepassen van CO_2 beprijzing. Een keur van efficiënte netwerken wordt in dit proefschrift gepresenteerd, in plaats van een enkele optimale oplossing. Deze verzameling van netwerken vormt een grens van minimale totale netwerkkosten en totale CO_2 emissies. De grens staat meerdere optimale netwerkoplossingen toe, gelet op de ten doel gestelde netwerkprestatie. Welke

- netwerkoplossing optimaal is, hangt af van de relatieve waarde die wordt gehecht aan CO_2 emissies.

Het proefschrift besluit met een visie op toekomstige modellen voor de vormgeving van goederenvervoernetwerken. Een potentiële onderzoeksrichting is het betrekken van de tijdsdimensie in het model. Deze uitbreiding maakt het mogelijk om dynamische vraag en betrouwbaarheid in het model te betrekken; het model kan dan worden toegepast op het synchroon plannen van intermodale vervoersdiensten. Voorts zal het voorzien in realistischere schattingen van vervoersemissies en analyses van netwerkbetrouwbaarheid, netwerkrobuustheid en robuustheid van diensten.

Referentie:

CEG (2009) 'MEDEDELING VAN DE COMMISSIE, Een duurzame toekomst voor het vervoer: naar een geïntegreerd, technologiegeleid en gebruikersvriendelijk systeem', Commissie van de Europese Gemeenschappen, Brussel.

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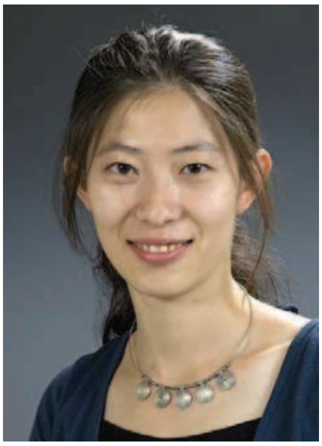

Mo Zhang was born in Qinhuangdao, China, on 28th May 1983. She studied hydraulic transmissions at the Faculty of Mechanical Engineering of Yanshan University in China. Following her Bachelor degree in 2005, she did her Master degree in management of technology at the Faculty of Technology, Policy, and Management of Delft University of Technology in the Netherlands, graduating in 2007. After working as a marketing, branding, and advertising consultant and project manager at Millward Brown, she joined the OTB Research Institute in Delft in 2009 to conduct her PhD research. In August 2010, together with the research group she worked with in OTB, she joined the Transport and Planning Department of the Faculty of Civil Engineering at Delft University of Technology. She enjoys working on optimization problems for complex systems, and has been working on optimization in the fields of logistics, marketing, and manufacturing. Mo Zhang currently works at the Department of Sustainable Transport and Logistics in TNO (Netherlands Organisation for Applied Scientific Research), with a focus on transport and logistics network design and optimization, policy impact assessment, and the development of GIS-based simulation systems.