Coordinated Model Predictive Control of Synchromodal Freight Transport Systems

Le Li

Cover design: Li Chen/陈莉

Coordinated Model Predictive Control of Synchromodal Freight Transport Systems

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 20 Juni 2016 om 15:00 uur
door

Le LI

Master of Science in Control Theory and Control Engineering,
Northwestern Polytechnical University,
geboren te Weinan, Shaanxi, China.

This dissertation has been approved by the promotors:

Prof. dr. ir. B. De Schutter
Dr. R.R. Negenborn

Composition of the doctoral committee:

Rector Magnificus	chairman
Prof. dr. ir. B. De Schutter	Delft University of Technology, promotor
Dr. R.R. Negenborn	Delft University of Technology, copromotor

Independent members:

Prof. dr. M.A. Botto	University of Lisbon
Prof. dr. A.W. Veenstra	Eindhoven University of Technology
Prof. dr. R.A. Zuidwijk	Erasmus University
Prof. dr. ir. G. Lodewijks	Delft University of Technology
Dr. J.M. Maestre	University of Seville
Prof. ir. T. Vellinga	Delft University of Technology (reserved)

This thesis has been completed in partial fulfillment of the requirements of the Dutch Institute of Systems and Control (DISC) for graduate studies. The research described in this disertation is supported by the China Scholarship Council (CSC) under grant 2011629027, the VENI project "Intelligent multi-agent control for flexible coordination of transport hubs" (project 11210), and the Delft Center for Systems and Control.

TRAIL Thesis Series T2016/9, the Netherlands TRAIL Research School
P.O. Box 5017
2600 GA Delft, The Netherlands
T: +31 (0) 15 278 6046
E: info@rstrail.nl

Published and distributed by: Le Li
E-mail: lilenwpu@gmail.com

ISBN 978-90-5584-205-6

Keywords: synchromodal freight transport, intermodal freight transport networks, model predictive control, distributed model predictive control, coordination.

Copyright © 2016 by Le Li

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without written permission of the author.

Printed in the Netherlands

Acknowledgements

It has been an enjoyable journey to finish my PhD in The Netherlands. It would not be such enjoyable without the help, support, and companion form many people in the past four and half years. Now, I want to thank all the people who have involved in this journey in one way and another.

First and foremost, I want to thank my promotors Prof.dr.ir Bart De Schutter and Dr. Rudy R. Negenborn for their consistent patience and professional supervision. Dear Bart, thank you for giving me the opportunity to join Delft Center for Systems and Control (DCSC) as a PhD candidate, and for your critical, detailed, and timely feedback on every piece of text that I had written in the progress reports, the papers, and the dissertation. There are two of your words that I really appreciate, i.e., 'Take your time!', and 'Who cares!'. Even though it took me some time to really get the meanings of these two words, they indeed helped me a lot in adapting the new working environment and life in Delft at the very beginning of my PhD, and in finishing my dissertation writing as planned at the last stage of my PhD. Dear Rudy, thank you for bringing me to the field of multi-agent and distributed model predictive control, and to an interesting application of synchromodal freight transport. As my daily supervisor, your way of scientific thinking, questioning, and writing has greatly influenced me in my PhD training process of being able to perform independent research. I really appreciate your help on improving my English, and your inspirations on exploring and choosing new research directions in our regular meetings. Special thanks to you for the handling of miscommunication issues in the evaluation process of my dissertation. Without your efforts, everything would not went so smoothly.

Next, I would like to thank my Ph.D committee members for their valuable time and comments. I appreciate the help from Prof. Lori Tavasszy for letting me be aware of the broad area of intermodal transport research done in operational research, and the help from Prof. Bart Jourquin for sharing his papers. I want to thank Guoqiang Zhang for sharing his knowledge, papers, and codes on distributed optimization algorithms. Even though the outcome of our joint work did not come up to our expectation, I will certainly continue working on this topic. I also greatly appreciate the valuable feedbacks from all participants of the User Committee meetings in the VENI project "Intelligent multi-agent control for flexible coordination of transport hubs".

I gratefully acknowledge the grant from the China Scholarship Council and the support from the Delft Center for Systems and Control, Delft University of Technology. Apart from this, I want to thank Ms. Franca Post and Mr. Cees Timmers for their kind welcome and support regarding the international student issues.

It was a wonderful experience to work with my colleagues at DCSC and MTT in the past years. Thanks my officemates, Yihui, Arner, Anil, Jan-Maarten, Amir, and Zhou for the pleasure of their company and understanding. I am thankful to Alfredo, Ali, Anahita, Anqi, Arman, Bart Kersbergen, Cees, Chenguang, Chengpu, Dieky, Edwin, Elena, Elisabeth, Esmaeil, Fan, Farid, Giannis, Guangming, Hans, Hai, Hildo, Huarong, Huizhen, Jia, Jialun, Jianbin, Jie, Joao, Juan, Jun, Kim, Laura, Laurens, Linying, Max, Mohammad, Noortje, Qu, Patricio, Rafael, Reinier, Renshi, Ruxandra, Sachin, Shahrzad, Shijie, Shuai Liu, Shuai Yuan, Stef, Teus, Tim, Sadeh, Subramanya, Vahab, Wenhua, Xiangwei, Xiao, Yashar, Yasin, Yiming, Yu, Yue, Zhe, Zhao, et al. for the happy memories of conferences, DISC and TRAIL courses, group discussions, coffee breaks, social events, dinner parties, bicycle trips, table football, badminton, BBQ, etc. Thanks Bart Kersbergen for translating my dissertation summary into Dutch. Thanks Simone for inviting me for a homemade Italian dinner and many short chats after work. Thanks Francesco for inviting me for a cycle trip in the flower field in Leiden and many helpful discussions. Many thanks also goes to the secretaries in DCSC: Kitty, Esther, Saskia, Marieke, Hellen, and Kiran for always being kind and helpful to me.

Furthermore, I want to thank all my friends in The Netherlands for your kindness and help that make me feel being at home. In particular, I want to thank my roomates, Wenbo, Yun, Wei, Ziru, Liang, Nali, Jin, Peijun, Chang, Liu, Peng, Peijian, and Meng Zhang for delicious food, beers, plenty of social and scientific discussions after dinner. I would also like to thank Yusong Pang, Gang Cheng, Jing Han, Mo Zhang, Meng Wang, and Yu Ding for their valuable discussions and suggestions on my research and career.

Of course, I should not forget the help and the support from China. I want to express my sincere gratitude to Prof. Weidong Liu in Northerwestern Polytechnical University (NPU), Xi'an, China for the guidance and the encouragement of doing PhD aboard. Many thanks goes to Prof. Li'e Gao, Prof. Huizhen Yang, and Prof. Jiajun Li in NPU for your help and hospitality every time I came to Xi'an. Meanwhile, I would like to thank all my friends in China for your friendship. I want to thank Li Chen for many enjoyable chats, which were the most comfortable things for me during the period of writing my dissertation. Thanks for your understanding and for your help with the designing of the cover picture for my dissertation.

Most importantly, I want to use this opportunity to thank all my relatives and family members for your consistent support and encouragement. Thanks my parents for your unconditional love and complete trust in me at every stage of my study and life. Your love and trust have been empowering me to overcome any hard times and to continue moving forward.

Le Li

Delft, June 2016

Contents

Chapter 1

Introduction

The focus of this thesis is on new network models and container flow control approaches for synchromodal freight transport planning of intermodal freight transport operators. In this chapter we first briefly introduce hinterland haulage and the concept of synchromodality in Section 1.1. After presenting the research problem of this thesis in Section 1.2, we formulate our research questions in Section 1.3. Finally, the contributions and the outline of this thesis are presented in Section 1.4 and in Section 1.5, respectively.

1.1 Synchromodal freight transport

This section introduces successively hinterland haulage and the concept of synchromodality in Sections 1.1.1 and 1.1.2, respectively.

1.1.1 Hinterland haulage

In global freight transport, major deep-sea ports act as gateways for import and export cargoes for certain geographical areas, for instance the Port of Rotterdam for North and West Europe. These geographical areas are called the hinterlands of the deep-sea ports. Hinterland haulage refers to freight transport between deep-sea ports and the origins/destinations of cargoes, and is an indispensable component of international maritime-based freight transport, handling over 80% of the volume of global trade [154]. The hinterland transport and logistics costs account for 40% – 80% of the total container shipping cost in international maritime-based freight transport [124]. Hence, hinterland accessibility has become a crucial port selection criterion for international shipping lines, and is also one of the most influential factors of seaport competition [3, 125, 157, 158]. Accessibility issues have been observed at main ports in Europe [58, 131], in Asia [175, 176], and in USA [33, 168]. It is therefore very important to investigate innovative concepts for hinterland transport at major deep-sea ports. This is in particular the case for the Port of Rotterdam, the biggest container port in Europe and a place where many innovations in transport and logistics have been emerged [131].

Increasing cargo throughput in the Port of Rotterdam has been forecasted by the Rotterdam Port Authority for the coming twenty years, i.e., from 430 million tonnes in 2010 to around 650 million tonnes in 2030 under the European Trend scenario with moderate economic growth and environmental policy in 2010 [131]. The container is the prevailing form of a loading unit for freight transport in modern logistics system. In the Port of

Rotterdam, container handling accounted for 25% of throughput in 2010, while in 2030 it will possibly represent 42% of the total freight [131]. These upcoming containerized cargo volumes will bring challenges for both the deep-sea port and its hinterland haulage. With the construction of Maasvlakte 2, the Port of Rotterdam will undergo a large increase in the capacities of cargo handling and storage [114, 131, 151]. However, its hinterland haulage has been facing challenges from increasing cargo volumes, limited capacities of transport infrastructures, traffic congestion on freeways, traffic emission issues, etc. These challenges necessitate an efficient and innovative way to organize, plan, and control hinterland haulage.

1.1.2 Synchromodality

Multiple transport schemes exist in freight transport: unimodal freight transport, multimodal freight transport, intermodal freight transport, combined freight transport, co-modal freight transport, and synchromodal freight transport [27, 37, 53, 72, 104, 137, 150, 152, 155, 161, 167]. These transport schemes differ from each other in many aspects, e.g., key added features, complexity, organizational and legal relations among different stakeholders in the freight transport. Figure 1.1 points out the relation between these transport schemes in terms of key added features. Unimodal freight transport uses only one mode of transport, and typically refers to truck transport. Multimodal freight transport is the transport of goods by at least two modes of transport [155]. Intermodal freight transport is a particular type of multimodal freight transport that moves goods in one and the same loading unit (e.g., standard containers) by successively two or more modes of transport without handling the goods themselves when changing modes [37, 155]. Combined freight transport is intermodal transport of goods while emphasizing using road transport only in the initial and/or final leg of the transport and making the distance as short as possible [155]. Co-modal freight transport is the efficient use of different modes of transport on their own and in combination for an optimal and sustainable utilization of resources [27, 167]. Synchromodal freight transport adds the aspect of real-time and flexible switching among different modalities according to the latest logistics information to intermodal freight transport and co-modal freight transport [53, 72, 104, 150, 152, 161, 167]. It is noteworthy that multiple definitions have been proposed for each transport scheme in literature and substantial overlaps also exist between several transport schemes, e.g., combined freight transport and co-modal freight transport. For clarification, in this thesis we use the term “intermodal” when referring to the physical interconnectivity between single-modal transport networks (e.g., intermodal terminal, intermodal freight transport networks, intermodal freight transport operators), and the term “synchromodal” when referring to planning interoperability between operations in different networks (e.g., synchromodal freight transport planning, synchromodal container transport services). We refer to [137] for a detailed discussion on these transport schemes.

Before explaining the concept of synchromodality, several newly developed concepts in port-hinterland container transport are briefly explained as follows:

- **Extended gates:** According to [164], an extended gate is an inland intermodal terminal directly connected to seaport terminals with high-capacity transport means, where customers can leave or pick up their standardized units as if directly

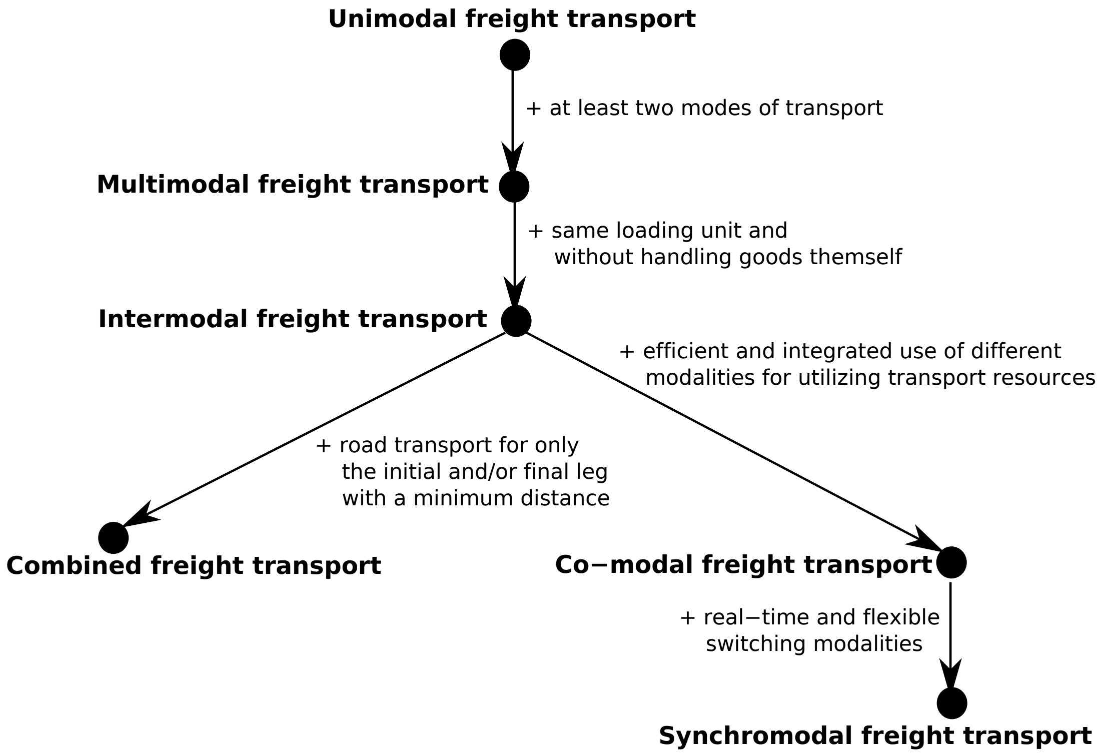

Figure 1.1: The relation between different transport schemes in terms of key added features.

interacting with a seaport, and where the seaport terminal operator can control the flow of containers to and from the inland terminal.

- **From pull to push:** In a push system for containers, containers no longer remain at the deep-sea terminals in anticipation of an action on the part of the recipient (pull), but are directly moved by barges or trains to inland terminals in the hinterland in a pro-active fashion (push). The transformation from a pull system for containers to a push system will prevent that containers unnecessarily remain at deep-sea terminals. The unnecessary staying at deep-sea terminals typically leads to short transport times for delivering containers to their final destinations in the hinterlands, and therefore necessitates the use of trucks [53].

- **Mode-free booking:** In the mode-free booking or a-modal booking, shippers sign transport contracts only covering price, time of delivery, level of service quality, without specifying which mode of transport is going to be used [54, 152]. This gives transport operators the freedom to select the most suitable modalities on the basis of the real-time planning information.

Motivated and facilitated by the above mentioned concepts, synchromodality or synchromodal freight transport moves one step forward from intermodal freight transport and co-modal freight transport by adopting the mode-free booking concept and allowing flexible selection and timely switching among multiple avaliable modalities based on the latest logistics information, e.g., the transport demand, traffic information, available transport capacities [53, 72, 150, 152, 161, 167]. Changes to transport plans can then be made at any time during the transport process. In this thesis we focus on the most important loading unit used for freight transport: containers. Synchromodal freight transport requires real-time logistics information collection and integration and timely and flexible modality changing to match capacity supply and transport demand in an integrated transport network. Multiple transport service packages and prices should be designed for and provided to shippers with various delivery requirements, e.g., regarding due time, delivery speed, reliability [150, 161]. Synchromodal freight involves multiple stakeholders, e.g., shippers, receivers, terminal operators, freight transport operators, freight forwarders, information service providers, infrastructure managers, and port authorities. The collaboration and coordination of actions among these stakeholders are also essential [53, 72, 150, 152, 157, 158, 161, 164, 167]. Moreover, mind shifts in transport planning and control are required to shift from the mode-specific booking, the mode-based planning, the "predict and prepare" operation, to the mode-free booking, the service-based planning, and the "sense and respond" operation, respectively [150].

An example of synchromodal freight transport is European Gateway Services (http://www.europeangatewayservices.com/) organized by European Container Terminal, a terminal operator, for moving containers in the hinterlands of the Port of Rotterdam. The first synchromodal freight transport pilot took place among Rotterdam, Moerdijk, and Tilburg in 2011 involving multiple terminal operators, logistics companies, and shippers [55, 104]. The pilot confirmed that a successful implementation of synchromodal freight transport concept requires, among others, a more efficient way for planning port hinterland container transport and performing coordinations. One way to achieve efficient planning and coordination is to apply modern theories and technologies on information and communication, computational logistics, distributed optimization, and systems and control in the field of freight transport. So, this thesis chooses to investigate synchromodal freight transport planning problems from a systems and control perspective and emphasizes the requirements of efficient information and communication technology systems and computational methods.

1.2 Problem statement

In this thesis, an intermodal freight transport operator is a special organization or enterprise that owns or hires transport vehicles, e.g., trucks, trains, and barges, and provides shippers with synchromodal container transport services in an Intermodal Freight Transport Network (IFTN). An IFTN is a network consisting of different single-modal transport networks, e.g., the road network, the railway network, and the inland waterway network. These single-modal transport networks connect to each other at intermodal terminals.

Based on the decision horizon of planning problems, research efforts on freight transport can be categorized into three decision-making levels: strategic level, tactical level, and operational level (see the review papers [24, 25, 37, 38, 84, 105, 147]). For an intermodal freight transport operator, strategic decisions concern the infrastructure investments, e.g., whether to increase or reduce the size of the IFTN that this operator works on, whether to purchase more transport vehicles or rent vehicles from leasing companies; tactical decisions consider aggregated container flows and are typically about service network design and network flow planning to optimally utilize the given infrastructure, e.g., modal choice and capacity allocation on each service, service frequencies and the timetables of trains and barges, equipment planning, and container flow assignment; operational

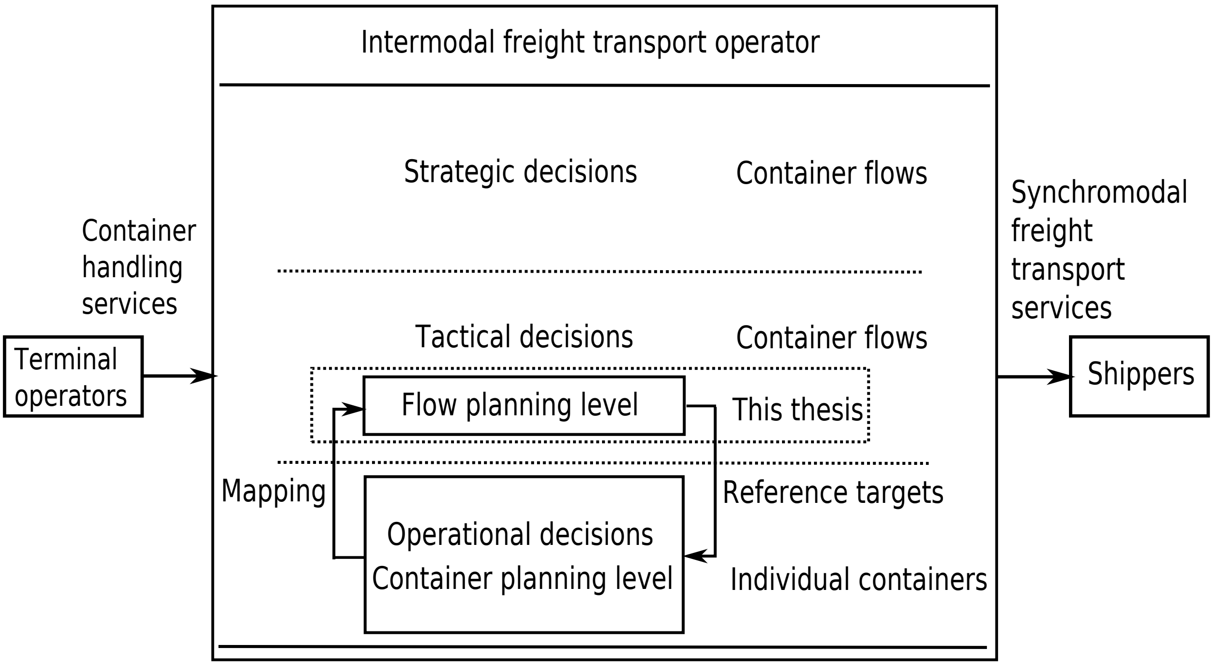

Figure 1.2: Overall framework of the proposed multi-level freight transport planning approach for an intermodal freight transport operator.

decisions consider the optimal routing of each individual container over certain service networks, e.g., intermodal routing, itinerary replanning. The operational freight transport planning problem faced by intermodal freight transport operators is in general a mixed integer optimization problem in which individual containers are directly modeled and scheduled in the planning. This problem is NP-hard and requires huge computational efforts to solve as the number of shipments or the size of the IFTN increase.

Therefore, this thesis proposes the multi-level freight transport planning approach shown in Figure 1.2. Instead of directly solving the operational freight transport planning problem, the multi-level planning approach addresses the planning problem within a two-level planning framework. At the flow planning level, the planning is carried out at the aggregated container flow level with the hour or day time scale, while at the container planning level transport decisions are made for each individual container with the time scale of second or minute. A mapping is necessary to aggregate the transport information of individual containers to the corresponding container flow information. The advantage of the proposed multi-level planning approach is that since the planning problem at the flow planning level considers the aggregated container flows, it typically involves relatively simple models resulting in a significant reduction in the number of integer variables so that it can be solved with an important reduction of computational efforts compared to directly solving the operational freight transport planning problem at the individual container level. The solution to the flow planning problem can then be taken as reference for the container planning problem. This reference contains the volumes of container flows leaving each terminal through associated transport connections or switching modalities at intermodal terminals. In addition, because of having planning intervals with different time scales, the flow planning problem in the proposed multi-level planning approach typically has a longer planning period at each planning interval than the planning period of the planning problem that directly plans each individual container. Therefore, the proposed multi-level planning approach can adjust planning decisions in advance to cope with possible transport conditions in a relatively long period.

The IFTN models and the container flow control approaches investigated in this thesis are for the flow planning problem at the tactical container flow level, and will facilitate more efficient decision making for the container planning problem at the operational individual container level. The evolution of the aggregated system behavior at the tactical container flow level can be predicted with the use of the aggregated system state, the aggregated network models, and the estimated aggregated transport demands and disturbances information. The aggregated system state can be generated by exchanging and aggregating the measurements of the system state at the operational planning level within the overall multi-level freight transport planning framework shown in Figure 1.2. The transport demand and disturbances information could be gathered by aggregating the estimated transport information (e.g., on the second or minute scale) at the operational planning level, and or by directly making aggregated estimations (e.g., on the hour or day scale).

For a better explanation of the scope of this thesis, we clarify some main issues as follows:

- **Main haulage:** In maritime-based international freight transport chains, hinterland haulage involves two steps: main haulage and pre-haulage or end-haulage (or collection or distribution). This thesis focuses on the main haulage part, and therefore investigates synchromodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage.

- **Information and Communication Technologies (ICT) system:** The intermodal freight transport operator is assisted by an efficient ICT system. This ICT system is assumed to be able to measure real-time container transport information regarding its own operations, timely exchange freight transport related information with the ICT systems of other parties involved (e.g., obtaining the measurements of traffic conditions on freeways from the traffic management system on the road network), integrate real-time freight transport related information from different sources, and further facilitate the freight transport planning done by the transport operator. We refer to [76] for an up-to-date overview of existing and emerging ICT technologies in freight transport.

- **Implementation:** In order to apply the network models and the container flow control approaches proposed in this thesis in practice, they should be integrated into an overall multi-level freight transport planning framework (see Figure 1.2). Hence, they need to be used together with the modeling and routing approaches at the operational individual container level, and also with the appropriate approaches to aggregate or disaggregate planning information between the tactical planning level and the operational planning level.

In summary, this thesis focuses on synchromodal freight transport planning and coordination problems 1) among deep-sea terminals and inland terminals in hinterland haulage for intermodal freight transport operators with efficient ICT systems; 2) at the tactical container flow level within the overall multi-level freight transport planning framework presented in Figure 1.2.

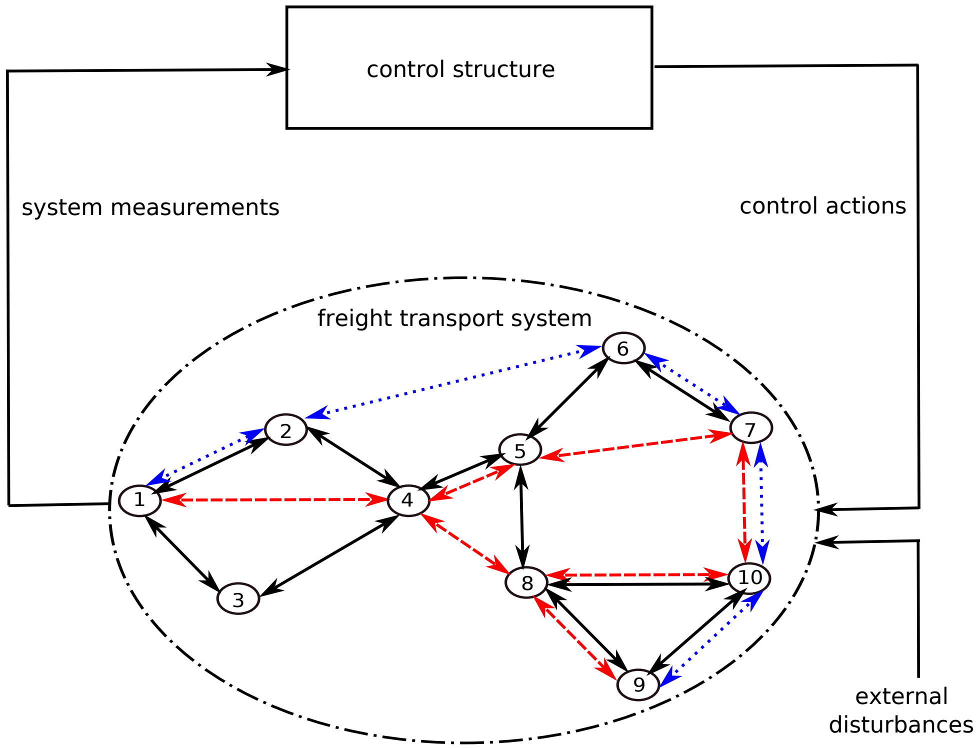

Figure 1.3: System and control view of a freight transport system. The circles with numbers represent intermodal terminals. The solid arcs, the dashed arcs, and the dotted arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

1.3 Research questions

This thesis aims to investigate *how to control and coordinate container flows for synchromodal freight transport at the tactical container flow level for intermodal freight transport operators.*

To achieve this aim, three key research questions are considered:

1. What are the key characteristics of intermodal freight transport systems and what intermodal freight transport network models can be developed to capture these characteristics adequately at the tactical container flow level?

2. How can a single intermodal freight transport operator control container flows for synchromodal freight transport planning with the dynamic transport demand and dynamic traffic conditions in an intermodal freight transport network?

3. How can multiple intermodal freight transport operators coordinate their container flow control actions for coordinated synchromodal freight transport planning in different but interconnected service areas?

This thesis proposes to investigate synchromodal freight transport from a systems and control perspective, and to adopt real-time control approaches, in particular, Model Predictive Control (MPC) [106, 136] and Distributed Model Predictive Control (DMPC) [23, 32, 107, 142] for synchromodal freight transport planning and coordination problems. The system and control view of a freight transport system is illustrated in Figure 1.3. To answer key research question 1, we will develop dynamic IFTN models, being the prerequisite for the deployment of the systems and control approach for synchromodal freight transport planning. The container flow control approaches that will be developed for addressing key research questions 2 and 3, will lead to decision supporting tools for planning port hinterland container transport in the realization of synchromodal freight transport concept.

1.4 Contributions of the thesis

The main contributions of this thesis are as follows:

- We propose a linear discrete-time intermodal freight transport network model that captures the key system characteristics at the tactical container flow level. As a model extension, a load-dependent IFTN model is proposed to include the impact of freight truck flows generated by the transport operator on the freeway transport times with a multi-class version of the nonlinear and non-convex speed-density relation model.

- We propose a Model Predictive container Flow Control (MPFC) approach for synchromodal freight transport planning of a single intermodal freight operator. A multi-start Iterative Linear Programming (ILP) approach is also proposed to efficiently solve the nonlinear and non-convex optimization problems in the MPFC approach with the load-dependent IFTN model.

- We propose three Distributed Model Predictive container Flow Control (DMPFC) approaches for coordinated synchromodal freight planning among multiple intermodal freight transport operators: the *parallel* Augmented Lagrangian Relaxation based DMPFC approach, the *serial* augmented Lagrangian relaxation based DMPFC approach, and the Alternating Direction Method of Multipliers (ADMM) based DMPFC approach.

1.5 Thesis outline

Figure 1.4 gives the overview of the relations between the chapters of this thesis. This thesis is organized as follows:

- **Chapter 2** presents the background knowledge and literature review on network modeling and transport planning approaches in intermodal freight transport as well as synchromodal freight transport. The model predictive control and distributed model predictive control methodologies and their applications in intermodal freight transport are also briefly introduced.

- In **Chapter 3** a linear discrete-time intermodal freight transport network model is first proposed to capture the modality change phenomena at intermodal terminals, time-dependent transport times on freeways, time schedules of trains and barges, and physical capacity limitations of the network. The linear IFTN model is extended as a load-dependent IFTN model that uses a multi-class version of the nonlinear and non-convex speed-density relation model to include the impact of freight truck flows

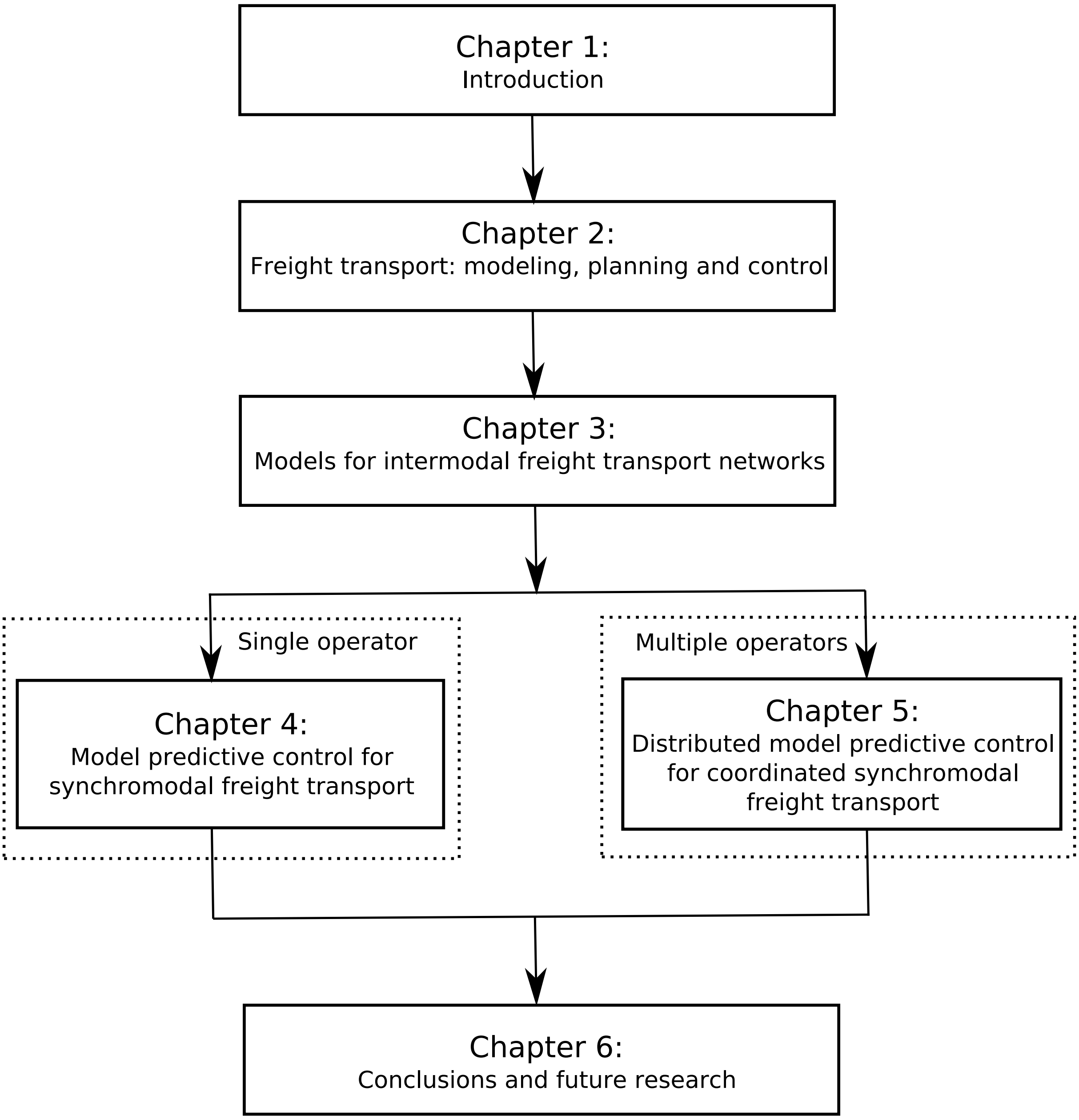

Figure 1.4: Outline of the thesis.

generated by the transport operator on the freeway transport times. Moreover, two benchmark systems that will be used in later chapters for analysis are also proposed.

Chapter 3 addresses key research question 1. The contents of Chapter 3 are based on [97] and have been partially presented in [92, 94, 95].

- In **Chapter 4** a model predictive container flow control approach is proposed to address timely and actively dynamic behavior of the transport demand and traffic conditions in synchromodal freight transport planning of a single intermodal freight operator. A multi-start iterative linear programming approach is developed to efficiently solve the nonlinear and non-convex optimization problems in the MPFC approach with the load-dependent IFTN model. The MPFC approach and the proposed solution approaches are analyzed and evaluated with both the linear IFTN model and the load-dependent IFTN model in a single-region IFTN benchmark system.

  Chapter 4 addresses key research question 2. The contents of Chapter 4 are based on [93, 97] and have been partially presented in [94, 95].

- In **Chapter 5** three distributed model predictive container flow control approaches for coordinated synchromodal planning among multiple intermodal freight transport operators are proposed: the *parallel* augmented Lagrangian relaxation based DMPFC approach, the *serial* augmented Lagrangian relaxation based DMPFC approach, and the alternating direction method of multipliers based DMPFC approach. The performance of these three DMPFC approaches is analyzed and evaluated with the linear IFTN model in a multiple-region IFTN benchmark system.

  Chapter 5 addresses key research question 3. The contents of Chapter 5 are based on [99] and have been partially presented in [96].

- **Chapter 6** states the main conclusions of this thesis and presents recommendations for future research.

Chapter 2

Freight Transport: Modeling, Planning, and Control

In the previous chapter we introduce the focus of synchromodal freight transport in this thesis. The concept of synchromodality has been recently proposed and is still far from mature both in academic research and in practical operations. The available research efforts dedicated to synchromodal freight transport are limited in literature. In fact, this concept is developed on the basis of intermodal freight transport, for which many works that investigate network modeling and planning approaches have been published in the literature. In this chapter we will therefore present a literature review on network modeling and planning approaches for intermodal freight transport as well as synchromodal freight transport in Section 2.1 and Section 2.2, respectively. Moreover, Model Predictive Control (MPC), Distributed Model Predictive Control (DMPC), and their applications in intermodal freight transport are reviewed in Section 2.3 and in Section 2.4.

2.1 Intermodal freight transport network modeling

Planning models for freight transport should be formulated to address specific planning problems of specific stakeholders at specific levels of decision making, i.e., strategic level, tactical level, and operational level [38]. We refer to the review paper [38] and references therein for a detailed review of the main problems, planning models, and solution methods at each level of the freight transport. Recent researches in intermodal freight transport are summarized and discussed in [24, 25, 37, 84, 105, 147, 149]. We now briefly introduce the main topics and the network modeling approaches at each of these three planning levels in intermodal freight transport. Moreover, the research on synchromodal freight transport in the literature will also be discussed at different planning levels.

Strategic planning problems relate to the highest level of management and consider capital investments on the infrastructures over a long time period. Models have been developed for hub location problems, terminal network design problems, policy making, and strategic cooperation problems among stakeholders [25, 105, 147]. The concept of virtual links is proposed in [75] to introduce multiple links corresponding to different levels of services using the same infrastructure in freight transport models. This concept is extended by [39] to model a multimodal network with transfer links connecting different single-modal networks. On the basis of the virtual link concept, a systematic and automatic way has been developed in [86] to generate a virtual network with all virtual links corresponding to the different operations on links and nodes of the physical network. Two commercial software packages, i.e., STAN [39], and NODUS [13, 86], have been developed using this virtual network representation, and have been used for many applications (e.g., policy making) in the strategic planning. Moreover, two similar concepts, i.e., supernetworks [145] and the multiple-node method [14], have also been developed in the literature. The concept of supernetworks is proposed to introduce transfer links between single-modal networks. The multiple-node method is used to represent each city by more than one node when the city has different modes of transport, and considers transport links and mode transfers with different transport times and costs. To the best knowledge of the author, there are currently no published works that explicitly analyze strategic planning problems in synchromodal freight transport.

Tactical planning problems concern choosing services and associated modes of transport, allocating their capacities to orders, and planning their itineraries and frequency in order to optimally utilize the current infrastructures. Models have been developed for Network Flow Planning (NFP) problems, and static and dynamic Service Network Design (SND) problems [25, 105, 147]. The models use continuous variables to represent the commodity flows in the network, and can be categorized into arc-based models and path-based models depending on whether the variables are used for representing flows on arcs or paths. The SND models differ from the NFP models in the introduction of binary variables for determining whether to select a service or not [147]. Static SND models typically introduce a fixed cost capacitated multicommodity network design formulation. Dynamic SND models add the time dimension to the static SND models, and are discrete multi-period models with a space-time network representation. Several researchers have investigated the service network design problems in synchromodal container transport planning. In [162] a service network design model, named Linear Container Allocation model with Time-restrictions (LCAT), with a path-based and minimum-flow network formulation was developed for the European Gateway Services network. This model allows for overdue delivery at a penalty cost, and takes into account self-operated and subcontracted barge and train services. These two types of services differ in their cost structures. The costs are paid for the entire barge or train in the self-operated services and for each Twenty-foot Equivalent Unit (TEU) in the subcontracted services, respectively. With the LCAT model, the impact and the relevance of disturbances (i.e., early service departure, late service departure, and cancellation of inland services) were assessed in [163]. The impact and the relevance are defined as the additional cost incurred by an updated planning in the case of a disturbance, and the cost difference between a fully updated plan and a locally updated plan, respectively. A fully updated plan will optimally generate new transport plans for all containers that have not been allocated before the arrival of the disturbance information. A locally updated plan will only reschedule the containers on the disturbed services. Moreover, a mathematical model was developed for integrated schedule design in a synchromodal freight transport system in [8]. This model can be used to determine an optimal schedule for multiple modes of transport for a specific time horizon. In [144] a continuous-time mixed-integer linear programming model was proposed for scheduled service network design with synchronization and transshipment constraints. This model evaluates the time of occurrence of transportation events and vehicle arrival and departure times by introducing an additional set of vehicle synchronization constraints that control the schedule of container flows.

Operational planning problems strive to allocate resources for satisfying the transport demand within required service criteria in a real-time and dynamic planning process. They are more concerned with the 'when' and 'real-time' aspects, e.g., when to start a given service, when to let a vehicle arrive at a destination or at an intermediary terminal [25, 38, 147]. Research results in operational planning have been grouped within two main topics in [147]: resource management and itinerary replanning. Resource management problems focus on how and when to optimally utilize the limited available resources, e.g., vehicles, empty loading units, and crews. Itinerary replanning problems concentrates on how to timely and optimally respond to the real-time system evolution in order to maximize the service quality and therefore the marginal profit. For operational synchromodal container transport planning, a real-time decision support system has been developed by generating a decision tree based on the offline optimal solutions of the LCAT model under historic demand patterns in [161]. This decision tree method is easily accepted and implemented by manual planners in practice and allows manual changes if necessary. However, it cannot directly take into account the dynamic behaviors of the transport demand and traffic conditions in a real-time manner. Based on a multi-objective K-shortest path problem formulation, a synchromodal transport planning approach with both an offline phase and an online phase is proposed in [115] to search for the K-shortest paths through a multimodal network with time windows, pre-determined timetables for trains and barges, and closing times of terminals. The offline pre-processing phase yields a reduced network for each origin-destination pair. The online phase is triggered when an order arrives, and enumerates all possible routes for this order, from which a list of K routes will be selected by the human planner through applying filters and changing weights on different objectives. Since there is no replanning considered for the existing orders when a new order arrives, the potential flexibility and efficency of synchromodal freight transport planning have still not been explored fully in [115].

For the flow control problems investigated in this thesis, an Intermodal Freight Transport Network (IFTN) model is needed to represent the system characteristics at tactical container flow level. These characteristics are modality changes at intermodal terminals, capacities of physical infrastructures, time-dependent transport times on freeways, and timetables for trains and barges. The existing IFTN models in the literature consider only a few of the above mentioned characteristics. We can, however, use certain elements of earlier work. First of all, the concept of a virtual network [39, 75, 86] and the multiple-node method [14] are adopted in our models to represent the multiple modalities and possible modality changes at intermodal terminals. Secondly, this thesis considers that trucks are always available at terminals for moving containers and timetables for container trains and barges are also predetermined. For synchromodal freight transport, models have been developed for service network design in [8, 144, 162]. Their determined train and barge services information can be used as inputs when formulating the network models in this thesis. Thirdly, time-dependent link transport times and physical capacity limitations will be taken into account when controlling container flows in the network. We propose to model these link-specific characteristics on the basis of their particular properties, i.e., traffic conditions on freeways, and timetables for trains and barges. Moreover, a discrete-time formulation, similar to the time-space network representation [147], will be used to enable the latter deployment of MPC strategies.

2.2 Intermodal freight transport planning

Intermodal freight transport planning involves three basic issues: intermodal routing, intermodal container flow assignment, and itinerary replanning. The following subsections review research that has been done on these basic issues.

2.2.1 Intermodal route selection

Intermodal route selection involves the selection of routes for shipments through an IFTN. Intermodal route selection is typically formulated as a shortest path problem. The intermodal route selection approaches can be categorized into three main directions: the direct shortest-path algorithm methods, the dynamic programming based methods, and the decomposition based methods.

The direct shortest-path algorithm methods have been intensively investigated in the literature. A number of intermodal route selection methods have been developed on the basis of the shortest-path algorithm and its different variants. In [6] a shortest-path procedure or a matching and bi-matching algorithm (depending on the cost structure of railways) is used to select intermodal routes with the minimum transport cost on a rail/road combination. A K-shortest path algorithm is presented in [14] to determine the K least expensive modal combinations for all origin-destination pairs. For the case of time-dependent arc travel times and modality switching delays, a time-dependent intermodal optimum path algorithm has been presented in [180]. The algorithm defines the label of one node as the cost or distance from a particular root node to this node in the network. The algorithm begins at the destination nodes and solves an optimality equation that is a necessary and sufficient condition for a label to be optimal in an iterative way and updates the value of labels during the iteration process of the algorithm.

The dynamic programming based methods adopt the methodology of dynamic programming to improve efficiency in solving complex intermodal route selection problems. The paper [71] derived dynamic programming formulations of an intermodal routing problem. The problem was solved by using Dijkstra's algorithm to find both a least-cost route subject to an upper bound constraint on lead time, and a least-lead-time route subject to an upper limit on total cost. A weighted constrained shortest-path problem was formulated for international container transport for both import and export in [30]. A dynamic programming algorithm that utilizes substructures of the original problem was used to find Pareto optimal transport routes with the objective of minimizing transport cost and transport time simultaneously. To implement this dynamic programming algorithm, a label setting algorithm together with pruning rules was selected to solve the constrained shortest-path problem.

The decomposition based methods partition the original IFTN into small subnetworks in order to reduce the complexity of the intermodal route selection problem. In [28] a heuristic algorithm is developed on the basis of relaxation and decomposition techniques to solve an international intermodal routing problem considering the time-dependent nature of the transport network. The corresponding subproblems after the decomposition were solved by existing or slightly modified shortest-path algorithms. A parallel algorithm for computing a global shortest-path solution in a transport network with multiple modalities and time-dependent transport times and costs was discussed in [5] based on the decomposition of the transport network according to regions and their associated transport modes. This algorithm involves multiple executions of a so-called inter modal task, which essentially computes the shortest paths from a starting point to any possible destination in the hypergraph representation of the transport network.

The above intermodal route selection approaches typically do not take into account the capacity constraints of the network. Intermodal container flow assignment approaches are needed to assign container flows to the intermodal routes resulting from these intermodal route selection approaches.

2.2.2 Intermodal container flow assignment

After the process of intermodal route selection, a list of candidate intermodal routes is typically selected with the aim to minimize a user-supplied objective function given by the intermodal freight transport operator, e.g., the total transport cost, the total transport time. These candidate intermodal routes are ordered according to their corresponding user-supplied objective function values. For intermodal container flow assignment, an intermodal freight transport operator determines at the origin node how much volumes of the transport demand are assigned to each of the candidate routes leading to the destinations.

The traditional freight assignment approaches can be categorized into four groups: all-or-nothing, equilibrium, stochastic multi-flow, and stochastic equilibrium [85]. This categorization is based on two characteristic features: whether or not capacity constraints are taken into account, and whether or not the variable perception of costs by users is considered. Capacity constraints refer to the limited capacity of links, which is typically captured by adding time penalties when traffic volumes on links surpass certain levels. The feature of the variable perception of costs reflects whether freight flows are assigned to the candidate intermodal routes only considering the lowest generalized cost, or whether there is also some stochasticity that influences the assignment of freight flows over several routes. These four groups of assignment approaches have been extensively used in the strategic and tactical level of freight transport planning. A recent analysis of these approaches was presented by [109].

Typically, an all-or-nothing approach is used in practice to assign container flows in intermodal freight transport planning. This approach assigns the entire volume of the transport demand to the route with the minimum value of the user-supplied objective function when considering unlimited capacities of transport connections. In the case of transport connections with limited capacity, transport demands will be assigned first to the route with the minimum objective value, and then to the next best candidate intermodal route, until these transport demands are completely served. This all-or-nothing approach is a greedy algorithm that can be easily implemented. However, this approach is not able to take into account the effect of container flow assignments on traffic conditions of the IFTN and will in general lead to a higher freight delivery cost.

For the flow control problem considered in this thesis, we will determine both route selections and flow assignments simultaneously by solving an optimization problem. We will also use the MPC and DMPC strategies to determine flow control actions while considering the predictions of flow evolution in the network with respect to future control actions and dynamic network behavior. Moreover, a comparison of the performance of our proposed flow control approach and the performance of the above introduced all-or-nothing approach will be carried out.

2.2.3 Itinerary replanning

Itinerary replanning involves efficient replanning methods to optimally and timely react to the dynamic behavior of the system, i.e., the dynamic transport demand, and dynamic traffic conditions. The updating procedure, its accuracy, and speed have a major influence on the performance of the replanning methods [147].

In [15], a real-time-oriented control approach is developed to deal with dynamically changing situations in the transport network, which are captured as dynamic disturbances for the transport planning step. In this approach, the total planning period is separated into a sequence of short uniform time intervals, called anticipation horizons, and the replanning of freight transport is done in a rolling-horizon fashion by simultaneously working on two different plans, i.e., the relevant plan at the process level and the theoretical plan at the adaptation level. At the beginning of each anticipation horizon, the relevant plan for this time interval is fixed and actually executed at the process level. In the remaining time of this anticipation horizon, the theoretical plan for the next anticipation horizon is tested and updated at the adaptation level on the basis of a simulation of the relevant plan for the current anticipation horizon. A pickup and delivery problem with time window constraints, which can be interpreted as a generalized version of the vehicle routing problem, is continuously solved with the use of a variable neighborhood structure to update the theoretical plan during this adaptation horizon. At the end of each anticipation horizon, all disturbances occurring during this anticipation horizon are integrated into both the relevant plan and the theoretical plan and a possible displacement of the relevant plan with the theoretical plan is checked. If the theoretical plan outperforms the relevant plan, the relevant plan will be replaced by the theoretical plan and executed at the next anticipation horizon. Otherwise, the original relevant plan will be implemented.

Motivated by the intermodal freight transport problem in the supply chain of an automobile manufacturer, the paper [69] formulated an integer optimization problem to determine shipments and their routes from suppliers to customers with the use of a time-expanded network model. This time-expanded network model is essentially obtained by expanding the original network through adding a copy of all nodes of the original network at each discrete time instant of the whole planning period. The arcs in the time-expanded network model represent the possible transshipment of shipments among terminals, and the possible transition from one discret time point to another during the freight transport processes. The initial freight transport plan is determined by selecting a set of arcs and the corresponding number of shipments traversing each of these arcs by solving an integer optimization problem. An updating mechanism is presented to adjust the initial freight transport plan to deal with unforeseen deviations between actual and planned transportation processes. Whenever the updated information about the progress of transport processes becomes available, this mechanism will update the freight transshipment information (i.e., origin and/or destination of the corresponding arcs in the network model) and solve again the formulated integer optimization problem while taking into account the executed part of the initial transport plan.

Both [15] and [69] apply replanning or updating strategies to address dynamic situations in intermodal freight transport. However, neither of them takes into account the future network evolution when determining the freight transport plan at the beginning of each anticipation horizon or time period. In addition, [15] and [69] directly work at the individual vehicle or shipment level and consequently encounter computational difficulties. We propose a multi-level freight transport planning approach to cope with these computational difficulties by using two interacted planning levels: a flow planning level, and a container planning level. This multi-level planning approach reduces the computational complexity of the planning problem by formulating the flow control problems with continuous variables for aggregated container flows, and having simpler container planning problems compared to the planning problem that directly considers the planning of individual containers in [15, 69]. Moreover, the MPC strategy will be applied for controlling container flows for intermodal freight transport operators. On the one hand, the MPC strategy works a receding horizon fashion that is similar to the replanning or updating strategies used in [15, 69]. On the other hand, the MPC strategy considers the future network evolution using a prediction network model when determining flow control actions.

2.2.4 Coordinated planning in intermodal freight transport

Coordinated planning problems in intermodal freight transport have been analyzed for multiple terminals at a seaport in [117, 140], for multiple stakeholders (e.g., carriers and freight forwarders) belonging to different intermodal chains [139], for multiple stakeholders in the same intermodal chain [50, 133].

In [140], a two-stage game method was used to investigate the benefits of joining the coalition for three container terminals within a port. A multi-agent MPC based approach was proposed in [117] for setting cooperative relations among terminals at a seaport. Following the two-state game method used in [140], vertical and horizontal cooperations among two truck-operating freight forwarders and a ship-operating freight forwarder are analyzed and compared [139]. Each of these three freight forwarders can move containers with either trucks or feeders between two locations, and tries to increase its market share. Moreover, a large amount of researches have investigated request allocation and profit sharing problems for cooperative planning of multiple truck carriers [79, 90, 166, 170].

In [133] collaborative planning among an intermodal freight transport operator and two carriers in the intermodal transport chain is considered. These two carriers are responsible for transporting containers from a shipper to an origin terminal and from a destination terminal to a receiver terminal, respectively. The intermodal operator selects services from ocean liners for the long-haul transport between the origin terminal and the destination terminal. A coordination scheme was proposed on the basis of an iterative exchange of transport proposals among the three parties, which generate transport proposals by solving their own optimization problems with mathematical planning models. The coordination procedure is stopped after a predefined number of iterations. In [50], cooperative receding horizon control scheme was used for coordinating terminal operations at nodes and transport operations on link of multimodal transport corridors.

In this thesis we present a new coordinated planning problem for multiple intermodal freight transport operators belonging to the same intermodal chain. These operators coordinate to provide synchromodal freight transport services among deep-sea terminals and inland terminals in the main haulage of port-hinterland container transport. Each of the operators controls container flows in different but interconnected service networks. These operators coordinate their actions to serve the transport demand at the lowest overall freight delivery cost. A related DMPC strategy has been used for coordinating multiple terminal operations in a seaport in [117], and for coordinating terminal operations and

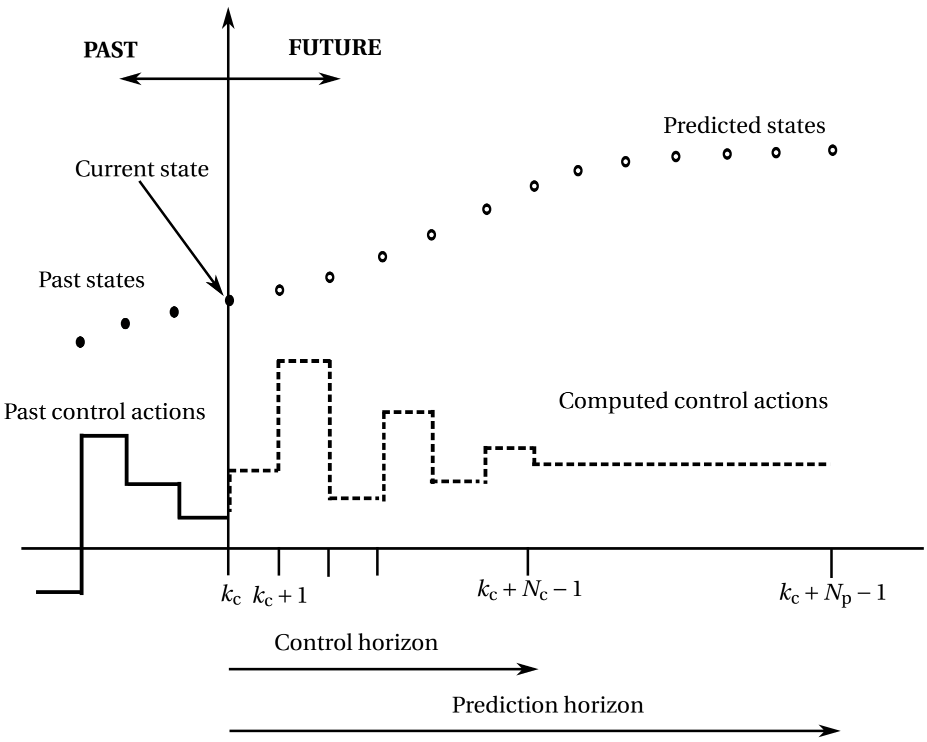

Figure 2.1: Conceptual representation of model predictive control (based on [63]).

transport operations in multimodal transport corridors in [50]. This thesis presents the DMPC strategy for coordinating the flow control actions of multiple intermodal freight transport operators.

2.3 Model predictive control

This section introduces the MPC methodology and its applications in intermodal freight transport in Section 2.3.1 and in Section 2.3.2, respectively.

2.3.1 The MPC methodology

MPC is an on-line model-based control strategy that solves a sequence of optimal control problems and implements them in a receding horizon way [63, 106, 136]. With the use of a dynamic system model and the current system information, MPC determines the control actions over a prediction period by making prediction and performing optimization, while only implementing the control actions for the current time step. This prediction and optimization process proceeds in a receding horizon fashion for each time step of the whole control period by moving one time step forward. Figure 2.1 shows the conceptual representation of MPC for time step k_c with a prediction period of N_p time steps. A control horizon of N_c time steps is typically introduced for reducing the computational complexity of the MPC problem. This control horizon means that all the control actions for time steps $k_\mathrm{c} + N_\mathrm{c}$ to $k_\mathrm{c} + N_\mathrm{p} - 1$ are fixed to the control actions for time step $k_\mathrm{c} + N_\mathrm{c} - 1$. After implementing the control actions computated for time step k_c, the same optimization based procedure will be performed for next time steps of the MPC problem.

MPC has been widely studied in industrial process control and more recently applied in traffic control [74, 78], power network control [48, 113, 121], water network management [123, 159], supply chain management [141, 169], and logistics [118, 119, 172, 173, 178]. In parallel with the various practical applications, the theoretical properties (e.g., the stability, the robustness) of MPC have also been investigated intensively [106, 136].

2.3.2 MPC for intermodal freight transport

There are a few papers in the literature on the application of MPC in intermodal freight transport. In [1] deep-sea container terminal operation is considered as a system of queues, with the queue lengths and container handling rates of equipment (e.g., cranes, reach stackers) as states and control actions, respectively. The dynamic evolution of these queues is described in terms of discrete-time equations. The terminal operation is formulated as an optimal control problem with the aim to minimize the transfer delays of containers at the terminal. The optimal control problem is solved using a receding horizon strategy. Recently, MPC has been used to control equipment (i.e., quay cranes, automated guided vehicles, and stacking cranes) for balancing throughput and energy consumption at terminals [172, 173], to achieve predictive path following for waterborne automated guided vehicles [178], to optimize the operation of terminals [118], and to achieve a desired modal split target at intermodal terminals [119].

The above mentioned papers focus on the application of MPC on issues inside terminals and among terminals inside a port. This thesis will consider both terminals and transport connections as an IFTN, and will propose a model predictive container flow control approach for synchromodal freight transport planning. The proposed network-wide MPC controller can interact with the lower-level MPC controllers developed for equipment [172, 173, 178], terminals [118], and ports [119] in port-hinterland container transport.

2.4 Distributed model predictive control

Centralized MPC will encounter challenges on the huge computational complexity, and the involvement of multiple stakeholders when applied for large-scale systems, e.g., railway networks, wind farms, and synchromodal freight transport. Especially, having multiple interacting stakeholders (or controllers) in the system will typically prevent a practical implementation of a centralized MPC approach, due to limited measurement, communication and control abilities of each stakeholder, the different, possibly conflicting, objectives of different stakeholders, the willingness and the level of coordination that these stakeholders want to participate in, etc. DMPC approaches are then proposed to address the above mentioned issues by allocating a MPC controller to each stakeholder for controlling each part of the systems, and performing certain coordination mechanisims among multiple MPC controllers in order to achieve certain system-wide performance while respect to the interests and abilities of each stakeholders [107]. A number of DMPC approaches have been developed and applied for various applications [23, 32, 107, 142].

This section will first review the literature on DMPC approaches based on the Augmented Lagrangian Relaxation (ALR) method and based on the Alternating Direction Method of Multipliers (ADMM) algorithm. These ALR-based DMPC approaches have been successfully applied for distributed control problems in various applications

[2, 48, 91, 113, 122, 123, 179]. The ADMM-based DMPC approach is a counterpart of the ALR-based DMPC approaches and has shown its effectiveness in coordinating control actions of multiple MPC controllers in many applications [34, 35, 56, 56, 87, 116, 146, 148]. There is so far no work in the literature applying ALR-based DMPC approaches or ADMM-based DMPC approaches for coordinated synchromodal freight transport planning.

2.4.1 ALR-based DMPC approaches

The augmented Lagrangian relaxation method [11, 138] employs two methods (i.e., auxiliary problem principle, and block coordinate descent) to decouple the quadratic terms in the augmented Lagrangian when the method of multipliers is directly applied to the original optimization problem with interconnecting constraints. These two methods will lead to two distributed optimization algorithms and consequently two ALR-based DMPC approaches, i.e., the parallel ALR-based DMPC approach and the serial ALR-based DMPC approach [122]. In [122] a detailed explanation on these two DMPC approaches is given and their control performance on interconnected linear time-invariant subsystems with an application to load-frequency control in a power network are compared. The numerical simulation shows that these two ALR-based DMPC approaches obtain the same performance as the performance resulted from a centralized MPC approach when the overall control problem is convex, and the serial ALR-based DMPC approach converges faster, by requiring fewer iterations, than the parallel ALR-based DMPC approach.

The parallel and serial ALR-based DMPC approaches have also been proposed and applied for frequency control in a multiple high-voltage-direct-current link power network [113], power flow management of a mixed energy network that integrates renewable energy sources and storage [48], reference tracking for water levels in irrigation canals [123], controlling the loss coefficient of valves and pressure injection of pumps in urban water supply networks [91], regulating the pneumatic valves in a three-tank benchmark [2], and signal split control in large-scale urban traffic networks [179]. Most of the applications are for interconnected linear time-invariant systems [2, 48, 91, 113, 122, 123], while the paper [179] consider transport networks with nonlinear and non-convex dynamics.

2.4.2 ADMM-based DMPC approaches

The alternating direction method of multipliers algorithm aims to combine the efficient convergence property of the method of multipliers and the decomposability of the dual ascent method. It was originally introduced in [62, 68]. In [20], a recent review on applying the ADMM algorithm for distributed optimization and statistical machine learning problems is presented. The ADMM algorithm and the method of multipliers share the same primal-variable-minimization and Lagrangian-multiplier-update structure in their iteration processes and both use the penalty parameter as the step size at the Lagrantian multiplier update steps. These two algorithms are different in the sense that the ADMM algorithm minimizes primal variables in an alternating fashion, while the method of multipliers minimizes them at the same time. Actually, the ADMM algorithm can be interpreted as a special case of the method of multipliers where the primal variables are not minimized jointly, but in a single Gauss-Seidel procedure [20, 148]. The Gauss-Seidel procedure consists of a series of iterations to solve an optimization problem with multiple variables. Each iteration only optimizes a part of the variables while using the most current information on the other variables [70].

Recently, some researches have focused on developing DMPC strategies for a network of coupled subsystems based on the ADMM algorithm. The papers [34, 35, 56, 87, 116, 148] consider linear time-invariant systems while the papers [56, 146] investigate nonlinear systems. The applications of the ADMM-based DMPC strategies cover various areas, e.g., a three tank system [87], a formation acquisition problem of multiple nonholonomic vehicles [56], TCP/IP congestion control [116], distributed control of a water delivery canal [35], and cooperative control of a wind farm [146].

2.4.3 DMPC for intermodal freight transport

Recently, research efforts in intermodal freight transport have been undertaken for developing hierarchical MPC schemes for intermodal container terminal operation [117, 118], and a cooperative MPC scheme for optimizing freight transport on multimodal corridors [50]. The paper [118] proposed to decompose the container terminal system into smaller subsystems, each of which is related to a transport connection available at the terminal. An MPC controller was adopted for the container flow assignment in each subsystem. A central coordinator was introduced to coordinate the use of limited handling resources at the terminal by all MPC controllers, and therefore a hierarchical MPC framework was established for optimizing terminal operations. Similarly, a multi-agent MPC system was also proposed to set cooperative relations among intermodal terminals for using transport capacity in a seaport [117]. The paper [50] decomposed the overall freight transport planning problem on multimodal corridors into terminal operations at network nodes and transport operations on network links. Either the terminal operation or the transport operation solves its own optimization problem with a particular planning goal and constraints. These operations interact two-by-two based on a cooperative receding horizon control scheme that uses Lagrangian relaxation for minimizing lateness of delivery of individual containers to end users.

Coordinated synchromodal freight transport planning approaches for multiple transport operators will be proposed using the ALR-based DMPC approaches and the ADMM-based DMPC approach in Chapter 5. The differences between the work in Chapter 5 and that in [50] lie in the reasoning and the way that the IFTN is partitioned. Instead of the node-link partition and the Lagrangian formulation of the cooperative planning problem used in [50], Chapter 5 considers that an IFTN is partitioned into a group of non-overlapping subnetworks because multiple operators are involved in the whole delivery process and each operator provides transport services in a subnetwork. Moreover, we will also adopt the augmented Lagrangian formulation of the coordinated planning problem instead of the Lagrangian formulation to overcome strict requirements on convexity or finiteness of the objective function.

2.5 Summary

The network modeling and transport planning approaches for intermodal freight transport and synchromodal freight transport in the literature have been reviewed in this chapter. We have also presented the basic concepts of model predictive control and distributed model predictive control, and discussed their various applications, in particular for intermodal freight transport. This overview brings out the challenges faced by existing approaches and motivates our proposed approaches in Chapters 3, 4, and 5 for overcoming these challenges.

Chapter 3

Models for Intermodal Freight Transport Networks

In this chapter, a linear Intermodal Freight Transport Network (IFTN) model is first proposed to represent the characteristics of intermodal freight transport systems at the tactical container flow level. Next, as an extension, a load-dependent IFTN model is presented to capture the impact of the freight truck flows generated by transport operators on the freeway transport times. Moreover, two benchmark systems are given to be used for evaluating container flow control strategies in later chapters.

The research presented in this chapter is based on [92, 94, 95, 97].

3.1 Introduction

As discussed in Chapter 1, a proper intermodal freight transport network model is an essential prerequisite for the employment of systems and control theory for the flow planning problem in an overall multi-level freight transport planning framework. This model should be capable of representing the characteristic behavior of intermodal freight transport systems up to the level of detail required by the flow planning problem investigated.

The intermodal freight transport system has several characteristics, e.g., modality changes at intermodal terminals, physical capacity constraints of terminals and transport connections, time-dependent transport times on freeways, timetables for trains and barges, and due time requirements for freight delivery. In this chapter we propose an IFTN model that does capture all of the above characteristic behaviors at the tactical flow level. First of all, adopting the concept of virtual network [39, 86] and the multiple-node method [14], this model allocates a node to each single-modal terminal at intermodal terminals and represents modality changes at intermodal terminals in terms of transfer links. This enables the analysis of both the transport connections and the modality changes in the same and explicit way. Secondly, the model formulates both generic dynamics and link-specific dynamics to model the common behavior shared by multiple types of transport connections in an IFTN and to capture their individual characteristic behavior, respectively. Thirdly, we adopt a discrete-time formulation, which enables the proposed model to represent the dynamic evolution of the IFTN and to make predictions of the network behavior at each control step. The proposed IFTN model is given in a linear discrete-time formulation.

As an extension of the linear IFTN model, a multi-class version of the nonlinear and non-convex speed-density relation model is proposed to include the impact of freight truck flows generated by the transport operator on the transport times on freeways. This extension leads to a load-dependent IFTN model. Moreover, two benchmark systems are constructed to illustrate the implementation of our proposed models. These two systems will later be used in Chapter 4 and in Chapter 5 for performance assessment in the simulation studies, respectively.

The reminder of this chapter is organized as follows. Section 3.2 presents the linear discrete-time IFTN model in detail. The extended load-dependent IFTN model is introduced in Section 3.3. The details of the two benchmark systems are given in Section 3.4. We conclude the chapter in Section 3.5.

3.2 The linear IFTN model

An intermodal freight transport network can be represented as a directed graph $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{M})$. The node set $\mathcal{V} = \mathcal{V}_{\text{road}} \cup \mathcal{V}_{\text{rail}} \cup \mathcal{V}_{\text{water}} \cup \mathcal{V}_{\text{store}}$ is a finite nonempty set with the sets $\mathcal{V}_{\text{road}}$, $\mathcal{V}_{\text{rail}}$, $\mathcal{V}_{\text{water}}$, and $\mathcal{V}_{\text{store}}$ representing truck terminals, train terminals, barge terminals, and storage yards shared by different single-modal terminals inside each intermodal terminal of the network, respectively. Single-modal terminals are separately presented even when they are part of a physical intermodal terminal. For a virtual network representation of an IFTN shown in Figure 3.1, there are four intermodal terminals indicated by dashed black ellipses, and at each of which there are multiple single-modal terminals and one storage yard located physically. For instant, intermodal terminal 1 consists of three single-modal terminals (i.e., truck terminal 1^{R}, train terminal 1^{T}, and barge terminal 1^{w}), and a storage yard 1^{S} that are respectively represented by nodes 1^{R}, 1^{T}, 1^{W}, and 1^{S}. The cardinalities of the node set $\mathcal{V}$, the truck-node set $\mathcal{V}_{\text{road}}$, the train-node set $\mathcal{V}_{\text{rail}}$, the barge-node set $\mathcal{V}_{\text{water}}$, and the store-node set $\mathcal{V}_{\text{store}}$ are $|\mathcal{V}| = N_{\text{node}}$, $|\mathcal{V}_{\text{road}}| = N_{\text{road}}$, $|\mathcal{V}_{\text{rail}}| = N_{\text{rail}}$, $|\mathcal{V}_{\text{water}}| = N_{\text{water}}$, and $|\mathcal{V}_{\text{store}}| = N_{\text{store}}$, respectively. The set $\mathcal{M} = \mathcal{M}_1 \cup \mathcal{M}_2$ represents transport modes and modality change types in the network with $\mathcal{M}_1 = \{\text{road}, \text{rail}, \text{water}, \text{store}\}$ and $\mathcal{M}_2 = \{m_1 \to m_2 | m_1 \in \mathcal{M}_1,\ m_2 \in \mathcal{M}_1 \text{ and } m_1 \neq m_2\}$. The link set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V} \times \mathcal{M}$ represents all available transport connections among nodes. A link (i, j, m) with $i \in \mathcal{V},\ j \in \mathcal{V}$, and $m \in \mathcal{M}$ will be denoted by $l_{i,j}^{m}$ in the network model. According to whether a modality change happens or not on a link, this link is categorized as a transfer link or a transport link, respectively. The cardinalities of the link set $\mathcal{E}$ and the link sets with different modalities are $|\mathcal{E}| = N_{\text{link}}$, $N_{\text{link}}^{\text{road}}$, $N_{\text{link}}^{\text{rail}}$, and $N_{\text{link}}^{\text{water}}$.

In Figure 3.1 the dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs indicate respectively, 4 transport links of the inland waterway network, 8 transport links of the road network, 2 transport links of the railway network, and 30 transfer links among four different types of transport modes (barges, trucks, trains, and store) at nodes of the IFTN.

The IFTN model is a discrete-time model with T_{s} (h) as the time step size. Since we focus on synchromodal freight transport planning at the tactical flow level, the use of a common discrete time step for all modalities (i.e., trucks, trains, and barges) in the dynamic network model is acceptable. The transport demand refers to the origin and destination pairs and the volumes of container flows that need to be delivered in the IFTN during the planning period. All origin and destination pairs belong to the set $\mathcal{O}_{\text{od}} \subseteq \mathcal{V} \times \mathcal{V}$ with cardinality of $|\mathcal{O}_{\text{od}}| = N_{\text{od}}$.

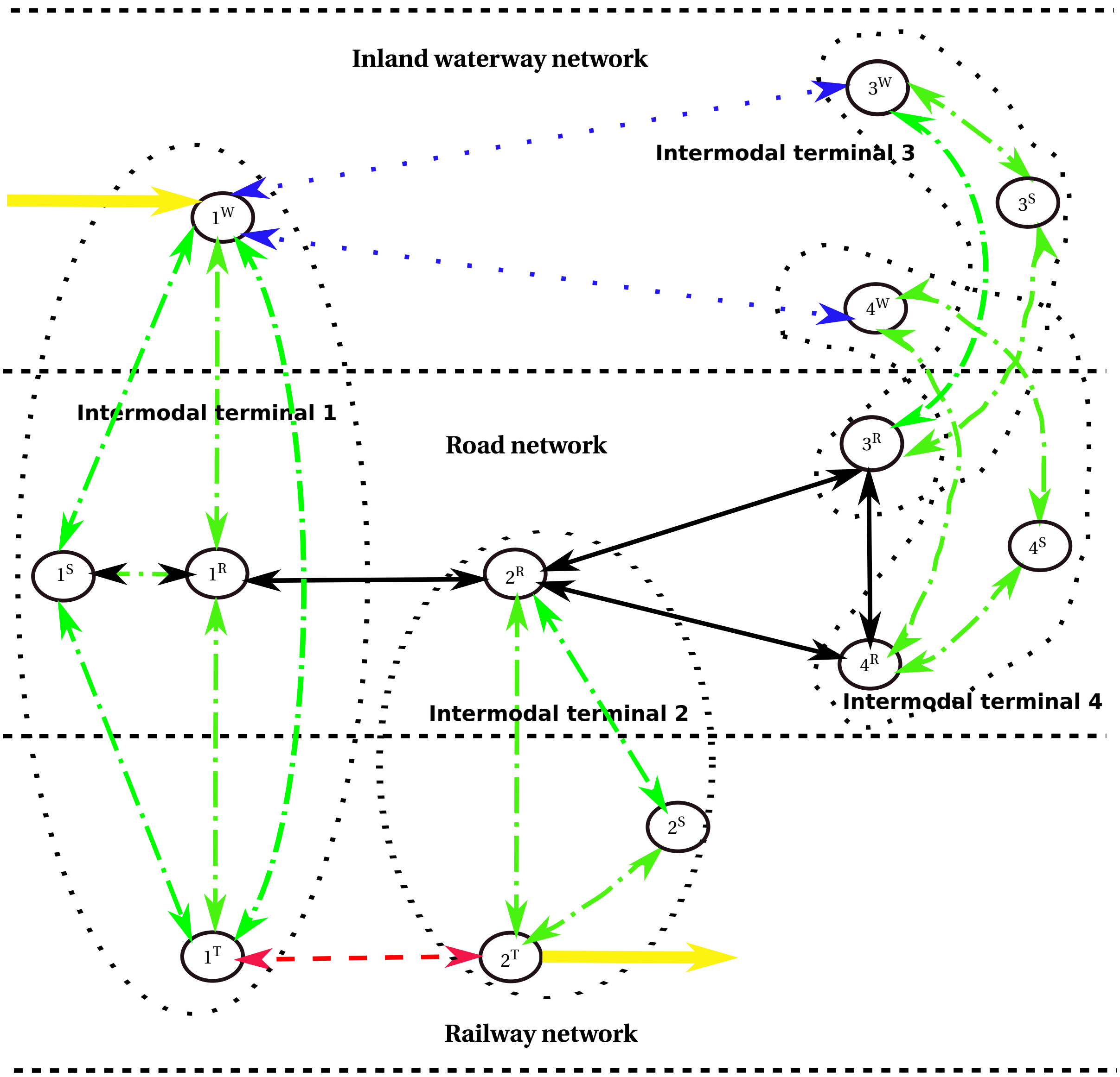

Figure 3.1: Example of a virtual network representation of an IFTN. Each double-headed arc in the figure represents two directed links with opposite directions. The two yellow arcs indicate the transport demand with the origin and destination pair (1^W, 2^T).

For each container flow with an origin and destination pair $(o,d) \in \mathcal{O}_{\text{od}}$, we denote its volume for time step k as $d_{o,d}(k)$. The dynamics of an IFTN consist of three parts: dynamics of nodes, dynamics of links, and dynamics of the interconnections among nodes and links. The dynamics of nodes describe the evolution of the incoming and outgoing container flows associated with the nodes while the dynamics of links describe that associated with the links. The evolution of container flows over the network is obtained by connecting container flows of both nodes and interconnecting links together. These dynamics will be modeled in more detail in the following subsections.

Before introducing the equations of the IFTN model, the main assumptions that are made throughout the modeling approach are listed:

- A common discrete time step is used for all modalities (i.e., trucks, trains, and barges) in the network model.
- Containers immediately leave the network once they arrive at their destinations.
- The link transport time is determined at the moment that a container flow enters a particular link. It is assumed that the transport time is fixed for this container flow while traveling on this link.
- Trains are operated under predetermined timetables on the railway links. Timetables for trains are predetermined in such a way that only one train can be loaded with containers at a specific time for each link of the railway network.
- Timetables for barges are modeled in the same way as timetables for trains.

We motivate the above assumptions as follows. First of all, different time scales should in general be used to represent the network behavior for different planning purposes in different types of transport networks. For example, the METANET traffic flow model typically uses a time step of 10 seconds [77, 127], while the freight train service network design models usually consider a time scale of one week [36]. For flow control purposes at the tactical planning level in synchromodal freight transport investigated in this thesis, a common time step of one or two hours is able to capture the evolution of container flows on links and at nodes of an IFTN.

Secondly, when containers arrive at their destination terminals in the main haulage, the drayage operators are informed to pick up and deliver containers to the shippers. This basically means that these containers leave the network of the intermodal freight operator.

Thirdly, transport times on links change dynamically as the traffic conditions (e.g., traffic volumes, and the possible occurrences of accidents) in the network change. The assumption on the link transport time is based on the consideration that traffic conditions will not change too much in a planning interval[1].

Fourthly, timetables are typically predetermined for container barges and freight trains, especially for the high-capacity barges and trains considered in this thesis. For the sake of simplicity, it is assumed that only one train can be loaded with containers at the origin terminal of a link at a specific time.

Finally, the timetables for trains determine the train transport information (e.g., the train departure time at the departure terminal, the train arrival time at the destination terminal,

[1] This thesis considers a planning interval of 1 or 2 hours. In the case of links with very long distances, they can be split into multiple links with shorter distances to guarantee our assumption.

and the train capacity) at the same level of detail as the barge transport information given by the timetables for barges. It is therefore reasonable to model timetables for trains and barges in the same way at the tactical container flow level.

3.2.1 Nodes in the IFTN

The dynamics of node i are formulated as

$$\begin{aligned} x_{i,o,d}(k+1) = x_{i,o,d}(k) + \sum_{(j,m)\in\mathcal{N}_i^{\text{in}}} y_{j,i,o,d}^m(k)T_\text{s} - \sum_{(j,m)\in\mathcal{N}_i^{\text{out}}} u_{i,j,o,d}^m(k)T_\text{s} + \\ d_{i,o,d}^{\text{in}}(k)T_\text{s} - d_{i,o,d}^{\text{out}}(k)T_\text{s}, \quad \forall (o,d)\in\mathcal{O}_\text{od}, \forall i,j\in\mathcal{V}, \forall m\in\mathcal{M}, \forall k, \end{aligned} \tag{3.1}$$

where

- $x_{i,o,d}(k)$ (TEU)[2] is the number of containers corresponding to the transport demand with origin and destination pair (o,d), staying at node i at time kT_s.

- $y_{j,i,o,d}^m(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), entering node i through link $l_{j,i}^m$, $(j,m)\in\mathcal{N}_i^{\text{in}}$ for time step k, where the set $\mathcal{N}_i^{\text{in}}$ is defined as

  $$\mathcal{N}_i^{\text{in}} = \{(j,m) \mid l_{j,i}^m \text{ is an incoming link for node } i\}.$$

  The value of $y_{j,i,o,d}^m(k)$ equals zero when $i=o$ (which implies that node i is actually the origin node o of the transport demand).

- $u_{i,j,o,d}^m(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), leaving node i through link $l_{i,j}^m$, $(j,m)\in\mathcal{N}_i^{\text{out}}$ for time step k, where the set $\mathcal{N}_i^{\text{out}}$ is defined as

  $$\mathcal{N}_i^{\text{out}} = \{(j,m) \mid l_{i,j}^m \text{ is an outgoing link for node } i\}.$$

  The value of $u_{i,j,o,d}^m(k)$ equals zero when $i=d$ (which implies that node i is actually the final destination node d of the transport demand).

- $d_{i,o,d}^{\text{in}}(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), entering node i from the outside of the network for time step k. The value of $d_{i,o,d}^{\text{in}}(k)$ equals $d_{o,d}(k)$ when $i=o$, otherwise it is zero.

- $d_{i,o,d}^{\text{out}}(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), arriving at the final destination node i for time step k. The value of $d_{i,o,d}^{\text{out}}(k)$ equals $\sum_{(j,m)\in\mathcal{N}_i^{\text{in}}} y_{j,i,o,d}^m(k)$ when $i=d$, otherwise it is zero.

[2]TEU stands for Twenty-foot Equivalent Unit, which is a standard unit for counting containers of various capacities and for describing the capacities of container trucks, container trains, container ships, and container terminals. In this thesis the number of containers is measured in TEUs.

The corresponding constraints for node i are formulated as:

$$\sum_{(o,d)\in\mathcal{O}_{\text{od}}}\left(\sum_{(j,m)\in\mathcal{N}_i^{\text{in}}} y_{j,i,o,d}^{m}(k)+d_{i,o,d}^{\text{in}}(k)\right)\le h_i^{\text{in}},\quad \forall i\in\mathcal{V},\forall k, \tag{3.2}$$

$$\sum_{(o,d)\in\mathcal{O}_{\text{od}}} x_{i,o,d}(k)\le S_i,\quad \forall i\in\mathcal{V},\forall k, \tag{3.3}$$

$$\sum_{(o,d)\in\mathcal{O}_{\text{od}}}\left(\sum_{(j,m)\in\mathcal{N}_i^{\text{out}}} u_{i,j,o,d}^{m}(k)+d_{i,o,d}^{\text{out}}(k)\right)\le h_i^{\text{out}},\quad \forall i\in\mathcal{V},\forall k, \tag{3.4}$$

$$x_{i,o,d}(k), y_{j,i,o,d}^{m}(k), u_{i,j,o,d}^{m}(k), d_{i,o,d}^{\text{in}}(k), d_{i,o,d}^{\text{out}}(k)\ge 0,\quad \forall (o,d)\in\mathcal{O}_{\text{od}},\forall i,j\in\mathcal{V},\forall m\in\mathcal{M},\forall k, \tag{3.5}$$

where

- h_i^{in} (TEU/h) and h_i^{out} (TEU/h) are the maximal container loading and unloading rates of the equipment at node i, respectively.
- S_i (TEU) is the storage capacity at node i.
- constraints (3.5) guarantee that the corresponding variables are non-negative.

3.2.2 Links in the IFTN

Transport links with different modalities in the IFTN exhibit both common behavior and link specific behavior. We first formulate the common dynamics for all links in the network, and then derive individual models for links with different modalities on the basis of their particular link properties, i.e., the density-speed relations on freeways, and the timetables for trains and barges.

The dynamics of link $l_{i,j}^{m}$ are formulated as:

$$q_{i,j,o,d}^{m,\text{out}}(k)=\sum_{k_{\text{e}}\in\mathcal{K}_{\text{e}}(k)} q_{i,j,o,d}^{m,\text{in}}(k_{\text{e}}),\quad \forall (i,j,m)\in\mathcal{E},\forall (o,d)\in\mathcal{O}_{\text{od}},\forall k, \tag{3.6}$$

$$x_{i,j,o,d}^{m}(k+1)=x_{i,j,o,d}^{m}(k)+\left(q_{i,j,o,d}^{m,\text{in}}(k)-q_{i,j,o,d}^{m,\text{out}}(k)\right)T_{\text{s}},\ \forall (i,j,m)\in\mathcal{E},\forall (o,d)\in\mathcal{O}_{\text{od}},\forall k, \tag{3.7}$$

where

- $q_{i,j,o,d}^{m,\text{out}}(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), leaving link $l_{i,j}^{m}$ for time step k.
- $q_{i,j,o,d}^{m,\text{in}}(k)$ (TEU/h) is the container flow corresponding to the transport demand with origin and destination pair (o,d), entering link $l_{i,j}^{m}$ for time step k.
- $\mathcal{K}_{\text{e}}(k)$ is defined as the set $\{k_{\text{e}} \mid k-t_{i,j}^{m,\max}\le k_{\text{e}}\le k-1 \text{ and } k_{\text{e}}+t_{i,j}^{m}(k_{\text{e}})=k\}$. The set $\mathcal{K}_{\text{e}}(k)$ consists of all the time steps k_{e} satisfying $k_{\text{e}}\ge k-t_{i,j}^{m,\max}$ and $k_{\text{e}}\le k-1$, at which if container flows enter link $l_{i,j}^{m}$, these flows will leave the link for time step k.
- $x_{i,j,o,d}^{m}(k)$ (TEU) is the number of containers corresponding to the transport demand with origin and destination pair (o,d), traveling in link $l_{i,j}^{m}$ at time kT_{s}.

- $t^{m}_{i,j}(k)T_{\mathrm{s}}$ (h) is the transport time on link $l^{m}_{i,j}$ at time kT_{s}. We assume that $T^{m}_{i,j}(k) = t^{m}_{i,j}(k)T_{\mathrm{s}}$ for some positive integer $t^{m}_{i,j}(k)$. Moreover, we assume that $t^{m}_{i,j}(k) \leq t^{m,\max}_{i,j}$ for some integer $t^{m,\max}_{i,j}$. The maximum transport time on link $l^{m}_{i,j}$ is $t^{m,\max}_{i,j}T_{\mathrm{s}}$ (h).

The corresponding constraints for link $l^{m}_{i,j}$ are formulated as:

$$\sum_{(o,d)\in\mathcal{O}_{\mathrm{od}}} q^{m,\mathrm{in}}_{i,j,o,d}(k) \leq C^{m,\mathrm{in}}_{i,j}(k), \quad \forall(i,j,m)\in\mathcal{E}, \forall k, \tag{3.8}$$

$$x^{m}_{i,j,o,d}(k), q^{m,\mathrm{in}}_{i,j,o,d}(k), q^{m,\mathrm{out}}_{i,j,o,d}(k) \geq 0, \ \forall(i,j,m)\in\mathcal{E}, \forall(o,d)\in\mathcal{O}_{\mathrm{od}}, \forall k, \tag{3.9}$$

where

- $C^{m,\mathrm{in}}_{i,j}(k)$ (TEU/h) is the maximum entering container flow of link $l^{m}_{i,j}$ for time step k.

- constraints (3.9) make sure that the corresponding variables are non-negative.

3.2.3 Dynamics of freeway links

We assume that freight trucks mainly use freeway connections in the road network for freight transport among terminals. In the rest of the thesis we will use freeways or freeway links when referring to the road network. Transport times on the freeway links are influenced by the traffic volumes on these links. Therefore, models of the dynamics of freeway links need to take into account the effect of traffic conditions on transport time. There are a number of possible models to represent the relationship between transport time and traffic conditions on freeway links, e.g., simple structured and static models found by historical data analysis, the link transmission model [177], and more complex dynamic models [40].

The modeling approach for dynamics of freeway links in this section is elaborated as follows. We propose to use a speed-density relation with a fundamental-diagram-like shape to model the transport times on freeways. The basic concepts regarding the fundamental diagram of traffic flow theory are summarized in Appendix A. We motivate the use of the proposed approach considering the fact that there are already some fundamental-diagram-shape-like models available in the literature to model speed-density relationships for large spatial and temporal urban areas [41, 42, 64, 65] and freeway networks [26, 31, 66], such as the macroscopic fundamental diagram model, or the network fundamental diagram model. The proposed speed-density relation involves two aggregated variables: the space-time mean traffic density, and the space-time mean speed. For the sake of simplification, we will use traffic density and traffic flow speed as the simplified names of space-time mean traffic density and space-time mean traffic flow speed in the rest of the thesis. The traffic flow speed on link $l^{\mathrm{road}}_{i,j}$ for time step k, $v^{\mathrm{road}}_{i,j}(k)$, and the corresponding transport time, $t^{\mathrm{road}}_{i,j}(k)$, are motivated as:

$$v^{\mathrm{road}}_{i,j}(k) = \max\left(v^{\mathrm{road}}_{i,j,\mathrm{free}} \exp\left[-\frac{1}{a^{\mathrm{road}}_{i,j}} \left(\frac{\rho^{\mathrm{road}}_{i,j}(k)}{\rho^{\mathrm{road}}_{i,j,\mathrm{crit}}} \right)^{a^{\mathrm{road}}_{i,j}} \right], v^{\mathrm{road}}_{i,j,\min} \right), \tag{3.10}$$

$$t^{\mathrm{road}}_{i,j}(k) = \mathrm{round}\left(\frac{L^{\mathrm{road}}_{i,j}}{v^{\mathrm{road}}_{i,j}(k)} \frac{1}{T_{\mathrm{s}}} \right), \tag{3.11}$$

where

- $L_{i,j}^{\text{road}}$ (km), $\rho_{i,j}^{\text{road}}(k)$ (veh/km/lane), $v_{i,j}^{\text{road}}(k)$ (km/h), and $t_{i,j}^{\text{road}}(k)$ (h) are the length of, the traffic density on, the average speed on, and the average transport time on link $l_{i,j}^{\text{road}}$ for time step k, respectively.

- $v_{i,j,\text{free}}^{\text{road}}$, $a_{i,j}^{\text{road}}$, and $\rho_{i,j,\text{crit}}^{\text{road}}$ are the model parameters of the speed-density relation model. The minimum speed on link $l_{i,j}^{\text{road}}$ is $v_{i,j,\text{min}}^{\text{road}}$ (km/h).

- $\rho_{i,j}^{\text{road,max}}$ (veh/km/lane) is the maximum allowed traffic density on link $l_{i,j}^{\text{road}}$. The maximum number of transport time steps $t_{i,j}^{\text{road,max}}$ is determined by $\rho_{i,j}^{\text{road,max}}$ through (3.10) and (3.11).

It is noteworthy that the nonlinear density-speed relation model (3.10)–(3.11) for freeways can be evaluated in an off-line fashion. Therefore, this density-speed relation model will not introduce nonlinearities in online computations involving the IFTN model.

Remark 3.1 The density-speed relation model (3.10)–(3.11) requires the predicted traffic density information on the freeways as an input. In case reliable travel time estimations in the road network are available from other parties (e.g., traffic management departments), these estimated travel times can directly be used in the presented linear IFTN model. Then there is no need to use the density-speed relation model (3.10)–(3.11), and consequently it is not necessary to require the predicted traffic density information on the freeways as an input. The main reason for including the density-speed relation model (3.10)–(3.11) in the IFTN model is to be consistent with the representation of the load-dependent IFTN model presented later on in Section 3.3. That load-dependent IFTN model takes into account the impact of freight trucks operated by the transport operator on the freeway transport times, and requires to explicitly consider the relation between traffic density and traffic speed. □

3.2.4 Dynamics of railway links

A key feature distinguishing railway and inland waterway transport from road transport is that there are typically timetables for operating container trains and barges. In this section, we model timetables for trains. We consider scheduled trains that are operated under predetermined timetables on the railway links. Timetables provide the detailed information of each transport service on each transport connection of the railway network during a given freight transport planning period, i.e., the time instant at which the trains become available at the departure terminal, the capacity of trains, the handling capacity of equipment for serving trains at the departure terminal, the departure time instants of trains at the departure terminal, and the arrival time instants of trains at the destination terminal.

The basic idea is to take into account both trains waiting at the departure terminal for loading containers and trains running on the railway links in the analysis and modeling of the evolution of container flows on the links. For link $l_{i,j}^{\text{rail}}$ in the railway network, we define the set of trains, $\mathscr{S}_{i,j}^{\text{rail}}$, that are scheduled to travel from terminal i to terminal j according to a pre-scheduled timetable. For a scheduled train $s \in \mathscr{S}_{i,j}^{\text{rail}}$, this timetable determines the train capacity $S_{i,j,s}^{\text{rail}}$ (TEU), the time instant $k_{i,j,s}^{\text{rail,available}} T_{\text{s}}$ (h) at which scheduled train s becomes available at terminal i, the container loading capacity of equipment for serving this train $h^{\text{rail}}_{i,j,s}$ (TEU/h) at terminal i, the train departure time instant $k^{\text{rail,departure}}_{i,j,s} T_{\text{s}}$ (h) from terminal i, and the train arrival time instant $k^{\text{rail,arrival}}_{i,j,s} T_{\text{s}}$ (h) at terminal j. To capture the discontinuity of transport services caused by these timetables, time-dependent transport times and time-dependent maximum entering container flows on links of the railway network are introduced.

First of all, the time-dependent transport time $t^{\text{rail}}_{i,j}(k)\, T_{\text{s}}$ on link $l^{\text{rail}}_{i,j}$ for time step k is the time that will be taken by container flows to arrive at terminal j if they enter the link $l^{\text{rail}}_{i,j}$ during time step k. The time-dependent transport time $t^{\text{rail}}_{i,j}(k)\, T_{\text{s}}$ includes $t^{\text{rail}}_{i,j,\text{waiting}}(k)\, T_{\text{s}}$, (i.e., the time that container flows spend waiting for the trains to depart from terminal i), and $t^{\text{rail}}_{i,j,\text{traveling}}(k)\, T_{\text{s}}$, (i.e., the actual train traveling time on link $l^{\text{rail}}_{i,j}$). Depending on whether a scheduled train is available at terminal i for time step k and will travel to terminal j via link $l^{\text{rail}}_{i,j}$, the value of $t^{\text{rail}}_{i,j}(k)$ can be calculated by:

$$\begin{aligned} t^{\text{rail}}_{i,j}(k) &= t^{\text{rail}}_{i,j,\text{waiting}}(k) + t^{\text{rail}}_{i,j,\text{traveling}}(k) \\ &= \begin{cases} k^{\text{rail,arrival}}_{i,j,s'} - k, & \text{if } k^{\text{rail,available}}_{i,j,s'} < k \le k^{\text{rail,departure}}_{i,j,s'}, \\ & \text{for some } s' \in \mathscr{S}^{\text{rail}}_{i,j}, \\ k^{\text{rail,arrival}}_{i,j,s} - k^{\text{rail,available}}_{i,j,s}, & \text{if } k^{\text{rail,departure}}_{i,j,s-1} < k \le k^{\text{rail,available}}_{i,j,s}, \\ & \text{for some } s \in \mathscr{S}^{\text{rail}}_{i,j}, \end{cases} \end{aligned} \tag{3.12}$$

where

- the first option in (3.12) means that: when there is a scheduled train $s' \in \mathscr{S}^{\text{rail}}_{i,j}$ waiting at terminal i for time step k, containers can be first loaded on the train s' during time step k, next they stay on this train for $t^{\text{rail}}_{i,j,\text{waiting}}(k) = k^{\text{rail,departure}}_{i,j,s'} - k$ time steps at terminal i, and finally they are carried by this train for $t^{\text{rail}}_{i,j,\text{traveling}}(k) = k^{\text{rail,arrival}}_{i,j,s'} - k^{\text{rail,departure}}_{i,j,s'}$ time steps to travel on link $l^{\text{rail}}_{i,j}$ to terminal j.

- the second option in (3.12) indicates that: when there are no scheduled trains waiting at terminal i for time step k, containers need to wait until the earliest next train $s \in \mathscr{S}^{\text{rail}}_{i,j}$ becomes available; next they can then be loaded on the train s during the earliest possible time step $k^{\text{rail,available}}_{i,j,s}$ and stay for $t^{\text{rail}}_{i,j,\text{waiting}}(k) = k^{\text{rail,departure}}_{i,j,s} - k^{\text{rail,available}}_{i,j,s}$ time steps at terminal i, and finally they are carried by this train for $t^{\text{rail}}_{i,j,\text{traveling}}(k) = k^{\text{rail,arrival}}_{i,j,s} - k^{\text{rail,departure}}_{i,j,s}$ time steps to travel on link $l^{\text{rail}}_{i,j}$ to terminal j.

As discussed in Section 3.1, it is assumed that timetables for trains are predetermined in such a way that only one train can be loaded with containers at a specific time for each link of the railway network. This assumption implies that $k^{\text{rail,available}}_{i,j,s} < k^{\text{rail,departure}}_{i,j,s}$ and $k^{\text{rail,available}}_{i,j,s} > k^{\text{rail,departure}}_{i,j,s-1}$, $\forall s \in \mathscr{S}^{\text{rail}}_{i,j}$ hold on each railway link $(i,j,\text{rail}) \in \mathscr{E}$. This guarantees that the two options in (3.12) are mutually exclusive. The maximum transport time $t^{\text{rail,max}}_{i,j} T_{\text{s}}$ (h) of link

$l_{i,j}^{\text{rail}}$ is determined by:

$$t_{i,j}^{\text{rail,max}} = \max_{s \in \mathscr{S}_{i,j}^{\text{rail}}} (k_{i,j,s}^{\text{rail,arrival}} - k_{i,j,s}^{\text{rail,available}}). \tag{3.13}$$

Secondly, the container loading process can only start after a train becomes available at the terminal and should stop when this train departs. This implies that containers can only be loaded on train $s \in \mathscr{S}_{i,j}^{\text{rail}}$ and simultaneously enter link $l_{i,j}^{\text{rail}}$ during a time period $\left[k_{i,j,s}^{\text{rail,available}} T_{\text{s}},\, k_{i,j,s}^{\text{rail,departure}} T_{\text{s}}\right)$. Therefore, the time-dependent maximum entering container flow $C_{i,j}^{\text{rail,in}}(k)$ on link $l_{i,j}^{\text{rail}}$ for time step k is determined as:

$$C_{i,j}^{\text{rail,in}}(k) = \begin{cases} h_{i,j,s}^{\text{rail}}, & \text{if } k_{i,j,s}^{\text{rail,available}} \le k < k_{i,j,s}^{\text{rail,departure}}, \text{ for some } s \in \mathscr{S}_{i,j}^{\text{rail}}, \\ 0, & \text{otherwise}, \end{cases} \tag{3.14}$$

where

- the first option in (3.14) states that: when there is a scheduled train $s \in \mathscr{S}_{i,j}^{\text{rail}}$ available at terminal i for time step k that will travel to terminal j via link $l_{i,j}^{\text{rail}}$, containers can be loaded on the train s during time step k. The maximum loading rate for train s at terminal i, i.e., $h_{i,j,s}^{\text{rail}}$ (TEU/h), is the container loading capacity of equipment that are allocated for serving this train at the terminal.

- the second option in (3.14) means that: when there are no scheduled trains that will travel to terminal j via link $l_{i,j}^{\text{rail}}$, available at terminal i for time step k, it is not possible to load containers on trains.

- the two options in (3.14) are naturally mutually exclusive.

Moreover, each scheduled train $s \in \mathscr{S}_{i,j}^{\text{rail}}$ on link $l_{i,j}^{\text{rail}}$ is associated with a train capacity $S_{i,j,s}^{\text{rail}}$ (TEU), which imposes constraints on the total volume of container flows being loaded on this train during the container loading process. These constraints are formulated as:

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \sum_{k_{\text{e}}=k_{i,j,s}^{\text{rail,available}}}^{k_{i,j,s}^{\text{rail,departure}}} q_{i,j,o,d}^{\text{rail,in}}(k_{\text{e}}) T_{\text{s}} \le S_{i,j,s}^{\text{rail}}, \quad s \in \mathscr{S}_{i,j}^{\text{rail}}, \forall \left(i, j, \text{rail}\right) \in \mathscr{E}. \tag{3.15}$$

3.2.5 Dynamics of inland waterway links

Container barges in the inland waterway network are different from container trains in the railway network in terms of their transport capacities, their operation rules, traffic control rules in the physical infrastructures that they operate, and handling equipments needed to serve them at terminals. But at the tactical container flow level container transport services provided by them are both characterized by the existence of timetables. In this section, we model timetables for barges in the same way as timetables for trains. For link $l_{i,j}^{\text{water}}$ in the inland waterway network, we define the set of barges, $\mathscr{S}_{i,j}^{\text{water}}$, that are scheduled to travel from terminal i to terminal j according to a pre-scheduled timetable. For a scheduled barge $s \in \mathscr{S}_{i,j}^{\text{water}}$, this timetable determines the barge capacity $S_{i,j,s}^{\text{water}}$ (TEU), the time instant

$k_{i,j,s}^{\text{water,available}} T_{\text{s}}$ (h) at which scheduled barge s becomes available at terminal i, the container loading capacity of equipment for serving this barge $h_{i,j,s}^{\text{water}}$ (TEU/h) at terminal i, the barge departure time instant $k_{i,j,s}^{\text{water,departure}} T_{\text{s}}$ (h) from terminal i, and the barge arrival time instant $k_{i,j,s}^{\text{water,arrival}} T_{\text{s}}$ (h) at terminal j. The time-dependent transport time $t_{i,j}^{\text{water}}(k) T_{\text{s}}$ (h), the maximum transport time $t_{i,j}^{\text{water,max}} T_{\text{s}}$ (h) of link $l_{i,j}^{\text{water}}$, and the time-dependent maximum entering container flows $C_{i,j}^{\text{water,in}}(k)$ of link $l_{i,j}^{\text{water}}$ in the inland waterway network are determined as:

$$
\begin{aligned}
t_{i,j}^{\text{water}}(k) &= t_{i,j,\text{waiting}}^{\text{water}}(k) + t_{i,j,\text{traveling}}^{\text{water}}(k) \\
&= \begin{cases} k_{i,j,s'}^{\text{water,arrival}} - k, & \text{if } k_{i,j,s'}^{\text{water,available}} < k \le k_{i,j,s'}^{\text{water,departure}}, \\ & \text{for some } s' \in \mathcal{S}_{i,j}^{\text{water}}, \\ k_{i,j,s}^{\text{water,arrival}} - k_{i,j,s}^{\text{water,available}}, & \text{if } k_{i,j,s-1}^{\text{water,departure}} < k \le k_{i,j,s}^{\text{water,available}}, \\ & \text{for some } s \in \mathcal{S}_{i,j}^{\text{water}}, \end{cases}
\end{aligned}
\tag{3.16}
$$

$$
t_{i,j}^{\text{water,max}} = \max_{s \in \mathcal{S}_{i,j}^{\text{water}}} \left(k_{i,j,s}^{\text{water,arrival}} - k_{i,j,s}^{\text{water,available}}\right),
\tag{3.17}
$$

$$
C_{i,j}^{\text{water,in}}(k) = \begin{cases} h_{i,j,s}^{\text{water}}, & \text{if } k_{i,j,s}^{\text{water,available}} \le k < k_{i,j,s}^{\text{water,departure}}, \text{ for some } s \in \mathcal{S}_{i,j}^{\text{water}}, \\ 0, & \text{otherwise.} \end{cases}
\tag{3.18}
$$

The constraints on the total volume of container flows being loaded on barges during the loading process are formulated as:

$$
\sum_{(o,d)\in\mathcal{O}_{\text{od}}} \sum_{k_{\text{e}}=k_{i,j,s}^{\text{water,available}}}^{k_{i,j,s}^{\text{water,departure}}} q_{i,j,o,d}^{\text{water,in}}(k_{\text{e}}) T_{\text{s}} \le S_{i,j,s}^{\text{water}}, \quad s \in \mathcal{S}_{i,j}^{\text{water}}, \forall \left(i,j,\text{water}\right) \in \mathcal{E}.
\tag{3.19}
$$

3.2.6 Interactions between nodes and links

Container flows travel over an IFTN and create interactions between nodes and links. These interactions are formulated as follows:

$$
q_{i,j,o,d}^{m,\text{in}}(k) = u_{i,j,o,d}^{m}(k), \quad \forall i \in \mathcal{V}, \forall (j,m) \in \mathcal{N}_i^{\text{out}}, \forall (o,d) \in \mathcal{O}_{\text{od}}, \forall k,
\tag{3.20}
$$

$$
y_{i,j,o,d}^{m}(k) = q_{i,j,o,d}^{m,\text{out}}(k), \quad \forall j \in \mathcal{V}, \forall (i,m) \in \mathcal{N}_j^{\text{in}}, \forall (o,d) \in \mathcal{O}_{\text{od}}, \forall k,
\tag{3.21}
$$

where

- equation (3.20) states the interactions between node i and each of its outgoing link $l_{i,j}^{m}$. It represents that the volumes of the container flows leaving node i through link $l_{i,j}^{m}$ are equal to the volumes of the container flows entering link $l_{i,j}^{m}$ for time step k.
- equation (3.21) states the interactions between each incoming link $l_{i,j}^{m}$ and node j. It represents that the volumes of the container flows leaving link $l_{i,j}^{m}$ and entering into node j are equal to the volumes of the container flows entering node j through link $l_{i,j}^{m}$ for time step k.

3.2.7 Quantities of the IFTN model

The complete IFTN model consists of (3.1)–(3.21). It is a linear discrete-time network model. Four types of quantities exist in this linear IFTN model. To make a distinction, they are listed as follows:

- Problem data (known):
  $h_i^{\text{in}}, S_i, h_i^{\text{out}}, C_{i,j}^{m,\text{in}}(k), L_{i,j}^{\text{road}}, \lambda_{i,j}^{\text{road}}, L_{\text{truck}}$, L_{other}, $v_{i,j,\text{free}}^{\text{road,truck}}(k)$, $a_{i,j}^{\text{road,truck}}$, $\rho_{i,j,\text{crit}}^{\text{road,truck}}$, $v_{i,j,\text{min}}^{\text{road}}$,
  $t_{i,j,s}^{\text{rail,available}}(k), t_{i,j,s}^{\text{rail,departure}}(k), t_{i,j,s}^{\text{rail,arrival}}(k), h_{i,j,s}^{\text{rail}}, S_{i,j,s}^{\text{rail}}$, $h_{i,j,s}^{\text{water}}$, $S_{i,j,s}^{\text{water}}$, $t_{i,j,s}^{\text{water,available}}(k)$, $t_{i,j,s}^{\text{water,departure}}(k)$, $t_{i,j,s}^{\text{water,arrival}}(k)$, T_{s},
- Disturbances (estimated):
  $d_{i,o,d}^{\text{in}}(k)$, $\rho_{i,j}^{\text{road,other}}(k)$,
- System states:
  $x_{i,o,d}(k), x_{i,j,o,d}^{m}(k), y_{j,i,o,d}^{m}(k), q_{i,j,o,d}^{m,\text{out}}(k)$, $d_{i,o,d}^{\text{out}}(k)$, $x_{i,j,o,d}^{\text{road}}(k)$, $\rho_{i,j}^{\text{road}}(k)$, $v_{i,j}^{\text{road}}(k)$, $t_{i,j}^{\text{road}}(k)$, $t_{i,j}^{\text{rail}}(k), t_{i,j,\text{waiting}}^{\text{rail}}(k), t_{i,j,\text{traveling}}^{\text{rail}}(k), C_{i,j}^{\text{rail,in}}(k)$, $C_{i,j}^{\text{water,in}}(k)$,
- Control actions:
  $u_{i,j,o,d}^{m}(k), q_{i,j,o,d}^{m,\text{in}}(k)$.

The first six state variables are guaranteed to be non-negative by the constraints (3.5) and (3.9) in this linear IFTN model. The last two state variables are limited to be non-negative by (3.14) and (3.18). The rest of state variables refers to the traffic densities, the traffic flow speed, and the transport times on links of the network, and will therefore not be negative. Moreover, we assume that the container handling and storage capacities at terminals are large enough to serve the possible largest transport demand in the network. This assumption will prevent the linear IFTN model from being infeasible in the transport planning process.

3.3 The load-dependent IFTN model

Typically, the truck flow generated by an intermodal freight transport operator has a limited or even negligible influence on transport time on freeways. Therefore, the speed-density relation given in Section 3.2.3 is usually adequate for modeling the transport times on freeways. However, a large-size transport operator might be able to influence the traffic conditions on freeways with its own freight truck flows under certain circumstances. These circumstances could occur on the freeways that connect a deep-sea port with nearby inland terminals around the port areas when the traffic densities on these freeways are quite high during rush hours. Explicitly taking into account the impact of the freight truck flow generated by a large-size transport operator will prevent assigning excessive containers to the freeways, and consequently reduce the occurrences of traffic congestion in the above mentioned circumstances. Therefore, this section proposes a multi-class version of the nonlinear and non-convex speed-density relation to model the influence of freight truck flows on transport time on freeways.

Taking into account the heterogeneity of traffic flows, we categorize them into two parts: the freight truck flows and other traffic flows. The freight truck flows correspond to intermodal container transport on freeway links. Essentially, these two types of traffic flows together determine transport times on freeway links. We adopt the concept of “equivalent vehicles” to take into account the differences in the typical lengths of the vehicle for each type of traffic flow [49]. This concept introduces a regular vehicle and expresses flow variables for different types of traffic flows in equivalent vehicles. For instance, a freight truck could count for three regular vehicles when choosing the passenger car as the regular vehicle. The freight truck flow speed on link $l_{i,j}^{\text{road}}$ for time step k, $v_{i,j}^{\text{road,truck}}(k)$, and the corresponding transport time, $t_{i,j}^{\text{road,truck}}(k)$, are derived as:

$$\rho_{i,j}^{\text{road,total}}(k) = \frac{L_{\text{truck}}}{L_{\text{other}}}\left(\sum_{(o,d)\in\mathcal{O}_{\text{od}}} \frac{1}{L_{i,j}^{\text{road}}\lambda_{i,j}^{\text{road}}} x_{i,j,o,d}^{\text{road}}(k)\right) + \rho_{i,j}^{\text{road,other}}(k) \tag{3.22}$$

$$v_{i,j}^{\text{road,truck}}(k) = \max\left(v_{i,j,\text{free}}^{\text{road,truck}} \exp\left[-\frac{1}{a_{i,j}^{\text{road,truck}}} \left(\frac{\rho_{i,j}^{\text{road,total}}(k)}{\rho_{i,j,\text{crit}}^{\text{road}}} \right)^{a_{i,j}^{\text{road,truck}}} \right], v_{i,j,\text{min}}^{\text{road}} \right), \tag{3.23}$$

$$t_{i,j}^{\text{road,truck}}(k) = \text{round}\left(\frac{L_{i,j}^{\text{road}}}{v_{i,j}^{\text{road,truck}}(k)} \frac{1}{T_{\text{s}}} \right), \tag{3.24}$$

where

- $\rho_{i,j}^{\text{road,total}}(k)$ (equiv.veh/km/lane) and $\rho_{i,j}^{\text{road,other}}(k)$ (veh/km/lane) are the total traffic density and the traffic density induced by the other traffic flows on link $l_{i,j}^{\text{road}}$ for time step k, respectively.

- L_{truck} (m) and L_{other} (m) are the typical lengths of freight trucks and other vehicles, respectively.

- $L_{i,j}^{\text{road}}$ (km) and $\lambda_{i,j}^{\text{road}}$ are the length and the number of lanes of link $l_{i,j}^{\text{road}}$, respectively.

- $v_{i,j}^{\text{road,truck}}(k)$ (km/h) and $t_{i,j}^{\text{road,truck}}(k)$ (km/h) are the average speed and the average transport time of containers on link $l_{i,j}^{\text{road}}$ for time step k, respectively.

- $v_{i,j,\text{free}}^{\text{road,truck}}$, $a_{i,j}^{\text{road,truck}}$ and $\rho_{i,j,\text{crit}}^{\text{road}}$ are the model parameters related to the freight truck flows in the multi-class version of the nonlinear and non-convex speed-density relation. The critical traffic density on link $l_{i,j}^{\text{road}}$ is $\rho_{i,j,\text{crit}}^{\text{road}}$. The minimum speed on freeway link $l_{i,j}^{\text{road}}$ is $v_{i,j,\text{min}}^{\text{road}}$ (km/h).

- $\rho_{i,j}^{\text{road,max}}$ (equiv.veh/km/lane) is the maximum allowed traffic density on link $l_{i,j}^{\text{road}}$. The corresponding constraints for link $l_{i,j}^{\text{road}}$ can be formulated as

$$\sum_{(o,d)\in\mathcal{O}_{\text{od}}} x_{i,j,o,d}^{\text{road}}(k) \le \left(\rho_{i,j}^{\text{road,max}} - \rho_{i,j}^{\text{road,other}}(k)\right) \frac{L_{\text{other}}}{L_{\text{truck}}} L_{i,j}^{\text{road}} \lambda_{i,j}^{\text{road}}, \quad \forall (i,j,m) \in \mathcal{E}, \forall k, \tag{3.25}$$

where the maximum number of transport time steps $t_{i,j}^{\text{road,max}}$ is determined by $\rho_{i,j}^{\text{road,max}}$ through (3.23) and (3.24).

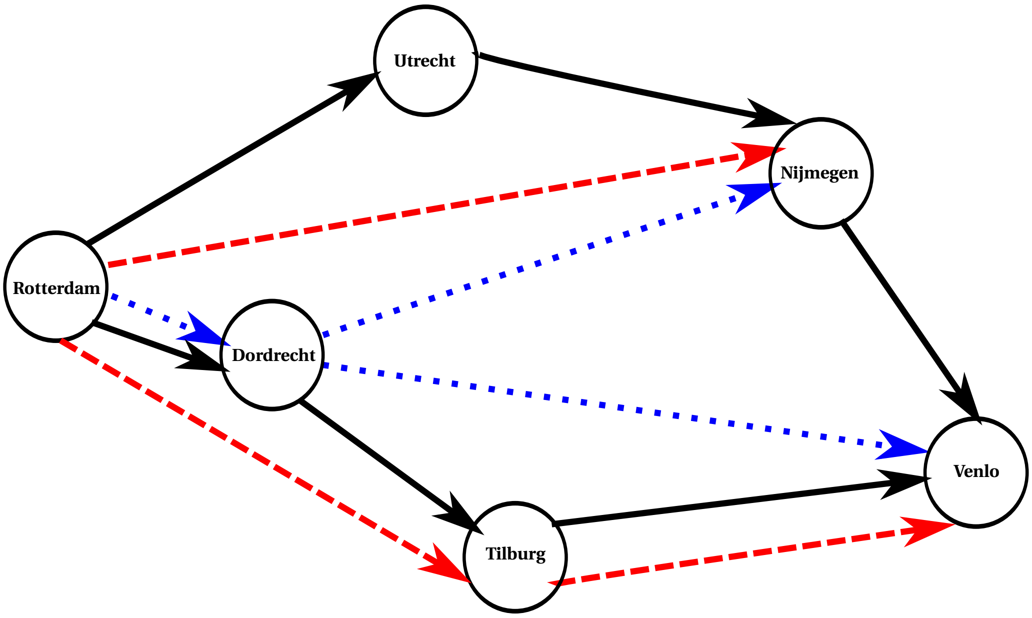

Figure 3.2: The topology of the single-region IFTN benchmark system from Rotterdam to Venlo. The solid black arcs, the dashed red arcs, and the dotted blue arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

In the multi-class version of the nonlinear and non-convex speed-density relation proposed in this section, the freight truck flow information, i.e., $x^{\text{road}}_{i,j,o,d}(k)$ is first included in (3.22), and consequently used by the nonlinear and non-convex relations (3.23) and (3.24). Therefore, the linear IFTN model developed in Section 3.2 will become a nonlinear and non-convex IFTN model when the freeway speed-density relations (3.10)–(3.11) are replaced by (3.22)–(3.25). The complete load-dependent IFTN model is given by (3.1)–(3.9), (3.12)–(3.21), and (3.22)–(3.25). The system state variables in the load-dependent IFTN model are non-negative either by definition or guaranteed by the constraints (3.5) and (3.9). The same assumption, as made in Section 3.2.7 for the linear IFTN model, holds for the load-dependent IFTN model for the guarantee of having feasible transport planning.

3.4 Benchmark systems

This section presents two benchmark systems. Section 3.4.1 presents a single-region IFTN connecting Rotterdam to Venlo in The Netherlands. This single-region IFTN will be used when considering the synchromodal freight transport planning problem in Chapter 4. Section 3.4.2 gives a multiple-region IFTN connecting Rotterdam with Antwerp and Frankfurt. This multiple-region IFTN consists of three subnetworks and will be used when investigating the cooperative synchromodal freight transport planning problem in Chapter 5.

3.4.1 Single-region IFTN benchmark system

This section presents a single-region IFTN benchmark system. The selection of the network is inspired by hinterland container transport for the Port of Rotterdam, and the availability of transport infrastructures and intermodal terminals in The Netherlands, such as

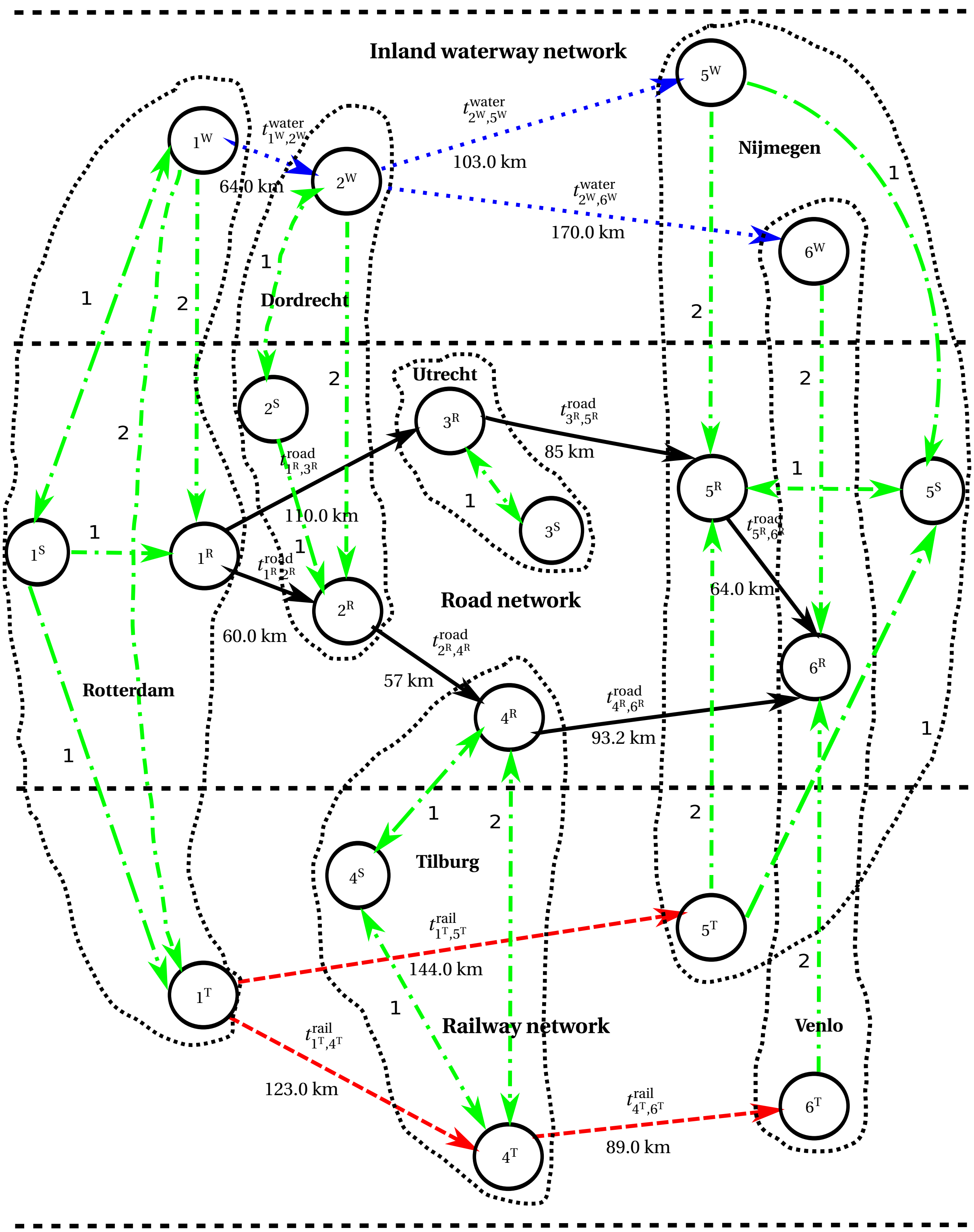

Figure 3.3: The corresponding virtual network representation of the network shown in Figure 3.2. Each double-headed arc in the figure represents two directed links with opposite directions.

Table 3.1: The typical transport time $r_{i,d}$ (h) is given as the number of time steps that is with a length of 1 hour. The element "–" denotes that there is no transport route from its corresponding row node to its corresponding column node in the IFTN shown in Figure 3.2.

$r_{i,d}$	1^{S}	1^{W}	1^{R}	1^{T}	2^{S}	2^{W}	2^{R}	3^{R}	3^{S}	4^{S}	4^{R}	4^{T}	5^{W}	5^{R}	5^{T}	5^{S}	6^{W}	6^{R}	6^{T}
1^{S}	0	1	1	1	8	6	3	4	6	8	6	6	14	10	6	10	18	15	10
1^{W}	1	0	1	1	6	4	4	4	6	9	7	6	12	10	6	10	16	14	10
1^{R}	–	–	0	–	–	–	1	2	4	5	3	5	–	5	–	7	–	9	9
1^{T}	–	–	–	0	–	–	–	–	–	6	6	4	–	6	4	6	–	9	8
2^{S}	–	–	–	–	0	1	3	–	–	7	5	7	9	11	–	–	13	14	11
2^{W}	–	–	–	–	1	0	1	–	–	5	3	5	7	9	–	12	11	12	9
2^{R}	–	–	–	–	–	–	0	–	–	3	1	3	–	–	–	–	–	7	7
3^{R}	–	–	–	–	–	–	–	0	1	–	–	–	–	2	–	4	–	4	–
3^{S}	–	–	–	–	–	–	–	1	0	–	–	–	–	4	–	6	–	6	–
4^{S}	–	–	–	–	–	–	–	–	–	0	1	1	–	–	–	–	–	6	5
4^{R}	–	–	–	–	–	–	–	–	–	1	0	1	–	–	–	–	–	5	5
4^{T}	–	–	–	–	–	–	–	–	–	1	1	0	–	–	–	–	–	5	3
5^{W}	–	–	–	–	–	–	–	–	–	–	–	–	0	1	–	1	–	3	–
5^{R}	–	–	–	–	–	–	–	–	–	–	–	–	–	0	–	1	–	1	–
5^{T}	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0	1	–	3	–
5^{S}	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	0	–	3	–
6^{W}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	1	–
6^{R}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	–
6^{T}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0

European Gateway Services (http://www.europeangatewayservices.com/), InlandLinks (https://www.inlandlinks.eu), and RailCargo (http://www.railcargo.nl). Figure 3.2 illustrates the topology of a single-region IFTN connecting Rotterdam to Venlo in The Netherlands. The corresponding virtual network representation of this single-region IFTN is shown in Figure 3.3. The numbers 1, 2, 3, 4, 5, and 6 labeling the nodes in the network model refer to Rotterdam, Dordrecht, Utrecht, Tilburg, Nijmegen, and Venlo, respectively. The dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs indicate respectively, 3 transport links of the inland waterway network, 6 transport links of the road network, 3 transport link of the railway network, and 27 transfer links among four different types of transport modes (barges, trucks, trains, and store) at nodes of the network.

The distance of and the transport time on each link of the network are shown in their labels in Figure 3.3. The lengths of freeway and inland waterway links are derived using Google Maps. The lengths of rail tracks are from the publications by ProRail [132]. Transport times on railway links and inland waterway links, i.e., $t^{\mathrm{water}}_{1^{\mathrm{W}},2^{\mathrm{W}}}$, $t^{\mathrm{water}}_{2^{\mathrm{W}},5^{\mathrm{W}}}$, $t^{\mathrm{water}}_{2^{\mathrm{W}},6^{\mathrm{W}}}$, $t^{\mathrm{rail}}_{1^{\mathrm{T}},4^{\mathrm{T}}}$, $t^{\mathrm{rail}}_{1^{\mathrm{T}},5^{\mathrm{T}}}$ and $t^{\mathrm{rail}}_{4^{\mathrm{T}},6^{\mathrm{T}}}$ are calculated with (3.12). Freeway transport times i.e., $t^{\mathrm{road}}_{1^{\mathrm{R}},2^{\mathrm{R}}}$, $t^{\mathrm{road}}_{1^{\mathrm{R}},3^{\mathrm{R}}}$, $t^{\mathrm{road}}_{2^{\mathrm{R}},4^{\mathrm{R}}}$, $t^{\mathrm{road}}_{4^{\mathrm{R}},6^{\mathrm{R}}}$, $t^{\mathrm{road}}_{3^{\mathrm{R}},5^{\mathrm{R}}}$, and $t^{\mathrm{road}}_{5^{\mathrm{R}},6^{\mathrm{R}}}$ are determined by (3.11) for the linear IFTN model in Section 3.2, and (3.24) for the load-dependent IFTN model in Section 3.3, respectively.

The typical transport time among any two nodes of the whole network is estimated according to the lengths of links and the average speeds of trucks, trains, and barges while taking into account the average transshipment times at terminals and the possibility of having multiple routes between two nodes in the network. Based on the NEA report [120] and after consulting experts in freight transport, the average speed of trucks, trains, and barges in freight transport are estimated as 55 km/h, 35 km/h, and 15 km/h, respectively. The typical transport time between any two nodes in the IFTN is given in Table 3.1. The typical delivery cost between any possible pair of nodes is approximated as the monetary cost of the corresponding typical transport time with a conversion factor of 25 (€/h). Modality change costs and modality change times are assumed to be 23.89 (€/TEU) and 2 (h) among any two modes of transport, i.e., trucks, trains, and barges; and are taken as 11.945 (€/TEU) and 1 (h) between the storage and any one of the above three modalities. The storage cost at terminals for a relatively short period (i.e., 1 or 2 days) is very small or even zero, therefore it is taken as 0.0001 (€/TEU/h).

The handling capacities of loading and unloading containers at nodes of the network are taken to be unlimited. The storage capacities at five storage nodes (i.e., 1^{S}, 2^{S}, 3^{S}, 4^{S}, and 5^{S}) are considered to be unlimited, while at other nodes they are 1000 (TEU). The maximum entering container flows of links with different modalities are 400 (TEU/h) for freeway links, determined by train and barge timetables for railway and inland waterway links, and 10000 (TEU/h) for modality change links. For freeway links, railway links, and inland waterway links, the distance-dependent transport costs are respectively 0.2758, 0.0635, and 0.0213 (€/TEU/km); and the time-dependent costs are 30.98, 7.54, and 0.6122 (€/TEU/h), respectively [156].

Trucks are assumed to be always available on the freeway links for delivering containers, and to have three times the length of other vehicles on freeways. There are two lanes on each freeway link and the minimum speed on freeways is 10 (km/h). For the linear IFTN model, the parameters in the density-speed relation (3.10)-(3.11) for the freeway links are respectively $v_{i,j,\mathrm{free}}^{\mathrm{road}} = 110$ (km/h), $a_{i,j}^{\mathrm{road}} = 1.636$, and $\rho_{i,j,\mathrm{crit}}^{\mathrm{road}} = 33.5$ (veh/km/lane) [88]. The maximum density on the freeway links is $\rho_{i,j,\mathrm{max}}^{\mathrm{road}} = 180$ (veh/km/lane). For the load-dependent IFTN model, the parameters in the multi-class density-speed relation model (3.22)–(3.24) for the freeway links in the road network are $v_{i,j,\mathrm{free}}^{\mathrm{road,truck}} = 82.8$ (km/h), $a_{i,j}^{\mathrm{road,truck}} = 1.6033$, and $\rho_{i,j,\mathrm{crit}}^{\mathrm{road}} = 28.9930$ (veh/km/lane), and $\rho_{i,j,\mathrm{max}}^{\mathrm{road}} = 61.34$ (veh/km/lane), respectively. These parameters are derived from [88] and [103] by doing curve fitting and taking convex combination.

We assumed that there are regular container train and barge services on railway links and inland waterway links: on link $l_{1^{\mathrm{T}},4^{\mathrm{T}}}^{\mathrm{rail}}$, a train is available at node 1^{T} every 3 hours, spends 2 hours for loading containers, and then departs from node 1^{T} and travels $t_{1^{\mathrm{T}},4^{\mathrm{T}},\mathrm{traveling}}^{\mathrm{rail}} =$ 6 hours to node 3^{T}; regular services on other railway links and inland waterway links are scheduled in the same way, only with different actual traveling times, 3 hours, 4 hours, 4 hours, 7 hours, and 11 hours for link $l_{4^{\mathrm{T}},6^{\mathrm{T}}}^{\mathrm{rail}}$, link $l_{1^{\mathrm{T}},5^{\mathrm{T}}}^{\mathrm{rail}}$, $l_{1^{\mathrm{W}},2^{\mathrm{W}}}^{\mathrm{water}}$, $l_{2^{\mathrm{W}},5^{\mathrm{W}}}^{\mathrm{water}}$, and $l_{2^{\mathrm{W}},6^{\mathrm{W}}}^{\mathrm{water}}$, respectively. The capacities of trains and barges are taken as 100 (TEU) and 200 (TEU), and the handling capacities of equipment for serving them are 100 (TEU/h) and 200 (TEU/h), respectively.

3.4.2 Multiple-region IFTN benchmark system

This section proposes a multiple-region IFTN benchmark system. The selection of the network is inspired by hinterland container transport for the Port of Rotterdam and the Port of Antwerp, and the availability of transport infrastructures and intermodal terminals in The Netherlands, Belgium, and Germany, such as European Gateway Services (http://www.europeangatewayservices.com/), and Trans-European Transport Network (http://ec.

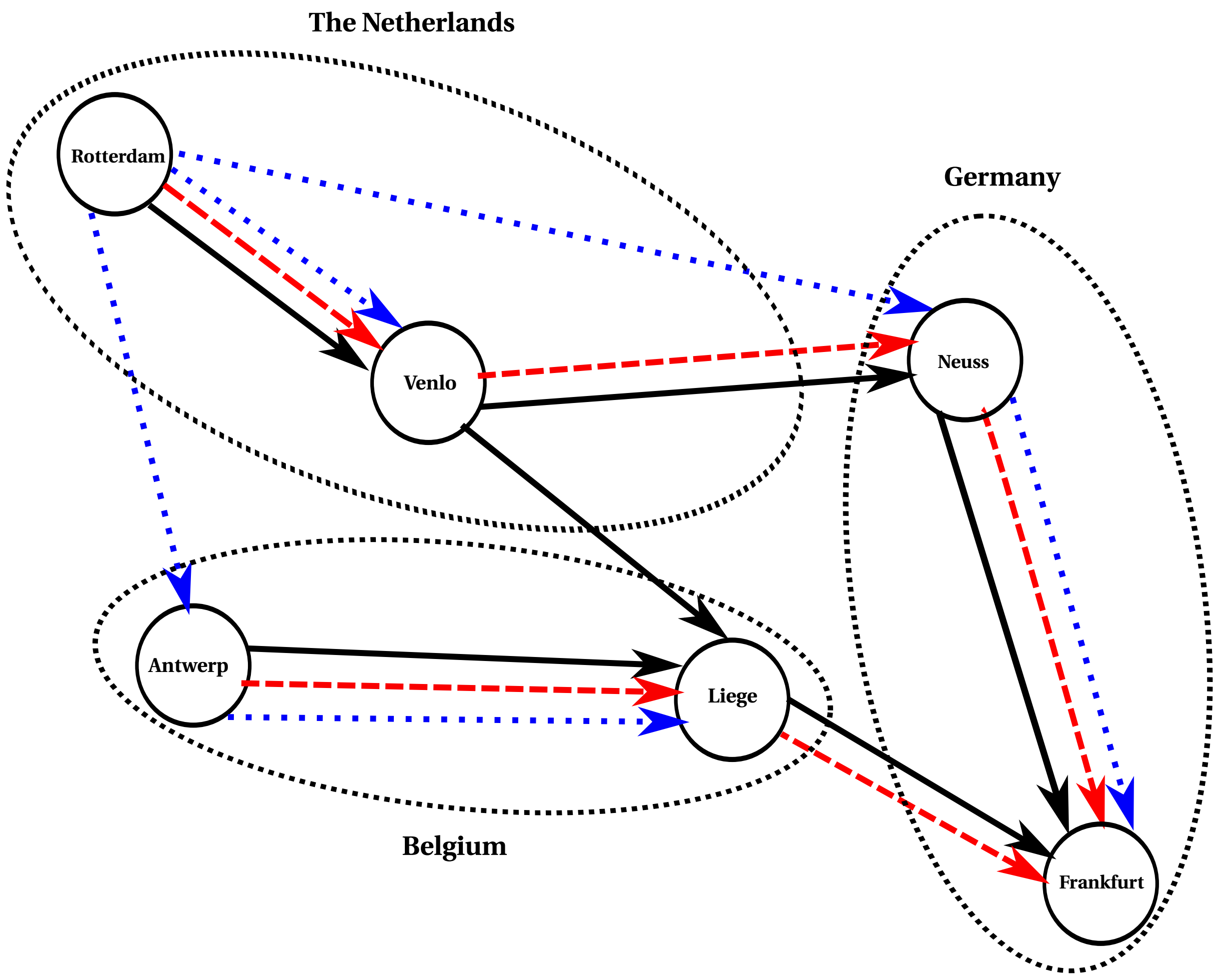

Figure 3.4: The topology of the multiple-region IFTN benchmark system between Rotterdam and Frankfurt. The solid black arcs, the dashed red arcs, and the dotted blue arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

europa.eu/transport/themes/infrastructure/tentec/). The topology of the multiple-region IFTN and the corresponding network model are shown by Figures 3.4 and 3.5, respectively. This network consists of 6 nodes, and 16 transport connections, i.e., 5 railway connections, 5 inland waterway connections, and 6 freeway connections. As indicated by the dotted black ellipses in Figure 3.4, the network consists of 3 non-overlapping subnetworks, in each of which one operator provides synchromodal freight transport services. The numbers 1, 2, 3, 4, 5, and 6 labeling the nodes in the network denote Rotterdam, Venlo, Antwerp, Liege, Neuss, and Frankfurt, respectively.

The distance of and the transport time on each link of the network are shown in their labels in Figure 3.5. The lengths of freeway and inland waterway links are derived using Google Maps. The lengths of rail tracks are from the publications by ProRail [132], Infrabel [82, 83], and Deutsche Bahn Netz AG [43]. Transport times $t^{\mathrm{road}}_{1^{\mathrm{R}},2^{\mathrm{R}}}, t^{\mathrm{road}}_{2^{\mathrm{R}},4^{\mathrm{R}}}, t^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}, t^{\mathrm{road}}_{3^{\mathrm{R}},4^{\mathrm{R}}}$, $t^{\mathrm{road}}_{4^{\mathrm{R}},6^{\mathrm{R}}}$, $t^{\mathrm{road}}_{5^{\mathrm{R}},6^{\mathrm{R}}}$, $t^{\mathrm{water}}_{1^{\mathrm{W}},2^{\mathrm{W}}}, t^{\mathrm{water}}_{1^{\mathrm{W}},3^{\mathrm{W}}}$, $t^{\mathrm{water}}_{1^{\mathrm{W}},5^{\mathrm{W}}}, t^{\mathrm{water}}_{3^{\mathrm{W}},4^{\mathrm{W}}}$, $t^{\mathrm{water}}_{5^{\mathrm{W}},6^{\mathrm{W}}}$, $t^{\mathrm{rail}}_{1^{\mathrm{T}},2^{\mathrm{T}}}$, $t^{\mathrm{rail}}_{2^{\mathrm{T}},5^{\mathrm{T}}}, t^{\mathrm{rail}}_{3^{\mathrm{T}},4^{\mathrm{T}}}$, $t^{\mathrm{rail}}_{4^{\mathrm{T}},6^{\mathrm{T}}}, t^{\mathrm{rail}}_{5^{\mathrm{T}},6^{\mathrm{T}}}$, are determined by their corresponding link dynamics in Section 3.2 and timetables for trains and barges in different subnetworks.

The typical transport time among any two nodes of the whole network is estimated

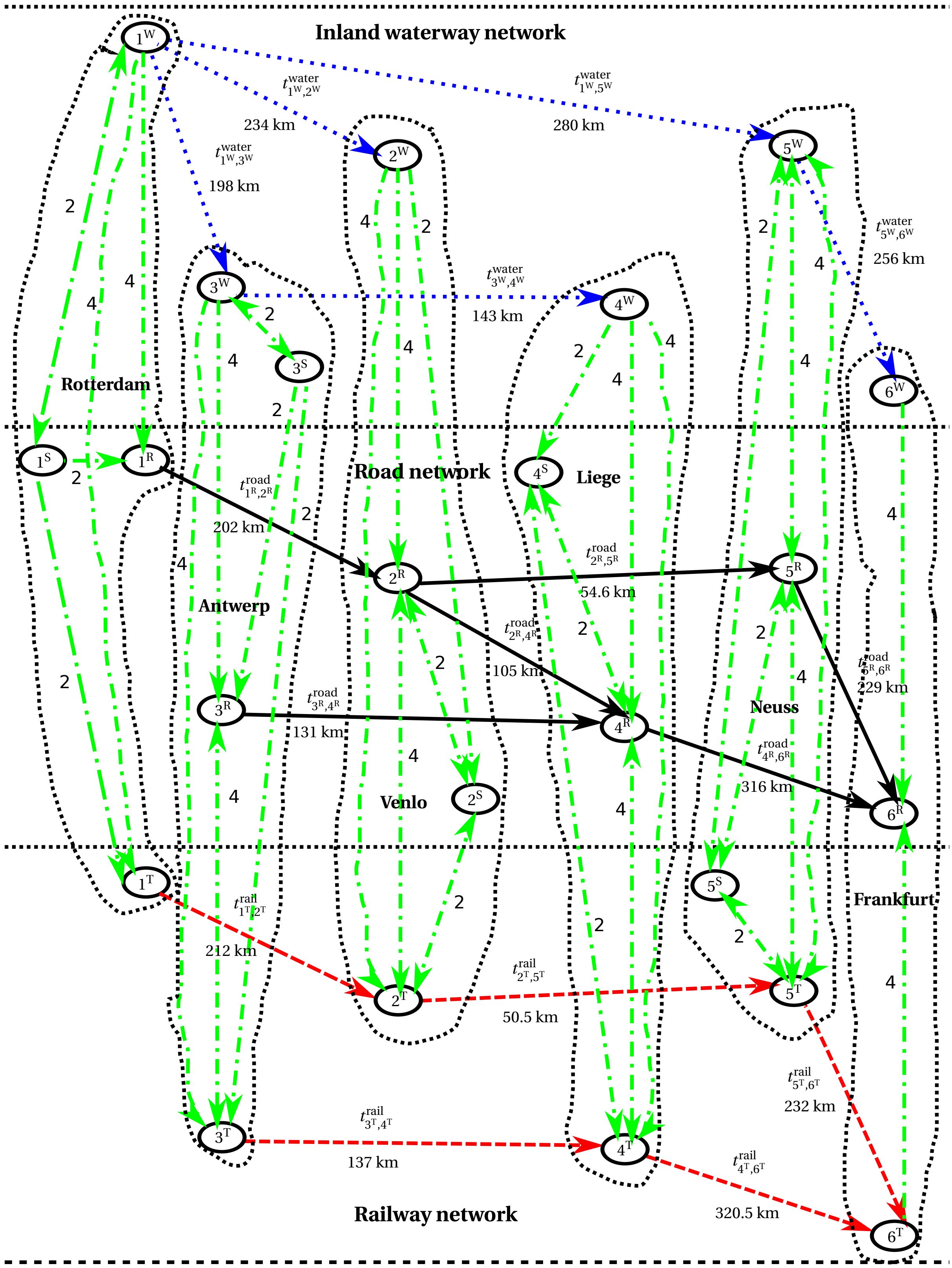

Figure 3.5: The corresponding virtual network representation of the network shown in Figure 3.4. Each double-headed arc in the figure represents two directed links with opposite directions.

Table 3.2: The typical transport time $r_{i,d}$ (h) is given as the number of time steps that is with a length of 2 hours. The symbol "–" indicates that there is no transport route from the corresponding row node to the corresponding column node in the IFTN shown in Figure 3.4.

$r_{i,d}$	1^S	1^W	1^R	1^T	3^W	3^R	3^T	3^S	2^W	2^R	2^T	2^S	4^S	4^W	4^R	4^T	5^W	5^R	5^S	5^T	6^W	6^R	6^T
1^S	0	1	1	1	8	11	11	10	10	4	5	8	13	14	6	14	11	6	10	7	20	9	15
1^W	1	0	2	2	6	9	9	8	8	5	6	8	12	12	7	12	9	7	10	8	18	10	15
1^R	–	–	0	–	–	–	–	–	–	2	5	5	7	–	4	7	7	4	8	7	16	7	11
1^T	–	–	–	0	–	–	–	–	–	6	3	6	11	–	8	11	11	8	10	5	20	11	12
3^W	–	–	–	–	0	2	2	1	–	–	–	–	7	5	8	8	–	–	–	–	–	12	13
3^R	–	–	–	–	–	0	–	1	–	–	–	–	4	–	1	4	–	–	–	–	–	5	9
3^T	–	–	–	–	–	–	0	1	–	–	–	–	5	–	5	2	–	–	–	–	–	9	7
3^S	–	–	–	–	1	1	1	0	–	–	–	–	6	7	3	4	–	–	–	–	–	7	9
2^W	–	–	–	–	–	–	–	–	0	2	2	1	6	–	4	7	7	4	6	4	16	7	10
2^R	–	–	–	–	–	–	–	–	–	0	2	1	3	–	1	4	5	2	4	4	14	5	8
2^T	–	–	–	–	–	–	–	–	–	2	0	1	6	–	4	7	5	4	4	2	14	8	6
2^S	–	–	–	–	–	–	–	–	1	1	1	0	5	–	3	6	6	3	5	3	15	6	10
4^S	–	–	–	–	–	–	–	–	–	–	–	–	0	1	1	1	–	–	–	–	–	5	6
4^W	–	–	–	–	–	–	–	–	–	–	–	–	1	0	2	2	–	–	–	–	–	6	7
4^R	–	–	–	–	–	–	–	–	–	–	–	–	1	–	0	2	–	–	–	–	–	3	7
4^T	–	–	–	–	–	–	–	–	–	–	–	–	1	–	2	0	–	–	–	–	–	6	5
5^W	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	2	1	2	8	5	6
5^R	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	0	1	2	11	2	6
5^S	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	0	1	10	4	6
5^T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	2	1	0	11	5	3
6^W	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	2	–
6^R	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	–
6^T	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	0

according to the lengths of links and the average speeds of trucks, trains, and barges while taking into account the average transshipment times at terminals and the possibility of having multiple routes between two nodes in the network. Based on the NEA report [120] and consulting experts in freight transport, the average speed of trucks, trains, and barges in freight transport are estimated as 55 km/h, 35 km/h, and 15 km/h. The typical transport time among any two nodes of the whole network is given in Table 3.2. The corresponding typical delivery cost is estimated as the monetary cost of the typical transport time with a conversion factor of 25 (€/h).

The cost and the time taken for changing between two different modalities, i.e., trucks, trains, and barges, are 23.89 (€/TEU) and 4 (h) [160]. The change between two modalities consists of two crane operations while moving containers from the central storage yard to a single-modal terminal requires one crane operation. For example, the modality change from water to rail includes one quay crane operation and one rail gantry crane operation, and the change from the central storage yard to a single-rail terminal involves one rail gantry crane operation. Therefore, the cost and time for changing between the storage and one of these three modalities are assumed to be 11.945 (€/TEU) and 2 (h) in this benchmark systems. Because containers can stay at terminals at a very low price or even free of charge for a short time period (i.e., 1 or 2 days), the storage cost at terminals is therefore taken as a small value i.e., 0.0001 (€/TEU/h).

The container loading and unloading capacity at each node of the network is taken to be unlimited. The storage capacity at storage nodes i.e., 1^{S}, 2^{S}, 3^{S}, 4^{S}, and 5^{S}, is assumed to be unlimited; at the other nodes it is taken to be 1000 (TEU). The maximum entering container flow is assumed to be 400 (TEU/h) on freeway links, determined by timetables of trains and barges for railway links and inland waterway links, and 10000 (TEU/h) for modality change links. The distance-dependent transport costs and the time-dependent transport costs are 0.2758 (€/TEU/km) and 30.98 (€/TEU/h) for freeway links, 0.0635 (€/TEU/km) and 7.54 (€/TEU/h) for railway links, and 0.0213 (€/TEU/km) and 0.6122 (€/TEU/h) for inland waterway links, respectively [156].

Trucks are assumed to be always available on the freeway links for delivering containers, and the freeway speed-density relation model parameters in the linear IFTN model are respectively $v_{i,j,\mathrm{free}}^{\mathrm{road}} = 110$ (km/h), $a_{i,j}^{\mathrm{road}} = 1.636$, and $\rho_{i,j,\mathrm{crit}}^{\mathrm{road}} = 33.5$ (veh/km/lane) [88]. The typical length of trucks is three times that of cars. Trains and barges are assumed to operate according to pre-determined timetables that plan regular train services and barge services on railway links and inland waterways links, respectively. On link $l_{3^{\mathrm{T}},4^{\mathrm{T}}}$, a train is available at node 3^{T} every 6 hours, spends 2 hours for loading containers, then departs from node 3^{T} and runs $t_{3^{\mathrm{T}},4^{\mathrm{T}}} = 4$ hours to arrive at node 4^{T}. On the other railway links and the inland waterways links, services are planned in the same way but with the following two differences: the service frequency on links from and to deep-sea ports (i.e., Rotterdam and Antwerp) is every 4 hours while the frequency on the other links is every 6 hours; the actual running times on links $t_{1^{\mathrm{T}},2^{\mathrm{T}}}$, $t_{2^{\mathrm{T}},5^{\mathrm{T}}}$, $t_{4^{\mathrm{T}},6^{\mathrm{T}}}$, $t_{5^{\mathrm{T}},6^{\mathrm{T}}}$, $t_{1^{\mathrm{W}},2^{\mathrm{W}}}$, $t_{1^{\mathrm{W}},3^{\mathrm{W}}}$, $t_{1^{\mathrm{W}},5^{\mathrm{W}}}$, $t_{3^{\mathrm{W}},4^{\mathrm{W}}}$, and $t_{5^{\mathrm{W}},6^{\mathrm{W}}}$ are 6 hours, 2 hours, 8 hours, 6 hours, 16 hours, 12 hours, 18 hours, 10 hours, and 16 hours, respectively. The capacity of trains and the allocated container handling capacities are assumed to be 100 (TEU) and 100 (TEU/h) and they are 200 (TEU) and 200 (TEU/h) for barges.

3.5 Summary

In this chapter we have proposed a linear discrete-time IFTN model from an aggregated container flow perspective to capture system characteristics, such as modality changes at intermodal terminals, capacities of physical infrastructures, time-dependent transport times on freeways, and timetables for trains and barges. We have extended the linear IFTN model to a load-dependent IFTN model to take into account the impact of the freight truck flows generated by the transport operator on the freeway transport times by modeling freeway dynamics with a multi-class version of the nonlinear and non-convex speed-density relation. Moreover, we have presented a single-region IFTN benchmark system and a multiple-region IFTN benchmark system for assessment of planning approaches in Chapters 4 and 5.

Chapter 4

MPC for Synchromodal Freight Transport Planning

In Chapter 3 two Intermodal Freight Transport Network (IFTN) models have been developed. This chapter investigates synchromodal freight transport planning problems for a single transport operator with the use of these two models. A Model Predictive container Flow Control (MPFC) approach is proposed to deal with the dynamic transport demand and dynamic traffic conditions in the network. We propose a multi-start Iterative Linear Programming (ILP) method for solving the nonlinear and non-convex MPFC problem with the load-dependent IFTN model. Moreover, we investigate the performance of the MPFC approach and the proposed solution approaches for both the linear IFTN model and the load-dependent IFTN model in a single-region IFTN benchmark system.

The research presented in this chapter is based on [93–95, 97].

4.1 Introduction

This chapter investigates synchromodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage for an intermodal freight transport operator at the tactical container flow level. This operator adopts the multi-level freight transport planning approach as presented in Section 1.2. The approaches developed in this chapter are for the flow planning problem within the framework.

In systems and control theory, a system is often represented using a model that describes the evolution of the system states on the basis of the system equations, the initial values of the system states, the disturbances, and the control actions. The systems and control approach has been applied for resource allocation problems in container terminal operation [1, 118, 119]. Considering a freight transport network as a system, the system states contain the characteristic information of the system, i.e., the number of containers at each intermodal terminal, the volumes of traffic flows on transport connections; the disturbances are the influences placed on the system by the outside environment, i.e., the dynamic transport demand and dynamic traffic conditions in the network; the control actions are the volumes of container flows entering each possible transport connection or changing modalities at each intermodal terminal during each time interval of the freight transport process. These control actions should be determined by the controllers (i.e., intermodal freight transport operators) so as to achieve a given system performance, e.g., minimizing the total delivery cost or achieving a certain modal split target. For an IFTN, system equations can be derived from the internal relations among system states, disturbances, and control actions of the synchromodal freight transport system. The two IFTN models developed in Chapter 3 are derived to capture these internal relations and present the mathematical formulation of the system equations. Systems and control theory provides a useful way to interpret and analyze a synchromodal freight transport system in terms of system states, system equations, disturbances, and control actions. Then, on-line control can be applied to solve planning problems in synchromodal freight transport.

Model Predictive Control (MPC) is an on-line model-based control strategy that has been identified as a promising control strategy with not only many successful applications but also well-established theoretical foundations [106, 136]. There are a few papers in the literature on the application of MPC in intermodal freight transport. In [1] deep-sea container terminal operation is considered as a system of queues, with the queue lengths and container handling rates of equipment (e.g., cranes, reach stackers) as states and control actions, respectively. The dynamic evolution of these queues is described in terms of discrete-time equations. The terminal operation is formulated as an optimal control problem with the aim to minimize the transfer delays of containers at the terminal. The optimal control problem is solved using MPC's receding horizon strategy. Recently, MPC has been used to control equipment (i.e., quay cranes, automated guided vehicles, and stacking cranes) for balancing throughput and energy consumption at terminals [172, 173], to optimize the operation of terminals [118], and to achieve a desired modal split target at intermodal terminals [119]. The above mentioned papers focus on the applications of MPC on issues inside terminals and among terminals inside a port. This chapter considers both terminals and transport connections as an IFTN, and proposes a Model Predictive container Flow Control (MPFC) approach for planning synchromodal freight transport.

The contributions of this chapter are as follows. Firstly, the flow control actions in synchromodal freight transport planning are determined by solving both the route selection problem and the container flow assignment problem simultaneously as an optimal container flow control problem. An MPFC approach is proposed to address timely and actively the dynamic behaviors of the transport demand and traffic conditions, e.g., unexpected transport order requests, transport order cancellation, and the dynamic evolution of transport times on freeway links. Secondly, a multi-start Iterative Linear Programming (ILP) method is proposed for efficiently solving the nonlinear and non-convex MPFC optimization problem with a load-dependent IFTN model. This ILP method requires less computational efforts than the Sequential Quadratic Programming (SQP) method, but is not able to guarantee the global optimality of the solution. We implement a multi-start version of the ILP method to improve the solutions to the original nonlinear and non-convex optimization problems. Moreover, the proposed MPFC approach is applied to synchromodal freight transport planning problems in the single-region IFTN benchmark system presented in Section 3.4.1 with the use of both the linear IFTN model and the load-dependent IFTN model. The performance of the MPFC approach and the solution approaches are compared with a greedy all-or-nothing approach, and are analyzed for different transport demand scenarios, and for different prediction errors on the transport demand and traffic conditions in the IFTN.

The reminder of this chapter is organized as follows. Section 4.2 and Section 4.3 formulate the optimal container flow control problem and the MPFC problem, respectively. Section 4.4 introduces the proposed multi-start ILP method. In Section 4.5, simulation studies are conducted to illustrate the potential of the MPFC approach and the proposed solution approaches. Conclusions and further research directions are given in Section 4.6.

4.2 Optimal container flow control

The optimal container flow controller actually determines a transport plan that achieves certain objectives. The selected planning objective function in this chapter is presented in Section 4.2.1. Section 4.2.2 formulates synchromodal freight transport planning as an optimal container flow control problem with the use of the dynamic IFTN models developed in Chapter 3.

4.2.1 The objective function

The planning objective of synchromodal freight transport is to determine the volumes of container flows leaving each node of the IFTN through each of its outgoing links for each time step[1] such that the total delivery cost for serving the given transport demand is minimized. The delivery cost structure of intermodal freight transport operators consists of vehicle transport costs, modality change costs, storage costs, and the value of container transshipment time. The vehicle can refer to a container truck, a container train, or a container barge depending on the modality that is used. Vehicle transport costs have two parts: time-dependent vehicle transport costs and distance-dependent vehicle transport costs. We assume that the distance-dependent transport cost is only incurred when a vehicle leaves the link. Based on this delivery cost structure, the objective function of the intermodal freight transport planning is defined as

$$J = \alpha(J_1 + J_2) + J_3 + J_4 \tag{4.1}$$

with

$$J_1 = \sum_{(o,d)\in\mathcal{O}_{\text{od}}} w_{o,d} \left[\sum_{k=1}^{N_{\text{planning}}-1} \left[\sum_{i\in\mathcal{V}} x_{i,o,d}(k) T_{\text{s}} + \sum_{(i,j,m)\in\mathcal{E}} x_{i,j,o,d}^{m}(k) T_{\text{s}} \right] \right] \tag{4.2}$$

$$J_2 = \sum_{(o,d)\in\mathcal{O}_{\text{od}}} w_{o,d} \left[\sum_{i\in\mathcal{V}} x_{i,o,d}(N_{\text{planning}}) r_{i,d} + \sum_{(i,j,m)\in\mathcal{E}} x_{i,j,o,d}^{m}(N_{\text{planning}}) r_{i,j}^{m,d} \right] \tag{4.3}$$

$$\begin{aligned} J_3 = \sum_{(o,d)\in\mathcal{O}_{\text{od}}} w_{o,d} \Bigg[\sum_{k=1}^{N_{\text{planning}}-1} \Bigg[& \sum_{i\in\mathcal{V}} x_{i,o,d}(k) T_{\text{s}} c_{i,\text{store}}(k) + \\ & \sum_{(i,j,m)\in\mathcal{E}} \left(x_{i,j,o,d}^{m}(k) T_{\text{s}} c_{i,j,\text{time}}^{m}(k) + y_{i,j,o,d}^{m}(k) T_{\text{s}} L_{i,j}^{m} c_{i,j,\text{distance}}^{m}(k) \right) \Bigg] \Bigg] \end{aligned} \tag{4.4}$$

$$J_4 = \sum_{(o,d)\in\mathcal{O}_{\text{od}}} w_{o,d} \left[\sum_{i\in\mathcal{V}} x_{i,o,d}(N_{\text{planning}}) c_{i,d} + \sum_{(i,j,m)\in\mathcal{E}} x_{i,j,o,d}^{m}(N_{\text{planning}}) c_{i,j}^{m,d} \right], \tag{4.5}$$

where

[1] To be consistent with the terminology in systems and control, this thesis uses the term ‘time step’ instead of the term ‘the planning time interval’ to indicate a certain length of time period according to which the freight transport planning process is divided and at the beginning of which the container flow control actions for a time period should be determined.

- J_1, J_3 are the total transport time and the total transport cost of transport demand and J_2, J_4 are penalties on the unfinished transport demand at the end of the whole planning period.

- $w_{o,d} \in [0,1]$ indicates the relative priority of the transport demand (o,d); the relation $\sum_{(o,d)\in\mathcal{O}_{\text{od}}} w_{o,d} = 1$ always holds.

- $c_{i,\text{store}}(k)$ (€/TEU/h) is the container storage cost at node i for time step k.

- $c^m_{i,j,\text{time}}(k)$ (€/TEU/h) and $c^m_{i,j,\text{distance}}(k)$ (€/TEU/km) are respectively time-dependent and distance-dependent vehicle transport or modality change costs for time step k. For the modality change links, only the time-dependent cost is used to model the modality change cost at intermodal terminals. This actually implies that the distance-dependent cost of modality change links is considered to be zero.

- $r_{i,d}$ (h/TEU), $c_{i,d}$ (€/TEU), $r^{m,d}_{i,j}$ (h/TEU) and $c^{m,d}_{i,j}$ (€/TEU) are the typical transport time and the typical delivery cost for containers being transported from node i or link $l^m_{i,j}$ to node d, respectively. They can be obtained from historical data.

- α (€/h) is the value of time for intermodal freight transport operators to convert container transport times, modality change times, and storage times to their equivalent monetary costs. Since this chapter considers aggregated container flows, it is essentially not possible to directly capture the due time requirement of containers in the system model. The value of time helps to address this requirement in an indirect way by adding the time cost in the objective function to push container flows to move to their destinations.

- $N_{\text{planning}}T_{\text{s}}$ (h) is the length of the planning horizon with $N_{\text{planning}} \in \mathbb{N}\backslash\{0\}$.

Remark 4.1 There are in general two approaches to consider the modal split in freight transport planning. On the one hand, the first approach does not include the modal split targets in the planning objectives of terminal and transport operations, and only reports the resulting modal split rate as an additional performance indicator. On the other hand, the second approach is to explicitly include the modal split targets as hard or soft planning constraints in the transport planning. In this thesis, we adopt the first approach; so we consider the modal split rate as an additional performance indicator when developing the synchromodal freight transport planning approaches. This is because intermodal transport operators essentially strive for the maximization of the profits while regulations or contracts on guaranteeing a given modal split target are still missing for transport operators at this stage. Since transport regulators are also currently interested in suggesting or even imposing modal split targets on hinterland freight transport [44, 119, 126], the synchromodal freight transport planning approaches presented in this thesis can be easily adapted to this new situation by deploying the second approach to address the issue of the modal split targeting. □

4.2.2 Optimal control

Synchromodal freight transport planning involves making decisions on the appropriate flow control action $u^m_{i,j}(k)$ for each time step k on each outgoing link $l^m_{i,j}$ of each node i

such that container flows move from their origins to the destinations over the IFTN while the objective function (4.1) is minimized. At time kT_{s} (h), the control actions in the synchromodal freight transport system, $\mathbf{u}(k)$[2] $\in \mathbb{R}^{N_{\mathrm{od}}N_{\mathrm{link}}}$, are the container flow control actions, or specifically the volumes of container flows entering each link $l_{i,j}^{m}$ at node i; the system states, $\mathbf{x}(k) \in \mathbb{R}^{N_{\mathrm{od}}(N_{\mathrm{node}}+N_{\mathrm{link}}+\sum_{(i,j,m)\in\mathscr{E}} t_{i,j}^{m,\max})}$, contain the number of containers at each node and on each link of the IFTN and the container flows entering each link $l_{i,j}^{m}$ in the previous $t_{i,j}^{m,\max}$ time steps; the disturbances, $\mathbf{d}(k) \in \mathbb{R}^{N_{\mathrm{od}}N_{\mathrm{node}}+N_{\mathrm{link}}^{\mathrm{road}}}$, comprise the volumes of container flows entering each node from the outside of the IFTN, i.e., $d_{i}^{\mathrm{in}}(k)$, and the traffic density on freeway links, i.e., $\rho_{i,j}^{\mathrm{road}}(k)$ or $\rho_{i,j}^{\mathrm{road,other}}(k)$; the system outputs, $\mathbf{y}(k) \in \mathbb{R}^{N_{\mathrm{od}}N_{\mathrm{link}}}$, are the volumes of container flows leaving each link of the network. The system states $\mathbf{x}(k)$, the control actions $\mathbf{u}(k)$, the disturbances $\mathbf{d}(k)$, and the system output $\mathbf{y}(k)$ of the synchromodal freight transport system at time kT_{s} (h) are then defined as follows:

$$\mathbf{x}(k) = \left[\left(\mathbf{x}_{i_1}(k)\right)^{\mathrm{T}}, \ldots, \left(\mathbf{x}_{i_{N_{\mathrm{node}}}}(k)\right)^{\mathrm{T}}, \left(\mathbf{x}_{i_1,j_1}^{m_1}(k)\right)^{\mathrm{T}}, \ldots, \left(\mathbf{x}_{i_{N_{\mathrm{link}}},j_{N_{\mathrm{link}}}}^{m_{N_{\mathrm{link}}}}(k)\right)^{\mathrm{T}}, \mathbf{u}^{\mathrm{previous}}(k)\right]^{\mathrm{T}}, \tag{4.6}$$

$$\mathbf{x}_{i}(k) = \left[x_{i,o_1,d_1}(k), \ldots, x_{i,o_{N_{\mathrm{od}}},d_{N_{\mathrm{od}}}}(k)\right]^{\mathrm{T}},$$
$$\mathbf{x}_{i,j}^{m}(k) = \left[x_{i,j,o_1,d_1}^{m}(k), \ldots, x_{i,j,o_{N_{\mathrm{od}}},d_{N_{\mathrm{od}}}}^{m}(k)\right]^{\mathrm{T}},$$

$$\begin{aligned}\mathbf{u}^{\mathrm{previous}}(k) = \Bigg[&\left(\mathbf{u}_{i_1,j_1}^{m_1}(k-t_{i_1,j_1}^{m_1,\max})\right)^{\mathrm{T}}, \ldots, \left(\mathbf{u}_{i_1,j_1}^{m_1}(k-1)\right)^{\mathrm{T}}, \cdots, \\ &\left(\mathbf{u}_{i_{N_{\mathrm{link}}},j_{N_{\mathrm{link}}}}^{m_{N_{\mathrm{link}}}}(k-t_{i_{N_{\mathrm{link}}},j_{N_{\mathrm{link}}}}^{m_{N_{\mathrm{link}}},\max})\right)^{\mathrm{T}}, \cdots, \left(\mathbf{u}_{i_{N_{\mathrm{link}}},j_{N_{\mathrm{link}}}}^{m_{N_{\mathrm{link}}}}(k-1)\right)^{\mathrm{T}}\Bigg]^{\mathrm{T}},\end{aligned}$$

$$\mathbf{u}(k) = \left[\left(\mathbf{u}_{i_1,j_1}^{m_1}(k)\right)^{\mathrm{T}}, \ldots, \left(\mathbf{u}_{i_{N_{\mathrm{link}}},j_{N_{\mathrm{link}}}}^{m_{N_{\mathrm{link}}}}(k)\right)^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{4.7}$$
$$\mathbf{u}_{i,j}^{m}(k) = \left[u_{i,j,o_1,d_1}^{m}(k), \ldots, u_{i,j,o_{N_{\mathrm{od}}},d_{N_{\mathrm{od}}}}^{m}(k)\right]^{\mathrm{T}},$$
$$\mathbf{d}(k) = \left[\left(\mathbf{d}_{i_1}^{\mathrm{in}}(k)\right)^{\mathrm{T}}, \ldots, \left(\mathbf{d}_{i_{\mathrm{N_{node}}}}^{\mathrm{in}}(k)\right)^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{4.8}$$
$$\mathbf{d}_{i}^{\mathrm{in}}(k) = \left[d_{i,o_1,d_1}^{\mathrm{in}}(k), \ldots, d_{i,o_{N_{\mathrm{od}}},d_{N_{\mathrm{od}}}}^{\mathrm{in}}(k)\right]^{\mathrm{T}},$$
$$\mathbf{y}(k) = \left[\left(\mathbf{y}_{i_1,j_1}^{m_1}(k)\right)^{\mathrm{T}}, \ldots, \left(\mathbf{y}_{i_{\mathrm{N_{node}}},j_{\mathrm{N_{node}}}}^{m_{i_{\mathrm{N_{node}}}}}(k)\right)^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{4.9}$$
$$\mathbf{y}_{i,j}^{m}(k) = \left[q_{i,j,o_1,d_1}^{m,\mathrm{out}}(k), \ldots, q_{i,j,o_{N_{\mathrm{od}}},d_{N_{\mathrm{od}}}}^{m,\mathrm{out}}(k)\right]^{\mathrm{T}}.$$

The synchromodal freight transport planning problem is thus formulated as the

[2]This thesis uses the bold notations to denote vectors.

following optimal container flow control problem:

$$\min_{\bar{\mathbf{x}},\bar{\mathbf{u}},\bar{\mathbf{d}},\bar{\mathbf{y}}} J(\bar{\mathbf{x}},\bar{\mathbf{u}},\bar{\mathbf{d}},\bar{\mathbf{y}}) \tag{4.10}$$

subject to

$$\mathbf{x}(k+1) = \mathbf{f_1}\left(\mathbf{x}(k),\mathbf{u}(k),\mathbf{d}(k),\mathbf{y}(k)\right), \tag{4.11}$$

$$\mathbf{y}(k+1) = \mathbf{f_2}\left(\mathbf{x}(k+1),\mathbf{u}(k),\mathbf{d}(k)\right), \tag{4.12}$$

$$\mathbf{g}\left(\mathbf{x}(k+1),\mathbf{u}(k),\mathbf{d}(k),\mathbf{y}(k+1)\right) \leq 0, \quad k = 0,\ldots,N_{\text{planning}}-1, \tag{4.13}$$

$$\mathbf{x}(0) = \mathbf{x}_0, \quad \mathbf{d}(k) = \mathbf{d}_k \tag{4.14}$$

where the vectors $\mathbf{u}(k)$ and $\bar{\mathbf{u}}$ contain the flow control actions at nodes of the IFTN for time step k and over the planning period $\left[0, N_{\text{planning}} T_{\text{s}}\right)$ (h) respectively, and the vectors $\mathbf{x}(k)$, $\bar{\mathbf{x}}$, $\mathbf{y}(k)$, $\bar{\mathbf{y}}$, $\mathbf{d}(k)$, and $\bar{\mathbf{d}}$ are defined in the same way; $\mathbf{x}_0$ is the initial states of the system; and $\mathbf{d}_k$ is the predicted disturbances for time step k as given by the transport demand and traffic condition information in the system. The control performance (4.10) is derived from the objective function given in (4.1). The system equations (4.11)–(4.12) and the constraints (4.13) are based on the dynamics of the IFTN presented in Chapter 3.

4.3 Model predictive container flow control

The synchromodal freight transport planning approach under investigation in this chapter has two main features: 1) it addresses dynamic behaviors of the transport demand and traffic condition in the IFTN by applying re-planning strategies; 2) it determines both transport routes and container flow assignments simultaneously by solving an optimization problem. MPC approaches can achieve these two features in a proper manner. First, MPC solves a sequence of control problems in a receding horizon fashion. In the proposed MPFC approach, for each time step k of the whole planning period $\left[0, N_{\text{planning}} T_{\text{s}}\right)$ (h), an optimal container flow control problem of the form (4.10)–(4.14) formulated for a finite prediction period $\left[kT_{\text{s}}, \left(k+N_{\text{p}}\right) T_{\text{s}}\right)$ (h) is solved to find the flow control actions $\tilde{\mathbf{u}}(k)$ on the basis of the dynamic IFTN model, the current system states $\mathbf{x}(k)$, and the information of system disturbances $\tilde{\mathbf{d}}(k)$ over the prediction period. The flow control actions for time step k are actually applied to the system. For the next time step $k+1$, this optimization procedure is implemented with the updated system states $\mathbf{x}(k+1)$ and system disturbances $\tilde{\mathbf{d}}(k+1)$. Secondly, an optimal container flow control problem of the form (4.10)–(4.14) formulated for a finite prediction period $\left[kT_{\text{s}}, \left(k+N_{\text{p}}\right) T_{\text{s}}\right)$ (h) solved for each time step evaluates the possible transport routes and container flow assignment options in terms of control actions for this prediction period.

The MPFC problem for time step k can be stated as:

$$\min_{\tilde{\mathbf{x}}(k),\tilde{\mathbf{u}}(k),\tilde{\mathbf{d}}(k),\tilde{\mathbf{y}}(k)} J(\tilde{\mathbf{x}}(k),\tilde{\mathbf{u}}(k),\tilde{\mathbf{d}}(k),\tilde{\mathbf{y}}(k)) \tag{4.15}$$

subject to

$$\mathbf{x}(k+1+l) = \mathbf{f_1}(\mathbf{x}(k+l), \mathbf{u}(k+l), \mathbf{d}(k+l), \mathbf{y}(k+l)), \tag{4.16}$$
$$\mathbf{y}(k+1+l) = \mathbf{f_2}(\mathbf{x}(k+1+l), \mathbf{u}(k+l), \mathbf{d}(k+l)), \tag{4.17}$$

$$\mathbf{g}(\mathbf{x}(k+1+l), \mathbf{u}(k+l), \mathbf{d}(k+l), \mathbf{y}(k+1+l)) \leq 0, \tag{4.18}$$

$$\mathbf{d}(k+l) = \mathbf{d}_{k+l}, \quad l = 0, \ldots, N_\mathrm{p} - 1, \tag{4.19}$$
$$\mathbf{x}(k) = \mathbf{x}_k, \tag{4.20}$$

where $\tilde{\mathbf{x}}(k)$, $\tilde{\mathbf{u}}(k)$, $\tilde{\mathbf{d}}(k)$, and $\tilde{\mathbf{y}}(k)$ are defined in the same way as $\mathbf{x}(k)$, $\mathbf{u}(k)$, $\mathbf{d}(k)$, and $\mathbf{y}(k)$ used in the optimal container flow control problem (4.10)–(4.14), but for a prediction period $\left[kT_\mathrm{s}, \left(k+N_\mathrm{p}\right)T_\mathrm{s}\right)$ (h) instead of only for time step k.

Recall from the IFTN model in Chapter 3 that the nonlinear speed-density relation model for freeway links given by (3.10)–(3.11) in Section 3.2.3 can be evaluated in an off-line way. Therefore, for the linear IFTN model the corresponding MPFC problem is essentially a linear programming (LP) problem. For time step k, the MPFC approach involves an LP problem with $N_\mathrm{od}N_\mathrm{p}N_\mathrm{link}$ variables, and $N_\mathrm{p}\left(4N_\mathrm{node} + 3N_\mathrm{link} + N^\mathrm{train}_\mathrm{scheduled}(k) + N^\mathrm{barge}_\mathrm{scheduled}(k)\right)$ inequality constraints. Here, $N^\mathrm{train}_\mathrm{scheduled}(k)$ and $N^\mathrm{barge}_\mathrm{scheduled}(k)$ respectively denote the number of the scheduled trains and barges in the network during the prediction period $\left[kT_\mathrm{s}, \left(k+N_\mathrm{p}\right)T_\mathrm{s}\right)$ (h). LP problems have a polynomial time complexity and can be solved efficiently with state-of-the-art algorithms, e.g., the simplex algorithm, or the interior-point algorithm [130].

However, applying the MPFC approach with the load-dependent IFTN model presented in Section 3.3 results in a nonlinear and non-convex optimization problem. The nonlinearity is caused by the exponential term, the maximization term, and the round operation in the multi-class version of the speed-density relation (3.22)–(3.24). In the next section we will therefore give two approaches for solving the resulting nonlinear and non-convex optimization problem.

4.4 Solution approaches

This section presents two approaches for solving the MPFC problem with the load-dependent IFTN model, i.e., nonlinear optimization in Section 4.4.1 and iterative linear programming in Section 4.4.2.

4.4.1 Nonlinear optimization

Nonlinear optimization approaches can generally be categorized as gradient-based approaches and gradient-free approaches. The gradient-based approaches require the gradient and Hessian information, which might not be analytically available in some cases and which then has to be approximated and calculated in a numerical way. The Sequential Quadratic Programming (SQP) algorithm is one widely used gradient-based approach. Theoretically it requires that the objective function and the constraints of the nonlinear programming problem are continuously differentiable [16]. The SQP algorithm transforms a nonlinear optimization problem into a sequence of quadratic optimization problems with a quadratic objective function and linear equality and inequality constraints. These quadratic optimization problems can be solved with efficient algorithms, e.g., active-set methods, or interior-point methods [130]. During the iterations, the solutions of these quadratic optimization problems converge to a solution of the nonlinear optimization problem [16–18].

It is well known that multiple local optima might exist for a nonlinear optimization problem. The multi-start method is required to find a better local optima or the global optima of this nonlinear optimization problem by solving the problem again with multiple random initial solutions [111].

Even though the constraints (3.22)–(3.24) of the nonlinear and non-convex optimization problem in the MPFC approach are not continuously differentiable, we can apply the SQP method in combination with the multi-start method for solving the synchromodal freight transport problem defined in Section 4.5.1 since it obtains good solutions in the simulation experiments in Section 4.5.3.

4.4.2 Iterative linear programming

This section proposes a multi-start iterative linear programming (ILP) method to solve the nonlinear and non-convex MPFC optimization problem using an iterative approach. The ILP method is motivated by the fact that the nonlinear and non-convex MPFC problem with the load-dependent IFTN model will reduce to a linear programming optimization problem in the case of fixed transport times on the links of the road network. The following two sections introduce the basic idea of the ILP method, and propose the stopping window method for determining when to stop the iteration process considering the occurrence of oscillations.

The ILP method

The iterative linear programming method involves an iterative implementation of a linear programming optimization and update procedure until certain stopping criteria are met. This procedure consists of two parts. In the first linear optimization part, the container flow control problem (4.15)–(4.20) for time step k over the prediction period $\left[kT_\mathrm{s}, \left(k+N_\mathrm{p}\right)T_\mathrm{s}\right)$ (h) is solved as a linear programming problem by considering fixed transport times on freeway links, i.e., $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$. The first part determines flow control actions $\tilde{\mathbf{u}}(k)$ and obtains the correspondingly predicted system states $\tilde{\mathbf{x}}(k)$. After that, the second update part updates $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$ using $\tilde{\mathbf{u}}(k)$ and $\tilde{\mathbf{x}}(k)$ obtained in the linear optimization part of the current iteration and using the multi-class version of the speed-density relation model (3.23)–(3.24). The updated $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$ values will be used as the input to the linear optimization part of the next iteration. The values of the fixed freeway transport times $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$ used in the linear optimization part of each iteration are determined as follows: at the first iteration, the $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$ values are initialized as $\mathbf{t}^{\mathrm{truck}}_{\mathrm{initial}}(k)$ (e.g., typical transport times needed to cross freeway links); at later iterations, the values of $\mathbf{t}^{\mathrm{truck}}_{\mathrm{fixed}}(k)$ are the results obtained in the update part of the previous iteration.

The stopping window method

This section introduces a so-called stopping window method to stop the iteration process of the ILP method. This method takes into account that an oscillation in the value

Algorithm 4.1 The iterative linear programming procedure with the stopping window method used by MPFC for time step k.

Input : N_{window}, $N_{\text{iteration}}^{\max} \geq 2N_{\text{window}}$, $\mathbf{t}^{\text{train}}(k)$, $\mathbf{t}^{\text{barge}}(k)$, $\mathbf{t}_{\text{initial}}^{\text{truck}}(k)$, $\mathbf{t}_{\text{typical}}^{\text{truck}}(k)$, system states $\mathbf{x}(k)$, disturbances $\tilde{\mathbf{d}}(k)$ over the prediction period $\left[kT_{\text{s}}, \left(k+N_{\text{p}}\right)T_{\text{s}}\right)$ (h), an IFTN

Initialization : $\mathbf{t}_{\text{initial}}^{\text{truck}}(k) \leftarrow \mathbf{t}_{\text{typical}}^{\text{truck}}(k)$, $s \leftarrow 1$, $\text{Flag}_{\text{stop}} \leftarrow 0$, $J_{\text{window}}^{\min} \leftarrow 0$, $J_{\text{window}}^{\text{mean}} \leftarrow 0$, $J_{\text{window}}^{\max} \leftarrow 0$, $J_{\text{window}}^{\text{min,previous}} \leftarrow \infty$, $J_{\text{window}}^{\text{mean,previous}} \leftarrow \infty$, $J_{\text{window}}^{\text{max,previous}} \leftarrow \infty$

while $s \leq N_{\text{iteration}}^{\max}$ and $\text{Flag}_{\text{stop}} == 0$ **do**
  if s==1 **then**
    $\mathbf{t}_{\text{fixed}}^{\text{truck}}(k) \leftarrow \mathbf{t}_{\text{initial}}^{\text{truck}}(k)$
  end if
  $J(s), \tilde{\mathbf{u}}(k), \tilde{\mathbf{x}}(k) \leftarrow$ solve the linear programming problem version of the MPFC problem (4.15)–(4.20) for $\mathbf{t}^{\text{train}}(k), \mathbf{t}^{\text{barge}}(k), \mathbf{t}_{\text{fixed}}^{\text{truck}}(k)$
  $\mathbf{t}_{\text{fixed}}^{\text{truck}}(k) \leftarrow$ actual transport times on freeway links updated using $\tilde{\mathbf{u}}(k), \tilde{\mathbf{x}}(k)$ based on (3.23)–(3.24)
  if $2N_{\text{window}} < s$ and $s \leq N_{\text{iteration}}^{\max}$ **then**
    $J_{\text{optimal}}(k), \tilde{\mathbf{u}}_{\text{optimal}}(k), \tilde{\mathbf{x}}_{\text{optimal}}(k) \leftarrow$ minimum value of $J(\cdot)$ from iteration $s - N_{\text{window}} + 1$ to iteration s and the corresponding solutions $\tilde{\mathbf{u}}(k), \tilde{\mathbf{x}}(k)$
    $J_{\text{window}}^{\min}, J_{\text{window}}^{\text{mean}}, J_{\text{window}}^{\max} \leftarrow$ minimum, mean, and maximum values of $J(\cdot)$ from iteration $s - N_{\text{window}} + 1$ to iteration s
    for $k_{\text{window}} = 1, 2, \ldots, N_{\text{window}}$ **do**
      $J_{\text{window}}^{\text{min,previous}}, J_{\text{window}}^{\text{mean,previous}}, J_{\text{window}}^{\text{max,previous}} \leftarrow$ minimum, mean, and maximum value of $J(\cdot)$ from iteration $s - k_{\text{window}} - N_{\text{window}} + 1$ to iteration $s - k_{\text{window}}$
      if $J_{\text{window}}^{\text{min,previous}} == J_{\text{window}}^{\min}$ and $J_{\text{window}}^{\text{mean,previous}} == J_{\text{window}}^{\text{mean}}$ and $J_{\text{window}}^{\text{max,previous}} == J_{\text{window}}^{\max}$ **then**
        $\text{Flag}_{\text{stop}} \leftarrow 1$
        Break for
      end if
    end for
  end if
  $s \leftarrow s + 1$
end while

Output : $J_{\text{optimal}}(k), \tilde{\mathbf{u}}_{\text{optimal}}(k), \tilde{\mathbf{x}}_{\text{optimal}}(k)$

of the objective function might occur during iterations. In general, for different types of nonlinearities embodied in the original nonlinear and non-convex optimization problem the iteration process of the ILP method may demonstrate different behaviors. For instance, the value of the objective function during the iterations may converge to a certain value, oscillate, or randomly fluctuate, etc. Therefore, one crucial decision in the implementation of the ILP approach is to set its stopping criteria. Here, we investigate a particular type of nonlinearity induced by the multi-class version of the speed-density relation model (3.23)–(3.24) for freeways in the MPFC problem.

For each time step of the MPFC problem, the evolution trajectory of the objective function during the iteration process of the ILP method might not converge, but could oscillate. The evolution pattern can be different for different initial values of $\mathbf{t}^{\text{truck}}_{\text{fixed}}(k)$ or among different time steps. Having oscillations in the evolution trajectory of the objective function is caused by the discretization of (continuous) transport times on freeways using (3.24). Generally, transport times on freeways have continuous real values. The discretized freeway transport times, $\mathbf{t}^{\text{truck}}(k)$, may jump among several positive integer values during the iteration process and correspondingly the evolution trajectory of the objective function may oscillate. Therefore, a stopping criterion for the ILP method in the MPFC problem should be developed to identify these oscillations and to select the solution with the minimum value of the objective function within the oscillations.

The stopping window method defines a stopping window with a length of N_{window} iterations, which is characterized by three parameters: the minimum, mean, and maximum values of the objective functions at iterations within the stopping window denoted by $J^{\text{min}}_{\text{window}}$, $J^{\text{mean}}_{\text{window}}$, and $J^{\text{max}}_{\text{window}}$, respectively. The stopping window method works in the following way: at each iteration s larger than or equal to $2N_{\text{window}}$, first calculate the characteristics $J^{\text{min}}_{\text{window}}(s)$, $J^{\text{mean}}_{\text{window}}(s)$, and $J^{\text{max}}_{\text{window}}(s)$ of the current stopping window from iteration $s - N_{\text{window}} + 1$ to s and store the solution $\mathbf{x}^*(s)$ corresponding to $J^{\text{min}}_{\text{window}}(s)$; next check whether the current stopping window has the same characteristic parameters as one of its previous N_{window} stopping windows, characterized by $J^{\text{min,previous}}_{\text{window}}$, $J^{\text{mean,previous}}_{\text{window}}$, and $J^{\text{max,previous}}_{\text{window}}$, from iteration $s - k_{\text{window}} - N_{\text{window}} + 1$ to $s - k_{\text{window}}$ for $k_{\text{window}} \in \{1, \dots, N_{\text{window}}\}$; if yes, take the solution $\mathbf{x}^*(s)$ as the final solution and terminate the iteration procedure; if not, move to the next iteration. When the iteration procedure reaches the pre-defined maximum iteration number $N^{\text{max}}_{\text{iteration}}$, it will be terminated and the solution $\mathbf{x}^*(N^{\text{max}}_{\text{iteration}})$ is taken as the optimal solution. The implementation of the stopping window method to the ILP method for time step k in the MPFC problem is presented in **Algorithm 4.1**.

In general, the ILP method does not guarantee obtaining the global optimal solution of the nonlinear and non-convex MPFC problem. Therefore, we apply a multi-start strategy in the implementation of the ILP method. Multiple values of $\mathbf{t}^{\text{truck}}_{\text{initial}}(k)$ are generated as random positive integers equal to or smaller than maximum transport times on freeways, and subsequently used in the iterative procedure given in **Algorithm 4.1**.

4.5 Simulation experiments

In this section, the MPFC approach is applied for synchromodal freight transport planning in the single-region IFTN benchmark system presented in Section 3.4.1. Section 4.5.1 introduces the setting of the synchromodal freight transport planning problem. The MPFC

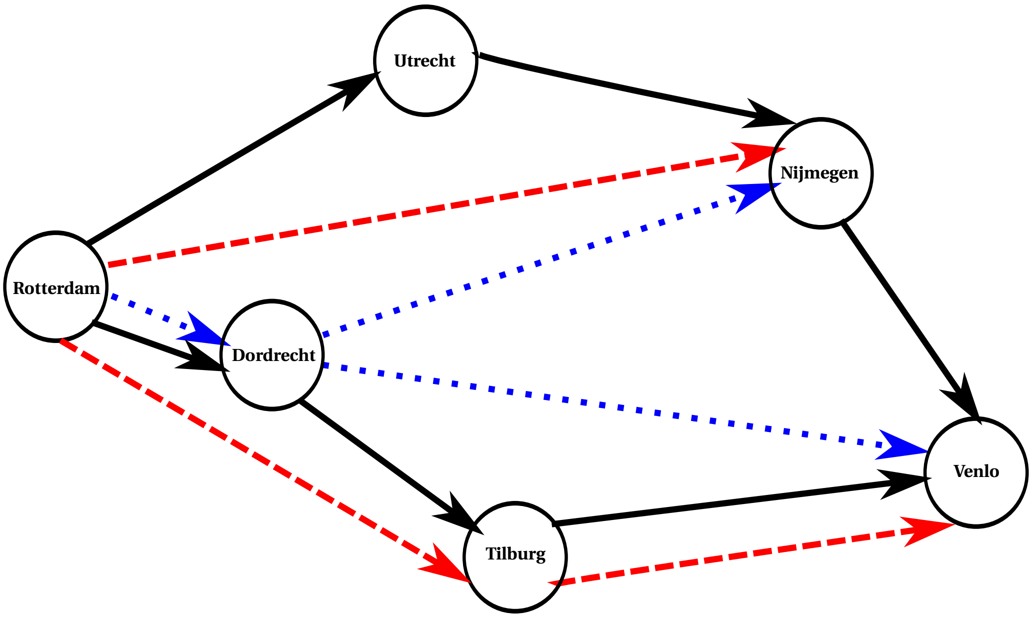

Figure 4.1: The topology of the single-region IFTN benchmark system from Rotterdam to Venlo. The solid black arcs, the dashed red arcs, and the dotted blue arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

approach and the all-or-nothing approach (as introduced in Section 2.2) are applied and compared in Section 4.5.2 for the linear IFTN model and in Section 4.5.3 for the load-dependent IFTN model, respectively. The MPFC approach is further examined under different demand scenarios and for different prediction error levels on the future transport demand and traffic conditions in the simulation.

4.5.1 The problem setting

In this section we consider synchromodal freight transport planning for an intermodal freight transport operator in the single-region IFTN benchmark system presented in Section 3.4.1. The network topology and the corresponding virtual network representation of the network are shown in Figures 4.1 and 4.2, respectively. The scenario setup and the controller and solver settings are then introduced in the following sections.

Scenario setup

We consider synchromodal freight transport planning for a period of 24 (h) with a time step $T_s = 1$ (h). The value of time in the objective function (4.1) is taken as 25 (€/h). Except for the prediction error analysis sections, the system disturbances (i.e., the transport demand, and traffic conditions in the network) within the prediction period $\left[kT_s, \left(k+N_p\right)T_s\right)$ (h) are assumed to be predicted accurately at time kT_s in the simulation study. Initially the network is taken to be empty (i.e., $x_{i,o,d}(k) = 0$ and $x^m_{i,j,o,d}(k) = 0$, $\forall (o,d) \in \mathcal{O}_{\text{od}}, \forall\ (i,j,m) \in \mathcal{E}, \forall\ k \le 0$).

Based on the above basic problem settings, we set up two synchromodal freight transport planning problems where the linear IFTN model and the load-dependent IFTN model are used, respectively. For the planning problem with the linear IFTN model, the piecewise constant transport demand from node 1^{W} to node 6^{R} is given in Table 4.1. The

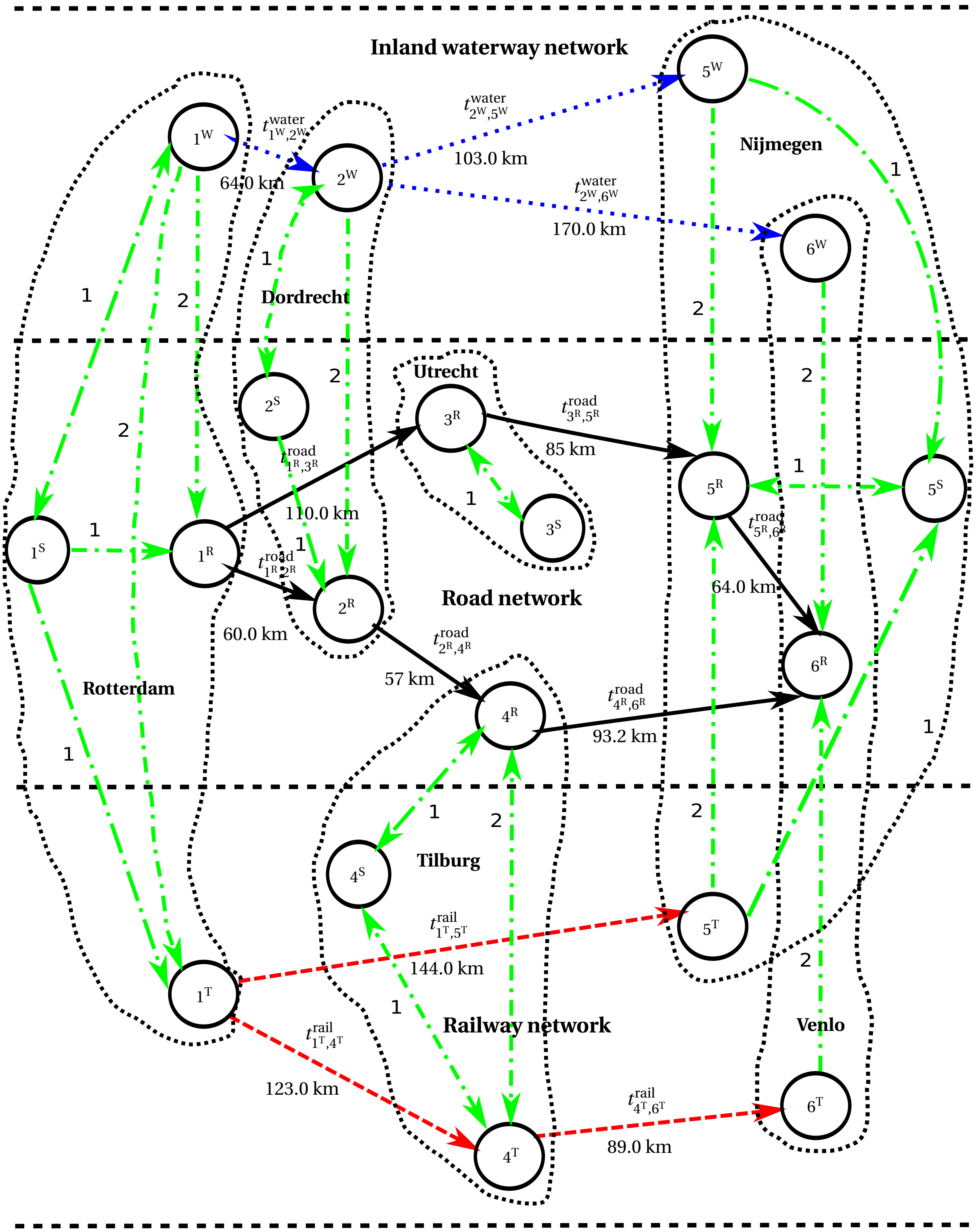

Figure 4.2: The corresponding virtual network representation of the network shown in Figure 4.1. Each double-headed arc in the figure represents two directed links with opposite directions.

Table 4.1: Densities of traffic flows on the freeway links and transport demand for the synchromodal freight transport planning problem with linear IFTN model.

Period (h)	0 – 3	3 – 9	9 – 15	15 – 21	22 – 34
$\rho^{\text{road,oth}}_{1^\text{R},2^\text{R}}, \rho^{\text{road,oth}}_{1^\text{R},3^\text{R}}, \rho^{\text{road,oth}}_{2^\text{R},4^\text{R}}$ (veh/km/lane)	45.0	65.0	45.0	25.0	20.0
$\rho^{\text{road,oth}}_{3^\text{R},5^\text{R}}, \rho^{\text{road,oth}}_{5^\text{R},6^\text{R}}, \rho^{\text{road,oth}}_{4^\text{R},6^\text{R}}$ (veh/km/lane)	20.0	65.0	25.0	45.0	20.0
$d_{1^\text{W},6^\text{R}}$ (TEU/h)	30	100	65	30	0

Table 4.2: Densities of traffic flows not induced by the freight trucks from the transport operator on the freeway links and transport demand for the synchromodal freight transport planning problem with the load-dependent IFTN model.

Period (h)	0 – 3	3 – 9	9 – 15	15 – 18	19 – 34
$\rho^{\text{road,oth}}_{1^\text{R},2^\text{R}}, \rho^{\text{road,oth}}_{1^\text{R},3^\text{R}}, \rho^{\text{road,oth}}_{2^\text{R},4^\text{R}}$ (veh/km/lane)	20.0	40.0	35.0	30.0	20.0
$\rho^{\text{road,oth}}_{3^\text{R},5^\text{R}}, \rho^{\text{road,oth}}_{5^\text{R},6^\text{R}}, \rho^{\text{road,oth}}_{4^\text{R},6^\text{R}}$ (veh/km/lane)	20.0	20.0	20.0	20.0	20.0
$d_{1^\text{W},6^\text{R}}$ (TEU/h)	300	400	350	300	0

density of traffic flows on the six freeway links of the single-region IFTN benchmark system are given in Table 4.1.

For the planning problem with the load-dependent IFTN model, Table 4.2 gives the piecewise constant transport demand with origin node 1^W and destination node 6^R. The volumes of the transport demand given in Table 4.2 are larger than the volumes of the transport demand presented in Table 4.1. This is to represent the situation that a large-size transport operator can influence the traffic conditions on freeways with its own freight truck flows, and consequently we have to use the load-dependent IFTN model. The densities of traffic flows induced by other vehicles except for freight trucks from the transport operator on the six freeway links are given in Table 4.2.

Controller and solver settings

We implement the MPFC approach proposed in Section 4.3 for the two synchromodal freight transport planning problems defined in the above sections as follows. For the planning problem with the linear IFTN model, the MPFC approach is implemented using the simplex method in the CPLEX solver of the TOMLAB Optimization Toolbox [81] for solving linear programming problems for each time step.

The MPFC approach involves solving a sequence of nonlinear and non-convex optimization problems when the load-dependent IFTN model is used. We use the two solution approaches proposed in Section 4.4 to solve these nonlinear and non-convex optimization problems. These two solution approaches are implemented as follows. First of all, a multi-start strategy is adopted in the implementation of these two approaches. A number of 25 different random initial starting points is used to compute the flow control actions for each time step of the MPFC approach. The number of initial starting points has been selected by carrying out simulation experiments on the planning problem considered in this section. The use of 25 initial starting points obtains an appropriate trade-off between the computation time needed to find solutions and the quality of the obtained solutions. Secondly, the SQP method in the SNOPT v7.2-5 solver of TOMLAB Optimization Toolbox [80] is chosen to solve directly the MPFC problem. Thirdly, the multi-start ILP method is implemented by using the simplex method in the CPLEX solver of the TOMLAB Optimization Toolbox [81] for solving linear programming problems at each iteration. Based on initial empirical experiments on the planning problem with the particular scenario setup presented in this section, the length of the stopping window and the maximum iteration number are selected as $N_{\text{window}} = 10$ and $N_{\text{iteration}}^{\max} = 50$, respectively. Finally, the multi-start optimization procedures of both the multi-start SQP method and the multi-start ILP method for solving the MPFC problem for each time step are stopped after being implemented for 25 times.

The simulation experiments are done using a desktop computer with an Intel® Core™ i5-2400 CPU with 3.10 GHz and 4 GB RAM.

4.5.2 MPFC with the linear IFTN model

This section applies the proposed MPFC approach for the planning problem with the linear IFTN model presented in Section 3.2, and compares it with an all-or-nothing approach summarized in Section 2.2.

All-or-nothing approach vs the MPFC approach

Table 4.3 presents the results of applying the all-or-nothing approach and the MPFC approach. The table shows the total delivery costs as defined in (4.1) for the entire planning period, the mean and maximum computation times for a single time step, and modal split rates. The terms "AON", and "$\text{MPFC}_n^{\text{LP}}$" denote the all-or-nothing approach and the MPFC approach with a prediction period of n time steps, respectively. The total delivery cost defined in (4.1) for the entire planning period and the penalty cost on unfinished transport demand inside the IFTN at the end of the planning period are denoted by "$J(\cdot)$" and "penalty", respectively. The all-or-nothing approach leads to the largest total delivery cost (i.e., 5.4021×10^5 €) in comparison to the MPFC approach with different prediction horizons, but only takes very little time to determine transport plans in the simulation.

The corresponding planning performance of the MPFC approach with different prediction horizons N_{p} is also shown in Table 4.3. It is clear from the table that the total delivery cost resulting from the MPFC approach becomes smaller when the prediction horizon N_{p} increases; a stable value is reached when N_{p} is large enough. In this particular case, the MPFC approach with a prediction horizon of $N_{\text{p}} = 12$ results in a 20.18% reduction of the total delivery cost compared with the all-or-nothing approach. Table 4.3 moreover shows that a larger N_{p} in the MPFC approach requires more computation time. This is because the increase of N_{p} will augment the number of optimization variables and constraints in the linear optimization problem to be solved for each time step.

The modal split rates as given in Table 4.3 and Table 4.4 are calculated for intermodal terminal 1. Essentially, the modal split rates resulting from the MPFC approach are determined by the planning problem setting and the parameter selection, e.g., the value of the prediction horizon.

Remark 4.2 When applying the MPC strategy for flow control problems in transport networks, the prediction horizon N_{p} is typically selected to be large enough to capture the dynamic evolution of the network. For the MPFC approach in this chapter, the prediction horizon can therefore be chosen as the maximum value of the typical transport times

Table 4.3: Comparison of the results of the all-or-nothing approach and the MPFC approach for the synchromodal freight transport planning problem with the linear IFTN model.

	$J(\cdot)$ (€)	$t_{\mathrm{cpu}}^{\max}$ (ms)	$t_{\mathrm{cpu}}^{\mathrm{mean}}$ (ms)	truck (%)	train (%)	barge (%)	penalty (€)
AON	5.4021×10^5	≤ 15.0	≤ 15.0	68.25	31.75	0.0	2.38×10^4
$\mathrm{MPFC}_5^{\mathrm{LP}}$	4.9265×10^5	48.6	32.0	87.30	12.70	0.0	0.15×10^4
$\mathrm{MPFC}_{10}^{\mathrm{LP}}$	4.4275×10^5	111.9	68.4	59.13	20.24	20.63	0.75×10^3
$\mathrm{MPFC}_{12}^{\mathrm{LP}}$	4.3056×10^5	127.1	85.1	74.60	15.08	10.32	0.75×10^3
$\mathrm{MPFC}_{14}^{\mathrm{LP}}$	4.3056×10^5	151.6	119.3	74.60	15.08	10.32	0.75×10^3

between any two nodes of the network given in Table 3.1. However, this maximum value might be larger than the prediction horizon suited for the particular transport demand and network properties (e.g., traffic conditions on freeways), and could consequently increase the computational complexity of the planning problem. Therefore, in this chapter the prediction horizon for the MPFC approach is determined by performing empirical simulation experiments on the problem setting defined in Section 4.5.1. These simulation experiments show that a prediction horizon $N_{\mathrm{p}} = 12$ is adequate for the planning problem in this section. □

Demand scenario analysis

Transport demands may vary a lot under different situations, e.g., normal seasons or holiday seasons, working days or weekends, and early mornings or mid-afternoons. Therefore, an efficient flow control approach should be able to obtain good planning performance in a consistent way under different demand scenarios. In this section, five demand scenarios are considered, i.e., a constant volume of 60 (TEU/h) during the period [0, 18] (h), a peak (as defined in Table 4.1 and taken as the reference scenario), half volume, double volume, and triple volume with respect to the reference scenario. The MPFC approach with a prediction period of $N_{\mathrm{p}} = 12$ time steps is applied for controlling flows in the network under these five demand scenarios.

In Table 4.4 the terms "$\mathrm{MPFC}_{\mathrm{scenario}}^{\mathrm{LP}}$" denote the MPFC approach for the five demand scenarios defined before. The planning performance in this table is calculated in the same way as for Table 4.3. As can be seen from the results in Table 4.4, the variations in the transport demand have a minimal impact on the implementation of the MPFC approach since roughly the same mean computation time for each single time step, $t_{\mathrm{cpu}}^{\mathrm{mean}}$, is needed by the MPFC approach under five demand scenarios.

Prediction error analysis

The predictions of system disturbances (i.e., the transport demand, and traffic conditions in the network) within the current prediction period could involve errors. This section examines the effects of prediction errors under two demand scenarios and makes two assumptions as follows: 1) at time kT_{s}, accurate predictions of system disturbances for time step k are available, and 2) at time kT_{s}, the predictions of system distributions for the remainder prediction period $\left[(k+1)T_{\mathrm{s}}, \left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$ (h) may contain errors. The two real

Table 4.4: Planning performance of the MPFC approach for the synchromodal freight transport planning problem with the linear IFTN model under five demand scenarios.

	$J(\cdot)$ (€)	$t_{\text{cpu}}^{\max}$ (ms)	$t_{\text{cpu}}^{\text{mean}}$ (ms)	truck (%)	train (%)	barge (%)	penalty (€)
$\text{MPFC}_{\text{constant}}^{\text{LP}}$	4.2776×10^5	100.3	84.5	71.43	19.05	9.52	0.15×10^4
$\text{MPFC}_{\text{reference}}^{\text{LP}}$	4.3056×10^5	127.1	85.1	74.60	15.08	10.32	0.75×10^3
$\text{MPFC}_{\text{half}}^{\text{LP}}$	2.1518×10^5	95.3	84.5	74.60	15.08	10.32	0.38×10^3
$\text{MPFC}_{\text{double}}^{\text{LP}}$	8.5190×10^5	98.0	85.6	62.70	20.63	16.67	0.15×10^4
$\text{MPFC}_{\text{triple}}^{\text{LP}}$	1.4035×10^6	93.6	83.1	64.68	20.63	14.68	0.23×10^4

scenarios consider the transport demand information and the densities of other traffic on the freeway links for the reference scenario and the triple volume scenario given in Table 4.1 as the nominal values. The three prediction error levels are defined as 5%, 10%, and 15%. The prediction errors in the transport demand and densities of other traffic on the freeway links are then assumed as uniformly distributed random variables with zero mean and a standard deviation equal to respectively 5%, 10%, and 15% times the nominal value.

In this section the MPFC approach uses a prediction horizon of $N_{\text{p}} = 12$. For each prediction error level, we run the closed-loop simulation 20 times and report the mean value, and the standard deviation of the total delivery cost $J_{\text{mean}}(\cdot)$, and $J_{\text{std}}(\cdot)$ for an entire planning period, and of the maximum and mean cpu times for a single time step, $t_{\text{cpu,mean}}^{\max}$, $t_{\text{cpu,std}}^{\max}$, $t_{\text{cpu,mean}}^{\text{mean}}$, and $t_{\text{cpu,std}}^{\text{mean}}$, respectively. The transport planning performance under two real demand scenarios with the four prediction error levels is presented in Table 4.5. The terms "$\text{MPFC}_{\text{demand},i}^{\text{LP}}$" correspond to the MPFC approach under either the reference demand scenario or the triple volume demand scenario with a prediction error level $i \in \{5\%, 10\%, 15\%\}$. This table gives the statistical values of the total freight delivery cost, the mean computation time, and the maximum computation time. For each simulation instance, the total freight delivery cost and the computation time are calculated in the same way as for Table 4.3.

As can be seen from the results in Table 4.5, the effect of the presence of prediction errors on the mean value of the total delivery cost turns out to be very small for both the reference demand scenario and the triple volume demand scenario, while the effect on the standard deviation of the total delivery cost increases for the triple volume demand scenario. The largest effect is observed for the case of a 10% prediction error level for the triple volume demand scenario, in which the standard deviation of the total delivery cost obtained by the MPFC approach reaches 0.24% of its mean value.

Moreover, the existence of prediction errors influences the maximum and mean cpu times required by the MPFC approach. The influences on $t_{\text{cpu,mean}}^{\text{mean}}$ are more perceptible for the triple volume demand scenario than for the reference demand scenario. It is expected that prediction errors could change the activation of the constraints in the optimization problem (4.15)–(4.20), and thus influence the computation time. Roughly speaking, under high-volume demand scenarios the presence of prediction errors has a bigger effect on guaranteeing the satisfaction of these constraints, and consequently has a relatively larger influence on the computation time and planning performance of the MPFC approach. It is noteworthy that the effect of prediction errors on the mean value of the total delivery cost for the triple volume demand scenario is actually quite small in Table 4.5. Possible reasons

Table 4.5: Planning performance of the MPFC approach for the synchromodal freight transport planning problem with the linear IFTN model under four prediction error levels.

	$J_{\text{mean}}(\cdot)$ (€)	$J_{\text{std}}(\cdot)$ (€)	$t^{\max}_{\text{cpu,mean}}$ (ms)	$t^{\max}_{\text{cpu,std}}$ (ms)	$t^{\text{mean}}_{\text{cpu,mean}}$ (ms)	$t^{\text{mean}}_{\text{cpu,std}}$ (ms)
$\text{MPFC}^{\text{LP}}_{\text{reference,real}}$	4.3056×10^5	–	127.1	–	85.1	–
$\text{MPFC}^{\text{LP}}_{\text{reference,5\%}}$	4.3056×10^5	0.0	99.1	8.9	84.2	2.0
$\text{MPFC}^{\text{LP}}_{\text{reference,10\%}}$	4.3056×10^5	0.0	106.4	8.8	86.0	1.4
$\text{MPFC}^{\text{LP}}_{\text{reference,15\%}}$	4.3056×10^5	0.0	122.1	26.2	87.5	3.2
$\text{MPFC}^{\text{LP}}_{\text{triple,real}}$	1.4035×10^6	–	93.6	–	83.1	–
$\text{MPFC}^{\text{LP}}_{\text{triple,5\%}}$	1.4037×10^6	1.45×10^3	137.8	26.7	91.2	2.9
$\text{MPFC}^{\text{LP}}_{\text{triple,10\%}}$	1.4025×10^6	3.33×10^3	116.0	22.2	91.3	3.1
$\text{MPFC}^{\text{LP}}_{\text{triple,15\%}}$	1.4036×10^6	2.30×10^3	122.8	14.7	93.4	1.9

for this phenomenon can be the following. First of all, the MPFC approach determines container flow control actions in a receding horizon way, which enables the transport operator to cope with the prediction errors by computing again the control actions implemented for a particular time step with the latest prediction information available at the beginning of this time step. Secondly, this chapter assumes that accurate predictions of system disturbances for time step k are available at time kT_{s}. This assumption guarantees that the computed control actions for time step k of the MPFC problem are feasible even though the predicted system disturbances for the remainder of the prediction period, i.e., for $\left[(k+1)\,T_{\text{s}}, \left(k+N_{\text{p}}\right)T_{\text{s}}\right)$ (h), may contain errors. Moreover, the volume of transport demand in the triple volume demand scenario is relatively small in comparison to the volumes considered in Section 4.5.3 where the effect of prediction errors on the mean value of the total delivery cost is clearly noticeable in Table 4.8.

4.5.3 MPFC with the load-dependent IFTN model

This section considers transport planning for a large-sized intermodal freight transport operator. The MPFC approach is implemented with the load-dependent IFTN model presented in Section 3.3.

Oscillations in the evolution trajectories of the objective function

As explained in Section 4.4.2, the evolution trajectories of the objective function during iterations of the multi-start ILP method may show oscillations. In order to show the occurrence of oscillations when solving the MPFC problem and to motivate the use of the stopping window method, this section uses a maximum number of iterations for determining when to stop the iteration procedure of the multi-start ILP method.

Oscillations are observed during the simulation experiments and shown in Figures 4.3 and 4.4. These two figures are obtained when implementing the multi-start ILP method for the MPFC approach with 25 different randomly generated positive freeway transport times $\mathbf{t}^{\text{truck}}_{\text{fixed}}(k)$. The iteration process was terminated when the iteration number exceeds a maximum number of iterations $N^{\max}_{\text{iteration}} = 50$. The evolution trajectories of the objective function J during the iteration process for time steps $k = 4$ and $k = 18$ are shown in Figures 4.3 and 4.4, respectively. The evolution trajectory in the case of different freeway transport

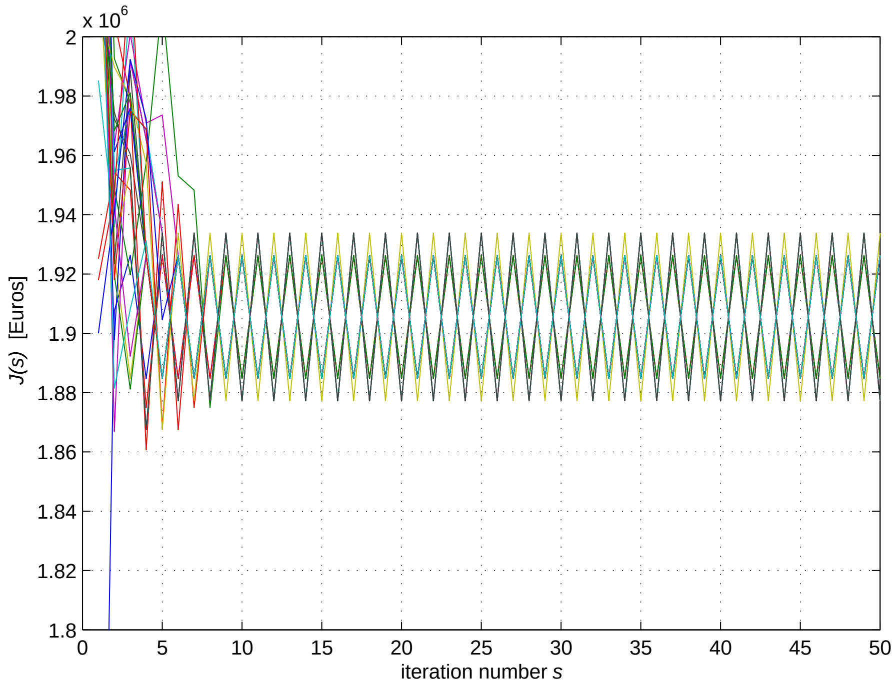

Figure 4.3: The evolution trajectories of the objective function J during the iteration process for time step $k = 4$ when implementing the multi-start ILP method for the MPFC approach.

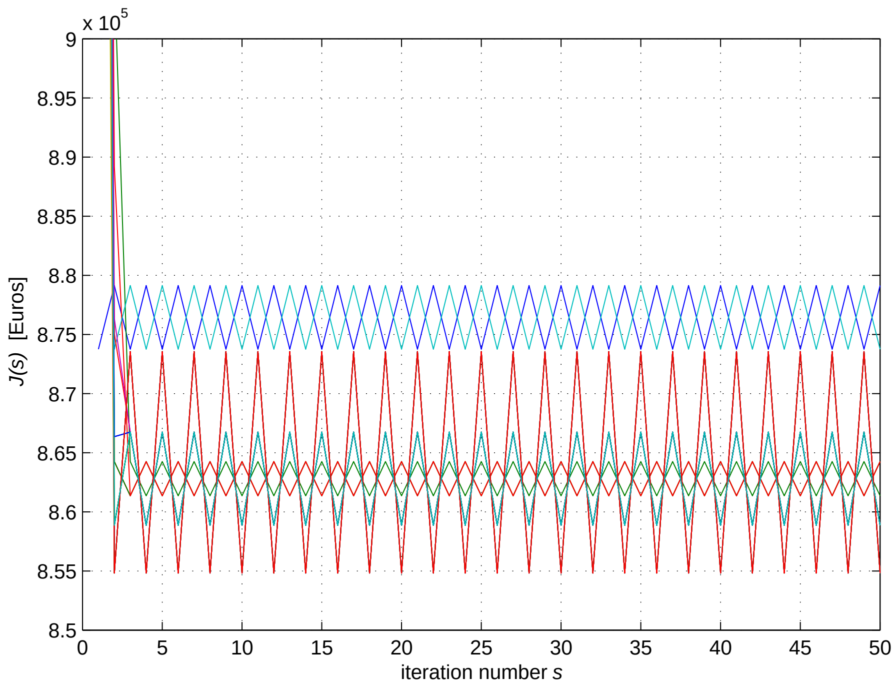

Figure 4.4: The evolution trajectories of the objective function J during the iteration process for time step $k = 18$ when implementing the multi-start ILP method for the MPFC approach.

times $\mathbf{t}_{\text{initial}}^{\text{truck}}(k)$ are indicated with different colors. Therefore, we will implement the multi-start ILP method in combination with the stopping window method for solving the MPFC problem with the load-dependent IFTN model in the rest of the simulation experiments.

All-or-nothing approach vs the MPFC approach

This section compares the all-or-nothing approach and the MPFC approach. Table 4.6 presents the planning performance of the all-or-nothing approach and the MPFC approach, i.e., total delivery costs as defined in (4.1) for the entire planning period, the mean and maximum computation times for a single time step, and the modal split rates. The elements “AON”, “$\text{MPFC}_n^{\text{SNOPT}}$”, and “$\text{MPFC}_n^{\text{ILP}}$” denote the all-or-nothing approach and the model predictive container flow control approach with a prediction period of n steps using either the multi-start SQP method or the multi-start ILP method proposed in this chapter. The all-or-nothing approach runs very fast but results in the largest total delivery cost (i.e., 4.7793×10^6 €) in comparison to the MPFC approach with different prediction horizons and optimization methods. The planning performance of each optimization method in the MPFC approach with different prediction horizons N_p is shown in Table 4.6. In this simulation study, modal split rates as given in Tables 4.6 and 4.3 are calculated for intermodal terminal 1. Because some containers might still stay within intermodal terminal 1 at the end of the planning period for some transport planning scenarios, e.g., $\text{MPFC}_5^{\text{SNOPT}}$, the “unfinished” term shows the percentage of unfinished transport demand at this terminal in Table 4.6.

It is clear from Table 4.6 that the total delivery cost resulting from the MPFC approach gets smaller when the prediction horizon N_p increases. For both the two optimization methods, the MPFC approach outperforms the all-or-nothing approach when the prediction horizon is large enough. In this particular case, the MPFC approach with a prediction horizon of $N_\text{p} = 10$ using the multi-start ILP method obtains a 37.18% reduction of the total delivery cost compared with the all-or-nothing approach.

For the MPFC approach with the same prediction horizon, Table 4.6 shows that the multi-start ILP method achieves a performance that is comparable with that of the multi-start SQP method, while it significantly reduces the computation time. For a prediction horizon of $N_\text{p} = 10$, compared to the multi-start SQP method, the multi-start ILP method achieves a 0.24% larger total delivery cost with only 1.67% of the mean computation time. In addition, there is a big relative difference between the maximum computation time and the mean computation time required by the multi-start SQP method. In particular, the relative difference is almost four times in the case of a prediction horizon of $N_\text{p} = 10$. For the multi-start ILP method, the relative difference is less than two times.

Table 4.6 shows that the maximum computation time resulting from the multi-start SQP method is larger than the one-hour planning time limitation when $N_\text{p} \geq 10$. Because flow control actions should be determined within a period of $T_\text{s} = 1$ hour for each time step of the MPFC problem considered in this section, this implies it is infeasible to solve the MPFC problem using the multi-start SQP method with 25 starting points in the desktop computer introduced in Section 4.5.1. To guarantee the feasibility of the multi-start SQP method implemented in our desktop computer for the MPFC problem with $N_\text{p} \geq 10$, a maximum allowed computation time (i.e., 1 hours) can be introduced to stop the multi-start SQP

Table 4.6: Comparison of the results of the all-or-nothing approach and the MPFC approach for the synchromodal freight transport planning problem with the load-dependent IFTN model.

	$J(\cdot)$ (€)	$t_{\mathrm{cpu}}^{\mathrm{max}}$ (min)	$t_{\mathrm{cpu}}^{\mathrm{mean}}$ (min)	truck (%)	train (%)	barge (%)	unfinished (%)	penalty (€)
AON	4.7793×10^6	≤ 0.1	≤ 0.1	100.0	0.0	0.0	0.0	8.5157×10^5
$\mathrm{MPFC}_5^{\mathrm{SNOPT}}$	3.4203×10^6	25.11	4.71	82.03	16.39	0.00	0.58	9.0543×10^4
$\mathrm{MPFC}_5^{\mathrm{ILP}}$	3.2012×10^6	0.23	0.22	85.71	14.29	0.00	0.00	9.0000×10^4
$\mathrm{MPFC}_8^{\mathrm{SNOPT}}$	3.0837×10^6	29.66	14.61	72.63	19.05	0.08	0.0	6.7504×10^4
$\mathrm{MPFC}_8^{\mathrm{ILP}}$	3.0628×10^6	0.71	0.35	73.02	17.46	9.52	0.00	6.6250×10^4
$\mathrm{MPFC}_{10}^{\mathrm{SNOPT}}$	2.9950×10^6	118.61	29.42	66.7	20.60	12.70	0.0	1.5594×10^5
$\mathrm{MPFC}_{10}^{\mathrm{ILP}}$	3.0023×10^6	0.70	0.49	65.08	19.05	15.87	0.00	1.5500×10^5
$\mathrm{MPFC}_{15}^{\mathrm{SNOPT}}$	3.8096×10^6	217.54	23.68	61.86	11.96	26.18	0.00	2.0330×10^5
$\mathrm{MPFC}_{15}^{\mathrm{ILP}}$	3.1105×10^6	2.44	1.24	65.08	19.05	15.87	0.00	1.1750×10^5

optimization process when the multi-start procedure is run less than 25 times but the computation time consumed reaches 1 hour. However, the resulting flow control actions will typically be less optimal than the flow control actions determined by the multi-start SQP method with a full implementation of 25 starting points. Therefore, in a given available one-hour computation time, the multi-start ILP method is expected to yield a better planning performance than the multi-start SQP method in the SNOPT v7.2-5 solver. Hence, in the MPFC problem considered in this section, the multi-start ILP method will be more preferable given its advantage in shortening computation times.

Demand scenario analysis

In this section, four demand scenarios are considered, i.e., a constant volume of 350 (TEU/h) during the period $[0, 18]$ (h), a peak (as defined in Table 4.2 and taken as the reference scenario), half volume and double volume with respect to the reference scenario. The MPFC approach using two optimization methods with the same parameter settings as in Section 4.5.3 is applied for controlling container flows under these four demand scenarios. A value of $N_{\mathrm{p}} = 10$ is chosen as the prediction horizon.

Table 4.7 illustrates the corresponding planning performance for four demand scenarios. In Table 4.7 the elements "$\mathrm{MPFC}_{\mathrm{scenario}}^{\mathrm{SNOPT}}$" and "$\mathrm{MPFC}_{\mathrm{scenario}}^{\mathrm{ILP}}$" denote the MPFC approach using either the multi-start SQP method or the multi-start ILP method for the given demand scenarios. The planning performance in this table is calculated in the same way as for Table 4.6. As can be seen from the results in Table 4.7, the multi-start ILP method prevails over the multi-start SQP method in terms of both mean computation time and the relative difference between maximum and mean computation times for all four demand scenarios. In terms of the total delivery cost, these two optimization methods yield a comparable planning performance for the reference demand scenario and the half-volume scenario. For the constant volume scenario, the multi-start SQP method results in a 3.77% lower total delivery cost than the total delivery cost achieved by the multi-start ILP method. For the double-volume scenario, compared to the multi-start SQP method, the multi-start ILP method achieves a 8.15% lower total delivery cost.

Table 4.7: Planning performance of the MPFC approach for the synchromodal freight transport planning problem with the load-dependent IFTN model under four demand scenarios.

	$J(\cdot)$ (€)	$t_{\text{cpu}}^{\text{max}}$ (min)	$t_{\text{cpu}}^{\text{mean}}$ (min)	truck (%)	train (%)	barge (%)	unfinished (%)	penalty (€)
$\text{MPFC}_{\text{constant}}^{\text{SNOPT}}$	2.8274×10^6	40.47	23.76	65.17	22.13	12.70	0.00	7.5958×10^4
$\text{MPFC}_{\text{constant}}^{\text{ILP}}$	2.9383×10^6	1.06	0.51	65.08	19.05	15.87	0.00	1.1750×10^5
$\text{MPFC}_{\text{reference}}^{\text{SNOPT}}$	2.9950×10^6	118.61	29.42	66.7	20.60	12.70	0.0	1.5594×10^5
$\text{MPFC}_{\text{reference}}^{\text{ILP}}$	3.0023×10^6	0.70	0.49	65.08	19.05	15.87	0.00	1.5500×10^5
$\text{MPFC}_{\text{half}}^{\text{SNOPT}}$	1.3201×10^6	239.85	40.09	42.06	34.92	23.02	0.00	4.8750×10^4
$\text{MPFC}_{\text{half}}^{\text{ILP}}$	1.3533×10^6	0.45	0.43	40.48	34.92	24.60	0.00	5.1250×10^4
$\text{MPFC}_{\text{double}}^{\text{SNOPT}}$	8.0242×10^6	487.45	62.46	74.75	12.70	9.52	3.03	1.5915×10^6
$\text{MPFC}_{\text{double}}^{\text{ILP}}$	7.3704×10^6	1.04	0.60	73.02	11.90	11.11	0.00	1.4325×10^6

Table 4.8: Planning performance of the MPFC approach for the synchromodal freight transport planning problem with the linear IFTN model under four prediction error levels.

	$J_{\text{mean}}(\cdot)$ (€)	P_{change} (%)	$J_{\text{std}}(\cdot)$ (€)	$t_{\text{cpu,mean}}^{\text{max}}$ (min)	$t_{\text{cpu,std}}^{\text{max}}$ (min)	$t_{\text{cpu,mean}}^{\text{mean}}$ (min)	$t_{\text{cpu,std}}^{\text{mean}}$ (min)
$\text{MPFC}_{\text{real}}^{\text{SNOPT}}$	2.9950×10^6	0.00%	–	118.61	–	29.42	–
$\text{MPFC}_{\text{real}}^{\text{ILP}}$	3.0023×10^6	0.24%	–	0.70	–	0.49	–
$\text{MPFC}_{2\%}^{\text{SNOPT}}$	3.0090×10^6	0.47%	8.1001×10^4	256.59	117.46	44.76	9.30
$\text{MPFC}_{2\%}^{\text{ILP}}$	3.0302×10^6	1.18%	3.4766×10^4	1.04	0.11	0.50	0.03
$\text{MPFC}_{5\%}^{\text{SNOPT}}$	3.0178×10^6	0.76%	4.4624×10^4	215.92	102.72	42.80	13.91
$\text{MPFC}_{5\%}^{\text{ILP}}$	3.0247×10^6	0.99%	3.1480×10^4	0.99	0.16	0.50	0.20
$\text{MPFC}_{10\%}^{\text{SNOPT}}$	3.0803×10^6	2.85%	6.6612×10^4	87.67	45.09	35.27	8.13
$\text{MPFC}_{10\%}^{\text{ILP}}$	3.0407×10^6	1.53%	4.0230×10^4	0.94	0.14	0.51	0.04

Prediction error analysis

This section investigates the effect of prediction errors and assumes that at time kT_s, accurate predictions of system disturbances for time step k are available while the predictions for the remaining perdiction period $\left[(k+1)T_\text{s}, \left(k+N_\text{p}\right)T_\text{s}\right)$ (h) may involve errors. The reference scenario considers the transport demand information and the densities of other traffic on the freeway links given in Table 4.2 as the nominal values. The three prediction error levels are defined as 2%, 5%, and 10%. The prediction errors in the transport demand and densities of other traffic on the freeway links are then assumed as normally distributed random variables with zero mean and a standard deviation equal to respectively 2%, 5%, and 10% times the nominal value.

For each prediction error level, we run the closed-loop simulation 10 times and report the mean value, the standard deviation of the total delivery cost, $J_{\text{mean}}(\cdot)$, and $J_{\text{std}}(\cdot)$ for an entire planning period, and that of the maximum and mean cpu times for a single time step, $t_{\text{cpu,mean}}^{\text{max}}$, $t_{\text{cpu,std}}^{\text{max}}$, $t_{\text{cpu,mean}}^{\text{mean}}$, and $t_{\text{cpu,std}}^{\text{mean}}$, respectively. The element P_{change} corresponds to the percentage change of the mean value of the total delivery cost with respect to that of the reference scenario using the SQP method, i.e., 2.9950×10^6.

The transport planning performance under the four prediction error levels is presented in Table 4.8. The elements "$\text{MPFC}_{\text{i}}^{\text{SNOPT}}$" and "$\text{MPFC}_{\text{i}}^{\text{ILP}}$" correspond to the MPFC approach using either the multi-start SQP method or the multi-start ILP method for a different prediction error level $i \in \{2\%, 5\%, 10\%\}$. As given in Table 4.8, in the presence of prediction errors the proposed approach will typically lead to reduced transport planning performance. In particular, for the case of a 10% prediction error level the total delivery cost obtained using the multi-start SQP method increases with 2.85% compared to the reference scenario. Moreover, the existence of prediction errors influences the maximum and mean cpu times required by the two optimization methods. It is expected that prediction errors could change the activation of the constraints in the optimization problem (4.15)–(4.20), and thus influence the computation time. Generally speaking, the presence of prediction errors has a larger influence on the computation time of the multi-start SQP method than that of the multi-start ILP method.

4.6 Conclusion

This chapter has investigated the synchromodal freight transport planning problem among deep-sea terminals and inland terminals in hinterland haulage for a single intermodal freight transport operator. We have proposed a Model Predictive container Flow Control (MPFC) approach to address the dynamic transport demand and traffic conditions in the network. For the linear IFTN model, the MPFC approach leads to a linear programming problem. For the load-dependent IFTN model, the implementation of the MPFC approach requires solving multiple nonlinear and non-convex optimization problems. We have proposed a multi-start Iterative Linear Programming (ILP) method to efficiently solve these nonlinear and non-convex optimization problems.

In the simulation experiment for the planning problem with the linear IFTN model in the single-region IFTN benchmark system, the proposed MPFC approach with an proper choice of the prediction horizon outperforms a greedy all-or-nothing approach in terms of the total delivery cost. For the planning problem with the load-dependent IFTN model in the single-region IFTN benchmark system, simulation experiments show that the proposed MPFC approach outperforms a greedy all-or-nothing approach, but requires a larger computation time when the multi-start Sequential Quadratic Programming (SQP) method is used. The multi-start ILP method results in a performance that is comparable to that of the multi-start SQP method, but takes much more less computation time. In simulation experiments the proposed MPFC approach with the multi-start ILP method achieves a good planning performance in a consistent manner under different demand scenarios.

Directions for future research are presented as follows. The complexity of synchromodal freight transport planning problems depends on a number of factors, such as the network size, demand scenarios, traffic conditions in the network, timetables for trains and barges. This chapter has already examined the effect of different demand scenarios and different prediction error levels on the planning performance of the MPFC approach. The investigation of the effect of other factors, e.g., non-periodical schedules for trains and barges and more complex transport network scenarios, is an important direction for future work. With respect to the implementation of the proposed MPFC approach with the load-dependent IFTN model, a centralized approach has been adopted for the single-region IFTN benchmark system in this chapter. To reduce the required computation time for more complex planning problems, other nonlinear and non-convex optimization methods (e.g., pattern search), and other computation or optimization schemes (e.g., parallel computation, distributed optimization) can be applied. In addition, multiple intermodal freight transport operators might be involved in the freight delivery process due to either organizational or commercial reasons. Therefore, in Chapter 5 we will investigate a distributed MPFC approach for cooperative planning among multiple operators such that the overall delivery cost is minimized while considering the interests of each individual operator.

Chapter 5

DMPC for Coordinated Synchromodal Freight Transport Planning

Chapter 4 has discussed the synchromodal freight transport planning problem for a single intermodal freight transport operator. In this chapter, we investigate coordinated synchromodal freight transport planning among multiple transport operators in different but interconnected service areas. The coordination goal is hereby to minimize the total delivery cost for serving the given transport demand. Each operator has independent planning authority in its own service network and participates in the coordinated planning by negotiating with other operators about transport plans (i.e., route choices and container flow assignments). We first formulate coordinated synchromodal freight transport planning as a Coordinated Model Predictive container Flow Control (CMPFC) problem, and then propose three Distributed Model Predictive container Flow Control (DMPFC) approaches to solve this problem. These DMPFC approaches are evaluated through simulation experiments using the multiple-region IFTN benchmark system presented in Section 3.4.2.

The research presented in this chapter is based on [96, 99].

5.1 Introduction

This chapter investigates coordinated planning among multiple intermodal freight transport operators that provide synchromodal container transport services among deep-sea terminals and inland terminals in hinterland haulage in different but interconnected service areas. These operators are either the customers or the service providers of other stakeholders (e.g., shippers, terminal operators) in the transport process. Each operator has its own service network, and coordinates with the other operators in accommodating the given transport demand. The coordinated planning is done at the tactical flow level by all operators. The coordination goal is to serve the transport demand at the lowest overall freight delivery cost. Each operator hereby aims to minimize its own container delivery cost while being willing to consider the interests of other operators in its planning process, although each operator still holds independent planning authority in its own service network. The trade-off between the coordination goal of all operators and the goal of each individual operator is obtained by negotiating with other operators about transport plans. For an operator, the transport plan consists of its route choices and flow assignments in the container delivery process. Operators coordinate to reach an agreement on the volumes of container flows that each operator will hand over to other operators in each planning time interval. This chapter considers that each operator adopts a Model Predictive Control (MPC) strategy for the flow planning problem within the overall multi-level freight transport planning framework presented in Section 1.2. Therefore, the resulting coordinated planning problem can be abstracted as a Distributed Model Predictive container Flow Control (DMPFC) problem over a set of interconnected service networks.

Distributed Model Predictive Control (DMPC) is a general control methodology that can cope with control problems arising in large-scale systems due to organizational couplings among different parties involved in a common task, limited measurement ability and control access of different parties, and different, possibly conflicting, objectives of different parties, etc. The papers and books [23, 32, 107, 142] review the basic concepts of, the research results in, and future research directions on DMPC. DMPC approaches have been investigated in various controlled systems and applications [45, 46, 48, 61, 67, 91, 102, 108, 113, 122, 123, 134, 135, 165, 179]. The Augmented Lagrangian Relaxation based Distributed Model Predictive Control (ALR-based DMPC) approaches [122] and the Alternating Direction Method of Multipliers based Distributed Model Predictive Control (ADMM-based DMPC) approaches have been successively developed based on the method of multipliers and the Alternating Direction Method of Multipliers (ADMM) algorithm [11, 19, 20]. The ALR-based DMPC approaches have been used to successfully solve distributed control problems in various applications [2, 48, 91, 113, 122, 123, 179]. The ADMM-based DMPC approach is a counterpart of the ALR-based DMPC approaches and has effectively been used to determine coordinated control actions for multiple MPC controllers in many applications [34, 35, 56, 56, 87, 116, 146, 148]. To the best knowledge of the author, no work has been done in the literature on applying ALR-based DMPC approaches or ADMM-based DMPC approaches for coordinated synchromodal freight transport planning. In this chapter, we propose to use these two classes of DMPC approaches for coordinated synchromodal freight transport planning.

The contributions of this chapter are as follows: 1) coordinated synchromodal freight transport planning problem is formulated as a Coordinated Model Predictive container Flow Control (CMPFC) problem among multiple operators; 2) three DMPFC approaches (i.e., the *parallel* ALR-based DMPFC approach, the *serial* ALR-based DMPFC approach, and also the ADMM-based DMPFC approach) are proposed to solve the CMPFC problem in a distributed way. In addition, we analyze the properties of these three DMPFC approaches and evaluate their performance by conducting numerical simulations with a linear discrete-time Intermodal Freight Transport Network (IFTN) model in the multiple-region IFTN benchmark system presented in Chapter 3.4.2.

The remainder of this chapter is organized as follows. Section 5.2 contains a detailed explanation of the considered coordinated synchromodal freight transport planning problem and gives the CMPFC formulation. Section 5.3 proposes three DMPFC approaches, presents three performance indicators of DMPFC approaches, and discusses several implementation aspects. A comparison of the three proposed DMPFC approaches is done by numerical simulation experiments in Section 5.4. Section 5.5 concludes the chapter with concluding remarks and directions for future research.

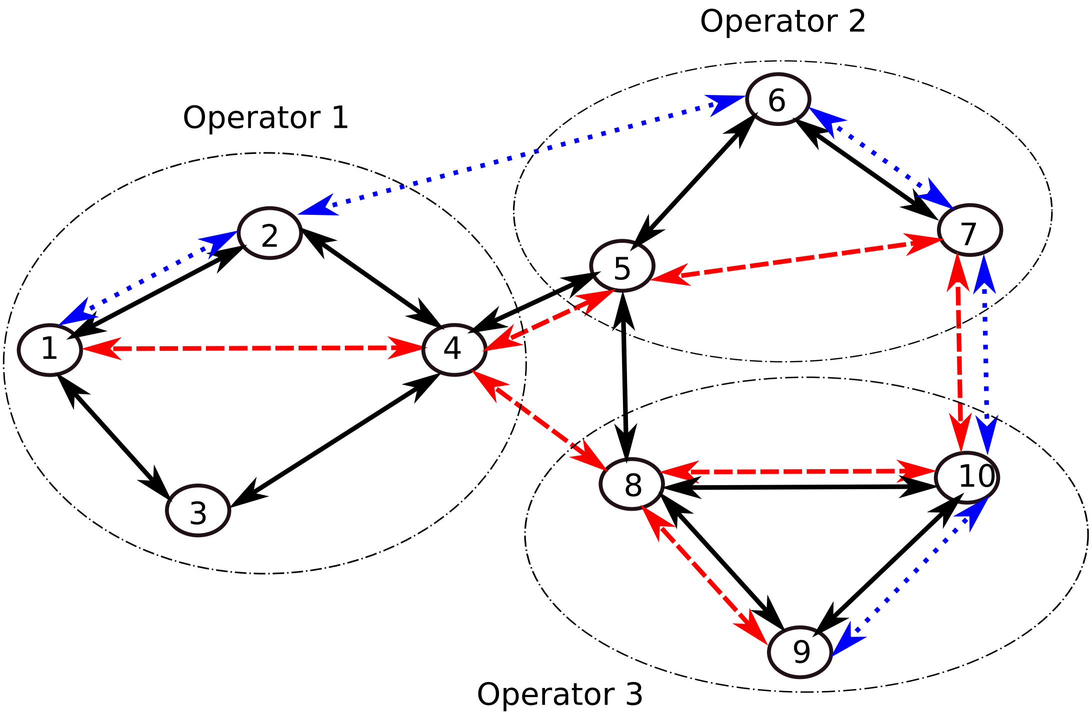

Figure 5.1: An example of a coordinated synchromodal freight transport planning architecture for three operators. The solid arcs, the dashed arcs, and the dotted arcs indicate freeway links, railway links, and inland waterway links in the network, respectively. For simplicity, the modality changes at intermodal terminals are not shown in this figure.

5.2 Coordinated synchromodal freight transport planning

We consider coordinated planning among a group of N_{sub} transport operators in an IFTN with dynamics as introduced in Section 3.2. Here, however, the network $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{M})$ is considered as the combination of a set of N_{sub} non-overlapping subnetworks $\mathcal{G}_n(\mathcal{V}_n,\mathcal{E}_n,\mathcal{M}_n)$, $n = 1,\ldots,N_{\text{sub}}$, i.e., $\mathcal{V} = \cup_{n=1}^{N_{\text{sub}}}\mathcal{V}_n$, $\mathcal{E} = \cup_{n=1}^{N_{\text{sub}}}\mathcal{E}_n$, $\mathcal{M} = \cup_{n=1}^{N_{\text{sub}}}\mathcal{M}_n$, $\mathcal{V}_n \cap \mathcal{V}_m = \varnothing$, $\mathcal{E}_n \cap \mathcal{E}_m = \varnothing$, $n \in \{1,\ldots,N_{\text{sub}}\}$, $m \in \{1,\ldots,N_{\text{sub}}\}$, $n \neq m$. Figure 5.1 presents an example of a coordinated synchromodal freight transport architecture among three operators. Each of these three operators controls the container flows in its subnetwork indicated by dash-dotted ellipses. A link connecting two subnetworks represents an interconnecting link, e.g., the railway link from node 4 to node 5 in Figure 5.1. Each interconnecting link between subnetworks is considered to always belong to the subnetwork from which it originates. An interconnecting link is called an incoming interconnecting link and an outgoing interconnecting link for the subnetwork it starts in and for the subnetwork it ends in, respectively. For example, the railway link from node 4 to node 5 has two functionalities: it is an incoming interconnecting link for subnetwork/operator 2, and an outgoing interconnecting link for subnetwork/operator 1. This railway link is assumed to belong to subnetwork 1, from which it starts. The set of incoming interconnecting links and the set of outgoing interconnecting links of a subnetwork n are denoted by $\mathcal{E}_n^{\text{in}}$ and $\mathcal{E}_n^{\text{out}}$. A subnetwork is considered as a neighboring subnetwork of another subnetwork if there is at least one interconnecting link from the former subnetwork to the latter subnetwork. The set of all neighboring subnetworks of subnetwork n is denoted by $\mathcal{N}_n^{\text{nei}}$.

Coordinated planning considers the transport demand with the origin and destination pairs and the volumes for time step k given as the set $\mathscr{O}_{\text{od}} \subseteq \mathscr{V} \times \mathscr{V}$ and $d_{o,d}(k), (o,d) \in \mathscr{O}_{\text{od}}$, respectively. In coordinated planning, operator n plans synchromodal freight transport in subnetwork n by solving a container flow control problem with the objective of minimizing its own total delivery cost,

$$\min_{\bar{\mathbf{x}}_n, \bar{\mathbf{u}}_n, \bar{\mathbf{y}}_n} J_n\big(\bar{\mathbf{x}}_n, \bar{\mathbf{u}}_n, \bar{\mathbf{y}}_n, \bar{\mathbf{v}}_n\big), \tag{5.1}$$

subject to the dynamics and planning constraints of subnetwork n:

$$\mathbf{x}_n(k+1) = \mathbf{f}_{\mathbf{1},n}\Big(\mathbf{x}_n(k), \mathbf{u}_n(k), \mathbf{d}_n(k), \mathbf{v}_n(k)\Big), \tag{5.2}$$

$$\mathbf{y}_n(k+1) = \mathbf{f}_{\mathbf{2},n}\Big(\mathbf{x}_n(k+1), \mathbf{u}_n(k), \mathbf{d}_n(k), \mathbf{v}_n(k)\Big), \tag{5.3}$$

$$\mathbf{g}_n\Big(\mathbf{x}_n(k+1), \mathbf{y}_n(k+1), \mathbf{u}_n(k), \mathbf{d}_n(k), \mathbf{v}_n(k)\Big) \leq \mathbf{0}, \tag{5.4}$$

where $\mathbf{x}_n(k)$, $\mathbf{y}_n(k)$, $\mathbf{d}_n(k)$, $\mathbf{v}_n(k)$, and $\mathbf{u}_n(k)$ are subnetwork states, subnetwork outputs, disturbances, and the remaining variables that influence the dynamics of subnetwork n and subsequently the container flow control actions of operator n for time step k, and $\bar{\mathbf{x}}_n$, $\bar{\mathbf{y}}_n$, $\bar{\mathbf{u}}_n$, $\bar{\mathbf{v}}_n$ include $\mathbf{x}_n(k)$, $\mathbf{y}_n(k)$, $\mathbf{u}_n(k)$, $\mathbf{v}_n(k)$ for the whole planning period, respectively. The disturbances include the volumes of container flows entering each node from the outside of the network and the traffic density on road links. Equations (5.2)–(5.3) and constraints (5.4) are derived from the linear discrete-time IFTN model proposed in Section 3.2.

Before presenting the CMPFC formulation, some important assumptions made in this chapter are listed as follows:

- The topology and properties of subnetwork n, as well as its transport capacities and traffic conditions, can only be measured/estimated/obtained by operator n.

- The typical transport time and the typical transport cost between two nodes or one node and one link in the whole network are obtained from historical data, assumed to be available for all operators.

- Transport demand information (e.g., the volume of the transport demand) can be estimated with a high accuracy and is shared by all operators.

- Operator n only coordinates with its neighboring operators $m \in \mathscr{N}_n^{\text{nei}}$. Operator n implements coordinated planning by sharing its container flow information for a given number of coming planning intervals with its neighboring operators and by taking into account the information shared by its neighboring operators. For operator n, the container flow information typically consists of two parts: the volumes of container flows leaving subnetwork n through all outgoing interconnecting links of subnetwork n, and the expected volumes of container flows entering subnetwork n through all incoming interconnecting links of subnetwork n. For clarification, operator n could optimize the volumes of the container flows entering subnetwork n according to its own planning objective, and share the optimized volumes to its neighboring operators in the coordinated planning. The optimized volumes, however, are the preferred volumes from the perspective of operator n, and are actually determined by the neighboring operators of operator n. We use the word

"expected" to emphasize this.
Depending on a particular coordinated planning approach, the information that is provided by so-called Lagrange multipliers represents the preferences of operators on whether to enlarge or reduce the volumes of container flows exchanged among them, and this information also needs to be shared among neighboring operators. The Lagrange multipliers used by the proposed DMPFC approaches will be explained in detail in Section 5.3.

- The coordination goal of all operators is to minimize the total delivery cost of serving the given transport demand, even if their individual objectives might be conflicting. This total delivery cost is the summation of the delivery costs of all operators. The objective of each operator is to minimize the delivery cost in its subnetwork.

- Synchromodal freight transport plans in subnetwork n are determined through a negotiation process among operator n and its neighboring operators by considering this operator's objective and the coordination goal. The final transport plans in subnetwork n will be determined only by operator n.

5.2.1 Interconnecting variables and interconnecting constraints

Incoming and outgoing container flows on interconnecting links create interactions with the states of neighboring subnetworks and further with the corresponding flow control decisions made by the operators. These interactions are captured by including input and output interconnecting variables and interconnecting constraints in the container flow control problem of each operator. For all incoming interconnecting links of subnetwork n, the input interconnecting variables $\mathbf{w}_{\mathrm{in},n}(k)$ represent the volumes of container flows that enter subnetwork n from its neighboring subnetworks for time step k. The output interconnecting variables $\mathbf{w}_{\mathrm{out},n}(k)$ are introduced in the same way. Specific to the container flow control problem of operator n, $\mathbf{w}_{\mathrm{in},n}(k)$ and $\mathbf{w}_{\mathrm{out},n}(k)$ are expressed as:

$$\mathbf{w}_{\mathrm{in},n}(k) = \mathbf{v}_n(k), \tag{5.5}$$

$$\mathbf{w}_{\mathrm{out},n}(k) = \mathbf{K}_n \mathbf{y}_n(k), \tag{5.6}$$

where the interconnecting output selection matrix $\mathbf{K}_n$ is constructed to select the output container flow variables on the outgoing interconnecting links of subnetwork n. Interconnecting links between subnetwork n and subnetwork m, with $m \in \mathcal{N}_n^{\mathrm{nei}}$ function both as outgoing interconnecting links of subnetwork n, and as incoming interconnecting links of subnetwork m simultaneously. Therefore, the following interconnecting constraints should be met:

$$\mathbf{w}_{\mathrm{in},m,n}(k) = \mathbf{w}_{\mathrm{out},n,m}(k), \quad m \in \mathcal{N}_n^{\mathrm{nei}}, \tag{5.7}$$

$$\mathbf{w}_{\mathrm{out},m,n}(k) = \mathbf{w}_{\mathrm{in},n,m}(k), \quad m \in \mathcal{N}_n^{\mathrm{nei}}, \tag{5.8}$$

where $\mathbf{w}_{\mathrm{in},m,n}(k)$ and $\mathbf{w}_{\mathrm{out},m,n}(k)$ represent the volumes of container flows that respectively enter or leave subnetwork n from or to its neighboring subnetwork m. The interconnecting variables $\mathbf{w}_{\mathrm{in},n}(k)$ and $\mathbf{w}_{\mathrm{out},n}(k)$ contain all $\mathbf{w}_{\mathrm{in},m,n}(k)$, $m \in \mathcal{N}_n^{\mathrm{nei}}$ and all $\mathbf{w}_{\mathrm{out},m,n}(k)$, $m \in \mathcal{N}_n^{\mathrm{nei}}$, respectively.

5.2.2 Coordinated model predictive container flow control

In coordinated planning, each operator adopts an MPC strategy for controlling container flows in its subnetwork. Therefore, coordinated synchromodal freight transport planning can be formulated as a CMPFC problem and solved with different DMPC approaches. The CMPFC problem for N_{sub} operators for time step k is formulated as follows:

$$\min_{\substack{\tilde{\mathbf{x}}_1(k+1),\tilde{\mathbf{u}}_1(k),\tilde{\mathbf{y}}_1(k+1)\\ \vdots \\ \tilde{\mathbf{x}}_{N_{\text{sub}}}(k+1),\tilde{\mathbf{u}}_{N_{\text{sub}}}(k),\tilde{\mathbf{y}}_{N_{\text{sub}}}(k+1)}} \sum_{n=1}^{N_{\text{sub}}} J_n\big(\tilde{\mathbf{x}}_n(k+1),\tilde{\mathbf{y}}_n(k+1),\tilde{\mathbf{u}}_n(k),\tilde{\mathbf{v}}_n(k)\big), \tag{5.9}$$

subject to,

$$\mathbf{x}_n(k+1+l) = \mathbf{f}_{\mathbf{1},n}\Big(\mathbf{x}_n(k+l),\mathbf{u}_n(k+l),\mathbf{d}_n(k+l),\mathbf{v}_n(k+l)\Big), \tag{5.10}$$

$$\mathbf{y}_n(k+1+l) = \mathbf{f}_{\mathbf{2},n}\Big(\mathbf{x}_n(k+1+l),\mathbf{u}_n(k+l),\mathbf{d}_n(k+l),\mathbf{v}_n(k+l)\Big), \tag{5.11}$$

$$\mathbf{g}_n\Big(\tilde{\mathbf{x}}_n(k+1),\tilde{\mathbf{y}}_n(k+1),\tilde{\mathbf{u}}_n(k),\tilde{\mathbf{d}}_n(k),\tilde{\mathbf{v}}_n(k)\Big) \leq \mathbf{0}, \tag{5.12}$$

$$\tilde{\mathbf{w}}_{\text{in},n}(k) = \tilde{\mathbf{v}}_n(k), \tag{5.13}$$

$$\tilde{\mathbf{w}}_{\text{out},n}(k) = \tilde{\mathbf{K}}_n\tilde{\mathbf{y}}_n(k), \tag{5.14}$$

$$\tilde{\mathbf{w}}_{\text{in},m,n}(k) = \tilde{\mathbf{w}}_{\text{out},n,m}(k), \quad \forall m \in \mathcal{N}_n^{\text{nei}} \tag{5.15}$$

$$\mathbf{x}_n(k) = \mathbf{x}_{n,k}, \tag{5.16}$$

$$\tilde{\mathbf{d}}_n(k) = \tilde{\mathbf{d}}_{n,k}, \tag{5.17}$$

$$\text{for } n = 1,\ldots,N_{\text{sub}}, \text{ for } l = 0,\ldots,N_{\text{p}}-1,$$

where

- The network states, the network outputs, the disturbances of subnetwork n, and the flow control actions of operator n in the finite prediction period $\big[kT_{\text{s}},(k+N_{\text{p}})T_{\text{s}}\big)$ are denoted by $\tilde{\mathbf{x}}_n(k+1) = \big[\mathbf{x}_n^{\text{T}}(k+1),\cdots,\mathbf{x}_n^{\text{T}}(k+N_{\text{p}})\big]^{\text{T}}$, $\tilde{\mathbf{y}}_n(k+1) = \big[\mathbf{y}_n^{\text{T}}(k+1),\cdots,\mathbf{y}_n^{\text{T}}(k+N_{\text{p}})\big]^{\text{T}}$, $\tilde{\mathbf{d}}_n(k) = \big[\mathbf{d}_n^{\text{T}}(k),\cdots,\mathbf{d}_n^{\text{T}}(k+N_{\text{p}}-1)\big]^{\text{T}}$, and $\tilde{\mathbf{u}}_n(k) = \big[\mathbf{u}_n^{\text{T}}(k),\cdots,\mathbf{u}_n^{\text{T}}(k+N_{\text{p}}-1)\big]^{\text{T}}$, respectively. The remaining variables that influence the dynamics of subnetwork n in the prediction period are included in $\tilde{\mathbf{v}}_n(k) = \big[\mathbf{v}_n^{\text{T}}(k),\cdots,\mathbf{v}_n^{\text{T}}(k+N_{\text{p}}-1)\big]^{\text{T}}$. The initial states of subnetwork n at time kT_{s} are given by $\mathbf{x}_{n,k}$ in (5.16). The disturbance information of subnetwork n in the prediction period at time time kT_{s} is given by $\tilde{\mathbf{d}}_{n,k}$ in (5.17).

- The input and output interconnecting variables of the MPFC problem of operator n with respect to that of operator $m \in \mathcal{N}_n^{\text{nei}}$ in the prediction period $\big[kT_{\text{s}},(k+N_{\text{p}})T_{\text{s}}\big)$ are expressed as

$$\tilde{\mathbf{w}}_{\text{in},n}(k) = \big[\mathbf{w}_{\text{in},n}^{\text{T}}(k),\cdots,\mathbf{w}_{\text{in},n}^{\text{T}}(k+N_{\text{p}}-1)\big]^{\text{T}},$$

$$\tilde{\mathbf{w}}_{\text{out},n}(k) = \big[\mathbf{w}_{\text{out},n}^{\text{T}}(k),\cdots,\mathbf{w}_{\text{out},n}^{\text{T}}(k+N_{\text{p}}-1)\big]^{\text{T}}.$$

The interconnecting output selection matrix $\tilde{\mathbf{K}}_n$ is constructed to select the output container flow variables on the interconnecting outgoing links from subnetwork n to all its neighboring subnetworks in the prediction period.

Equations (5.10)–(5.11) represent the dynamics of subnetwork n. All the planning constraints in the planning problem of operator n are included in inequalities (5.12). The equalities (5.13)–(5.14) corresponds to the definition of input and output interconnecting variables in the MPFC problem of operator n. The interconnecting constraints between the planning problem of operator n and that of subnetwork $m \in \mathcal{N}_n^{\text{nei}}$ are included in the equalities (5.15). In the coordinated planning setting considered in this chapter, the incoming container flow information of subnetwork n from neighboring subnetwork $m \in \mathcal{N}_n^{\text{nei}}$, $\tilde{\mathbf{w}}_{\text{in},m,n}(k)$, is not directly available for operator n and has to be exchanged with neighboring operators. The value of $\tilde{\mathbf{w}}_{\text{in},m,n}(k)$ can be negotiated by operator n with its neighboring operator m through an iterative process, but will finally be determined by operator m after the negotiation even in case no feasible agreements have been reached. This is because for concerns of information privacy and independent operations each operator persists to have the independent power in planning freight transport in its subnetwork when participating in the coordinated planning. Therefore, the CMPFC problem (5.9)-(5.17) has to be solved in a distributed way.

5.3 Distributed model predictive container flow control

In the CMPFC problem (5.9)–(5.17), the interconnecting variables from different MPFC problems appear in the interconnecting constraints (5.15). Therefore, problem (5.9)–(5.17) cannot be directly distributed as a group of MPFC problems, each of which can be solved by an operator independently. Three algorithms are first presented in this chapter to address the issue of handling interconnecting constraints, correspondingly resulting in three DMPFC approaches for solving the problem (5.9)–(5.17). These three algorithms are the *parallel* ALR algorithm, the *serial* ALR algorithm, and the ADMM algorithm. Moreover, this section presents performance indicators for these three DMPFC approaches, and discusses a number of implementation aspects.

5.3.1 ALR-based DMPFC approaches

The ALR-based DMPC approaches have been introduced in [11, 122, 138]. In this section the ALR-based DMPFC approaches cope with interconnecting constraints (5.15) by constructing an augmented Lagrangian formulation of the problem (5.9)–(5.17) that captures the interconnecting constraints (5.15) in the control objective function as a combination of linear and quadratic terms:

$$\sum_{n=1}^{N_{\text{sub}}} \Big[J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{y}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{v}}_n(k)\big) + \sum_{m\in\mathcal{N}_n^{\text{nei}}} \Big[\boldsymbol{\lambda}_{\text{in},m,n}^T(k) \big(\tilde{\mathbf{w}}_{\text{in},m,n}(k) - \tilde{\mathbf{w}}_{\text{out},n,m}(k)\big) + \frac{\rho}{2} \|\tilde{\mathbf{w}}_{\text{in},m,n}(k) - \tilde{\mathbf{w}}_{\text{out},n,m}(k)\|_2^2 \Big] \Big], \quad (5.18)$$

where $\boldsymbol{\lambda}_{\text{in},m,n}(k)$ and $\rho > 0$ are the Lagrangian multipliers associated with interconnecting constraints (5.15) and a penalty parameter. Due to the appearance of the non-separable quadratic terms, the control objective function (5.18) cannot be distributed over the operators. In order to solve the augmented Lagrangian formulation of the problem (5.9)–(5.13) in a distributed way, the non-separable quadratic terms have to be decoupled such that the control objective function (5.18) can be distributed across operators for a distributed implementation.

The *parallel* ALR-based DMPFC approach is obtained by using an ALR-based DMPC approach, which applies the auxiliary problem principle to decouple the quadratic terms in (5.18). Adopting the basic framework of the ALR-based DMPC approach, the *serial* ALR-based DMPFC approach uses block coordinate descent to decouple the quadratic terms in (5.18). **Algorithm 5.1** presents the implementation of the *parallel* ALR-based DMPFC approach for time step k. In **Algorithm 5.1** operators are ordered according to a predetermined coordination and communication protocol, i.e., operator 1, ..., operator N_{sub}. The distinction between the *serial* ALR-based DMPFC approach and the *parallel* ALR-based DMPFC approach mainly lies on the **Iteration process** for performing coordination among operators. Therefore, **Algorithm 5.2** only gives the **Iteration process** part of the implementation of the *serial* ALR-based DMPFC approach.

5.3.2 ADMM-based DMPFC approach

The ADMM-based DMPC approach has been introduced in [20, 34, 56, 62, 68, 87, 116, 148]. In this section, the ADMM-based DMPC approach uses a set of global optimization variables to deal with the interconnecting constraints (5.15). The global optimization variables contain the outgoing container flow volumes on all interconnecting links among all subnetworks over the prediction period, denoted by $\tilde{\mathbf{z}}(k) = \left[\tilde{\mathbf{z}}_1^{\mathrm{T}}(k), \ldots, \tilde{\mathbf{z}}_{N_{\mathrm{sub}}}^{\mathrm{T}}(k)\right]^{\mathrm{T}}$.

The CMPFC problem (5.9)–(5.17) can then be reformulated as an extended version of the general form consensus optimization problem [12] by replacing interconnecting constraints (5.15) with

$$\tilde{\mathbf{w}}_{\mathrm{in},m,n}(k) = \mathbf{E}_{m,n}\tilde{\mathbf{z}}(k), \quad \forall m \in \mathcal{N}_n^{\mathrm{nei}} \tag{5.21}$$

$$\tilde{\mathbf{w}}_{\mathrm{out},m,n}(k) = \mathbf{E}_{n,m}\tilde{\mathbf{z}}(k), \quad \forall m \in \mathcal{N}_n^{\mathrm{nei}}, \tag{5.22}$$

where $\mathbf{E}_{m,n}$ and $\mathbf{E}_{n,m}$ are constructed to select the outgoing container flow information on interconnecting outgoing links from subnetwork m to subnetwork n and that from subnetwork n to subnetwork m, i.e., $\tilde{\mathbf{z}}_{m,n}(k) = \mathbf{E}_{m,n}\tilde{\mathbf{z}}(k)$ and $\tilde{\mathbf{z}}_{n,m}(k) = \mathbf{E}_{n,m}\tilde{\mathbf{z}}(k)$, respectively. The variables $\tilde{\mathbf{z}}_n(k)$ include operator n's local copies of some components of the global optimization variable, i.e., $\tilde{\mathbf{z}}_n(k) = \left[\mathbf{E}_{m_1,n}, \cdots, \mathbf{E}_{m_{|\mathcal{N}_n^{\mathrm{nei}}|},n}\right]^T \tilde{\mathbf{z}}(k)$. Operator n updates and stores $\tilde{\mathbf{z}}_n(k)$ at each time step such that there is no need for a central coordinator in the implementation. The ADMM-based DMPFC approach applies the ADMM algorithm to solve the augmented Lagrangian formulation of the resulting extended version of the problem (5.9)–(5.17). The detailed implementation of the ADMM-based DMPFC approach is presented in **Algorithm 5.3**.

Algorithm 5.1 The *parallel* ALR-based DMPFC approach using the auxiliary problem principle for time step k

Input : $\mathbf{x}_{n,k}$, $\tilde{\mathbf{d}}_n(k)$, T_{allowed} (h), iteration stopping threshold ε, positive parameters ρ and b, $b \geq 2\rho$

Initialization : iteration count $s \leftarrow 1$, $\varepsilon^s \leftarrow \infty$, current computation time $t_n(k) \leftarrow 0$ (h) spent by operators $n = 1, \cdots, N_{\text{sub}}$ for time step k,
$\tilde{\mathbf{u}}_n^s(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^s(k)$, $\tilde{\mathbf{w}}_{\text{out},m,n}^s(k)$, and Lagrangian multipliers $\boldsymbol{\lambda}_{\text{in},m,n}^s$, $n = 1, \ldots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$ in the prediction period $\left[kT_{\text{s}}, (k+N_{\text{p}})T_{\text{s}}\right)$ are initialized as zeros when $k = 1$, and are initialized by using a *warm start* strategy with their values computed during time step $k-1$ when $k > 1$.

Iteration process :

while $\varepsilon^s \geq \varepsilon$ and $\max_{n=1,\cdots,N_{\text{sub}}} t_n(k) \leq T_{\text{allowed}}$ **do**

for operators $n = 1, \ldots, N_{\text{sub}}$, in a parallel fashion **do**

Compute $\tilde{\mathbf{u}}_n^{s+1}(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ for a local MPFC problem (5.19) subject to subnetwork dynamics (5.10)–(5.17) as follows:

$$
\begin{aligned}
\min_{\substack{\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1) \\ \tilde{\mathbf{w}}_{\text{in},n}(k), \tilde{\mathbf{w}}_{\text{out},n}(k)}} \quad & J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{y}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{v}}_n(k)\big) + \\
\sum_{m \in \mathcal{N}_n^{\text{nei}}} \Bigg[& \begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m,n}^s \\ -\boldsymbol{\lambda}_{\text{in},n,m}^s \end{bmatrix}^T \begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}(k) \end{bmatrix} + \frac{\rho}{2} \left\| \begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},n,m}^s(k) - \tilde{\mathbf{w}}_{\text{out},m,n}(k) \\ \tilde{\mathbf{w}}_{\text{out},n,m}^s(k) - \tilde{\mathbf{w}}_{\text{in},m,n}(k) \end{bmatrix} \right\|_2^2 + \\
& \frac{b-\rho}{2} \left\| \begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}(k) - \tilde{\mathbf{w}}_{\text{in},m,n}^s(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}(k) - \tilde{\mathbf{w}}_{\text{out},m,n}^s(k) \end{bmatrix} \right\|_2^2 \Bigg]
\end{aligned}
\tag{5.19}
$$

end for

Send $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ to the neighboring operators $m \in \mathcal{N}_n^{\text{nei}}$ and receive $\tilde{\mathbf{w}}_{\text{in},n,m}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k)$ from the neighboring operators correspondingly

Update $\boldsymbol{\lambda}_{\text{in},m,n}^{s+1} \leftarrow \boldsymbol{\lambda}_{\text{in},m,n}^s + \rho\left(\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k) - \tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k)\right)$, $n = 1, \cdots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$

Send $\boldsymbol{\lambda}_{\text{in},m,n}^{s+1}$ to the neighboring operators $m \in \mathcal{N}_n^{\text{nei}}$ and in parallel receive $\boldsymbol{\lambda}_{\text{in},n,m}^{s+1}$ from the neighboring operators

Compute $\varepsilon^{s+1} \leftarrow \left\| \begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m_1,1}^{s+1} - \boldsymbol{\lambda}_{\text{in},m_1,1}^s \\ \vdots \\ \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_1^{\text{nei}}|},1}^{s+1} - \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_1^{\text{nei}}|},1}^s \\ \boldsymbol{\lambda}_{\text{in},m_1,2}^{s+1} - \boldsymbol{\lambda}_{\text{in},m_1,2}^s \\ \vdots \\ \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_{N_{\text{sub}}}^{\text{nei}}|},N_{\text{sub}}}^{s+1} - \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_{N_{\text{sub}}}^{\text{nei}}|},N_{\text{sub}}}^s \end{bmatrix} \right\|_\infty$

$s \leftarrow s+1$

end while

Output : $\tilde{\mathbf{u}}_n^s(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^s(k)$, $\tilde{\mathbf{w}}_{\text{out},m,n}^s(k)$, and $\boldsymbol{\lambda}_{\text{in},m,n}^s$, $n = 1, \cdots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$.

Algorithm 5.2 The **Iteration process** part of a *serial* ALR-based DMPFC approach using block coordinate descent for time step k

while $\varepsilon^s \geq \varepsilon$ and $\sum_{n=1}^{N_{\text{sub}}} t_n(k) \leq T_{\text{allowed}}$ **do**

for operators $n = 1, \ldots, N_{\text{sub}}$, in a serial fashion **do**

Compute $\tilde{\mathbf{u}}_n^{s+1}(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$, and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ for a local MPFC problem (5.20) subject to subnetwork dynamics (5.10)–(5.17) as follows:

$$\begin{aligned}\min_{\substack{\tilde{\mathbf{x}}_n(k+1),\tilde{\mathbf{u}}_n(k),\tilde{\mathbf{y}}_n(k+1)\\ \tilde{\mathbf{w}}_{\text{in},n}(k),\tilde{\mathbf{w}}_{\text{out},n}(k)}} \quad & J_n\big(\tilde{\mathbf{x}}_n(k+1),\tilde{\mathbf{y}}_n(k+1),\tilde{\mathbf{u}}_n(k),\tilde{\mathbf{v}}_n(k)\big)+\\ & \sum_{m\in\mathcal{N}_n^{\text{nei}},m<n}\left[\begin{bmatrix}\boldsymbol{\lambda}_{\text{in},m,n}^s\\ -\boldsymbol{\lambda}_{\text{in},n,m}^s\end{bmatrix}^T\begin{bmatrix}\tilde{\mathbf{w}}_{\text{in},m,n}(k)\\ \tilde{\mathbf{w}}_{\text{out},m,n}(k)\end{bmatrix}+\frac{\rho}{2}\left\|\begin{bmatrix}\tilde{\mathbf{w}}_{\text{in},n,m}^{s+1}(k)-\tilde{\mathbf{w}}_{\text{out},m,n}(k)\\ \tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k)-\tilde{\mathbf{w}}_{\text{in},m,n}(k)\end{bmatrix}\right\|_2^2\right]+\\ & \sum_{m\in\mathcal{N}_n^{\text{nei}},m>n}\left[\begin{bmatrix}\boldsymbol{\lambda}_{\text{in},m,n}^s\\ -\boldsymbol{\lambda}_{\text{in},n,m}^s\end{bmatrix}^T\begin{bmatrix}\tilde{\mathbf{w}}_{\text{in},m,n}(k)\\ \tilde{\mathbf{w}}_{\text{out},m,n}(k)\end{bmatrix}+\frac{\rho}{2}\left\|\begin{bmatrix}\tilde{\mathbf{w}}_{\text{in},n,m}^{s}(k)-\tilde{\mathbf{w}}_{\text{out},m,n}(k)\\ \tilde{\mathbf{w}}_{\text{out},n,m}^{s}(k)-\tilde{\mathbf{w}}_{\text{in},m,n}(k)\end{bmatrix}\right\|_2^2\right]\end{aligned} \tag{5.20}$$

Send $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ to the neighboring operators $m \in \mathcal{N}_n^{\text{nei}}$

end for

Update $\boldsymbol{\lambda}_{\text{in},m,n}^{s+1} \leftarrow \boldsymbol{\lambda}_{\text{in},m,n}^{s} + \rho\left(\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k) - \tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k)\right)$, $n = 1, \cdots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$

Send $\boldsymbol{\lambda}_{\text{in},m,n}^{s+1}$ to neighboring operators $m \in \mathcal{N}_n^{\text{nei}}$ and in parallel receive $\boldsymbol{\lambda}_{\text{in},n,m}^{s+1}$ from the neighboring operators

Compute $\varepsilon^{s+1} \leftarrow \left\|\begin{bmatrix}\boldsymbol{\lambda}_{\text{in},m_1,1}^{s+1}-\boldsymbol{\lambda}_{\text{in},m_1,1}^{s}\\ \vdots\\ \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_1^{\text{nei}}|},1}^{s+1}-\boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_1^{\text{nei}}|},1}^{s}\\ \boldsymbol{\lambda}_{\text{in},m_1,2}^{s+1}-\boldsymbol{\lambda}_{\text{in},m_1,2}^{s}\\ \vdots\\ \boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_{N_{\text{sub}}}^{\text{nei}}|},N_{\text{sub}}}^{s+1}-\boldsymbol{\lambda}_{\text{in},m_{|\mathcal{N}_{N_{\text{sub}}}^{\text{nei}}|},N_{\text{sub}}}^{s}\end{bmatrix}\right\|_\infty$

$s \leftarrow s+1$

end while

Algorithm 5.3 The ADMM-based DMPFC approach for time step k

Input : $\tilde{\mathbf{x}}_{n,k}$, $\tilde{\mathbf{d}}_n(k)$, T_{allowed} (h), iteration stopping threshold ε, positive parameters ρ

Initialization : iteration count $s \leftarrow 1$, $\varepsilon^s \leftarrow \infty$, current computation time $t_n(k) = 0$ (h) spent by operators $n = 1, \cdots, N_{\text{sub}}$ for time step k,

$\tilde{\mathbf{u}}_n^s(k)$, $\tilde{\mathbf{z}}_n^s(k)$, and Lagrangian multipliers $\boldsymbol{\lambda}_{\text{in},m,n}^s$, $\boldsymbol{\lambda}_{\text{out},m,n}^s$, $\boldsymbol{\lambda}_{\text{in},n,m}^s$, and $\boldsymbol{\lambda}_{\text{out},n,m}^s$ corresponding to constraints (5.21)–(5.22) for $n = 1, \ldots, N_{\text{sub}}$ in the prediction period $\left[kT_{\text{s}}, (k+N_{\text{p}})T_{\text{s}}\right)$ are initialized as zeros when $k = 1$, and are initialized by using a *warm start* strategy with their values computed during time step $k-1$ when $k > 1$.

Iteration process :

while $\varepsilon^s \geq \varepsilon$ and $\max_{n=1,\cdots,N_{\text{sub}}} t_n(k) \leq T_{\text{allowed}}$ **do**

for agents $i = 1, \ldots, N_{\text{sub}}$, in a parallel fashion **do**

Compute $\tilde{\mathbf{u}}_n^{s+1}(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$, and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ for a local MPFC problem (5.23) subject to subnetwork dynamics (5.10)–(5.14), (5.16)–(5.17), and (5.21)–(5.22) as follows:

$$\min_{\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)} \quad J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{y}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{v}}_n(k)\big) +$$
$$\sum_{m \in \mathcal{N}_n^{\text{nei}}} \left[\begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m,n}^s \\ \boldsymbol{\lambda}_{\text{out},m,n}^s \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}(k) - \tilde{\mathbf{z}}_{m,n}^s(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}(k) - \tilde{\mathbf{z}}_{n,m}^s(k) \end{bmatrix} + \frac{\rho}{2} \left\| \begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}(k) - \tilde{\mathbf{z}}_{m,n}^s(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}(k) - \tilde{\mathbf{z}}_{n,m}^s(k) \end{bmatrix} \right\|_2^2 \right] \tag{5.23}$$

Send $\tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k)$ to neighboring operator $m \in \mathcal{N}_n^{\text{nei}}$ and in parallel receive $\tilde{\mathbf{w}}_{\text{in},n,m}^{s+1}(k)$ and $\tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k)$ from the neighboring operators

Compute $\tilde{\mathbf{z}}_n^{s+1}(k)$ with the relation (5.24)

$$\tilde{\mathbf{z}}_{m,n}^{s+1}(k) \leftarrow \frac{1}{2} \left(\begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k) \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{w}}_{\text{out},n,m}^{s+1}(k) \\ \tilde{\mathbf{w}}_{\text{in},n,m}^{s+1}(k) \end{bmatrix} \right) \tag{5.24}$$

end for

Update $\begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m,n}^{s+1} \\ \boldsymbol{\lambda}_{\text{out},m,n}^{s+1} \end{bmatrix} \leftarrow \begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m,n}^{s} \\ \boldsymbol{\lambda}_{\text{out},m,n}^{s} \end{bmatrix} + \rho \left(\begin{bmatrix} \tilde{\mathbf{w}}_{\text{in},m,n}^{s+1}(k) \\ \tilde{\mathbf{w}}_{\text{out},m,n}^{s+1}(k) \end{bmatrix} - \tilde{\mathbf{z}}_{m,n}^{s+1}(k) \right)$, $n = 1, \cdots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$

Compute $\varepsilon^{s+1} \leftarrow \mathbf{max}_{n=1,\cdots,N_{\text{sub}}, m \in \mathcal{N}_n^{\text{nei}}} \left\| \begin{bmatrix} \boldsymbol{\lambda}_{\text{in},m,n}^{s+1} - \boldsymbol{\lambda}_{\text{in},m,n}^{s} \\ \boldsymbol{\lambda}_{\text{out},m,n}^{s+1} - \boldsymbol{\lambda}_{\text{out},m,n}^{s} \end{bmatrix} \right\|_\infty$

$s \leftarrow s+1$

end while

Output : $\tilde{\mathbf{u}}_n^s(k)$, $\tilde{\mathbf{w}}_{\text{in},m,n}^s(k)$, and $\tilde{\mathbf{w}}_{\text{out},m,n}^s(k)$, $n = 1, \cdots, N_{\text{sub}}$, $m \in \mathcal{N}_n^{\text{nei}}$.

5.3.3 Performance indicators and implementation aspects

To make a comparison of the performance of different DMPFC approaches, the following performance indicators are employed:

- The total delivery cost J_{total} (€) : the sum of the delivery costs incurred in the transport planning of all operators when the operators coordinate to complete the given transport demand, i.e.,

$$J_{\text{total}} = \sum_{k=1}^{N_{\text{planning}}} \sum_{n=1}^{N_{\text{sub}}} J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{y}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{v}}_n(k)\big). \tag{5.25}$$

  The whole planning period is $N_{\text{planning}}T_{\text{s}}$ (h), where T_{s} is the length of the planning time interval and also the control time step. This indicator corresponds to the coordinated planning goal of all N_{sub} operators.

- The communication cost J_{com} (float): the total number of floating-point numbers transmitted between operators during the whole coordinated planning process.

- The computation time T_{com} (h): the total amount of time taken by operators to perform coordinated planning in the whole planning period.

For practical implementation of the DMPFC approaches, coordinated planning decisions should be made during each time step even if agreement cannot be obtained by the operators. To achieve this, a fixed maximum computation time T_{allowed} is allowed for all operators to achieve agreement on the container flow control actions for each time step of the coordinated planning process. The maximum allowed computation time is typically set to be equal to or smaller than T_{s}. In the case that the operators cannot reach agreement within a period of length T_{allowed} during a particular time step, the coordinated planning will be done in a master-slave fashion by operators in a given pre-defined order based on the distances between the main seaport and different subnetworks, i.e., operators 1, 2, and 3 in a sequence.

The implementation of different DMPFC approaches in practice is influenced by different properties. Three main properties are:

- The coordination mechanism: Whether the mechanism operates in parallel or in a serial way.

- The degree of confidentiality of information exchange: We use the number of information types that are exchanged and the number of information exchanges among operators to indicate the degree of confidentiality.

- The way of information processing: How each type of information shared by one operator is used by its neighboring operators.

Table 5.1 gives a comparison of these main properties of the DMPFC approaches presented in Sections 5.3.1 and 5.3.2. First of all, the *serial* ALR-based DMPFC approach performs coordination in a serial way while the *parallel* ALR-based DMPFC approach and the ADMM-based DMPFC approach coordinate in a parallel fashion. In terms of the degree of confidentiality of information exchange, the ADMM-based DMPFC approach requires only

Table 5.1: A comparison of the main properties of the proposed DMPFC approaches. The lables 'sDMPFC', 'pDMPFC' and 'ADMM' in the 'DMPFC approaches' colum stands for the serial *ALR-based DMPFC approach, the* parallel *ALR-based DMPFC approach, and the ADMM-based DMPFC approach, respectively. The lables 'I' and 'L' in the third column denote interconnecting variables and Lagrange multipliers, respectively.*

DMPFC approaches	Coordination mechanism	Information exchange	Information process
sDMPFC	Serial	I, L	Directly
pDMPFC	Parallel	I, L	Directly
ADMM	Parallel	I	Indirectly

to exchange the interconnecting variables among neighboring operators, while the two ALR-based DMPFC approaches need to exchange both the interconnecting variables and the Lagrange multipliers. Thirdly, the ADMM-based DMPFC approach first uses the information of interconnecting variables received from neighboring operators to update the local copy of a part of the global optimization variables, i.e., $\tilde{\mathbf{z}}_n^{s+1}(k)$ in (5.24), and then indirectly to update the Lagrange multipliers and to implement the optimization (5.23) at the next iteration. The exchanged information is used by the two ALR-based DMPFC approaches for directly updating the Lagrange multipliers and performing the optimization (5.20) or (5.19) at the next iteration.

5.4 Simulation experiments

This section evaluates the three DMPFC approaches proposed in Section 5.3 when applied to the multiple-region IFTN benchmark system presented in Section 3.4.2. Section 5.4.1 introduces the basic setting of the coordinated planning problem. The performance of the three DMPFC approaches is analyzed and evaluated in Section 5.4.2.

5.4.1 The coordinated planning problem

This section considers coordinated synchromodal freight transport planning among three operators in the multiple-region IFTN benchmark system presented in Section 3.4.2. The network topology and the corresponding virtual network representation of the network are shown in Figures 5.2 and 5.3, respectively. The scenario setup, and the controller and solver settings are then introduced in the following sections.

Scenario setup

We consider coordinated planning over a period of 48 (h) with a time step $T_s = 2$ (h). The densities of traffic flows on the freeway links are given in Table 5.2. The transport demand enters subnetwork 1 from node 1^{W} with the destination node 6^{R} in subnetwork 3. The transport demand has a piecewise constant shape as shown in Figure 5.4. The value of time for the transport demand is taken as 25 (€/h). All subnetworks are initially considered to be empty (i.e., $\tilde{\mathbf{x}}_i(k) = 0$, $i = 1, \ldots, N$, $k \leq 0$).

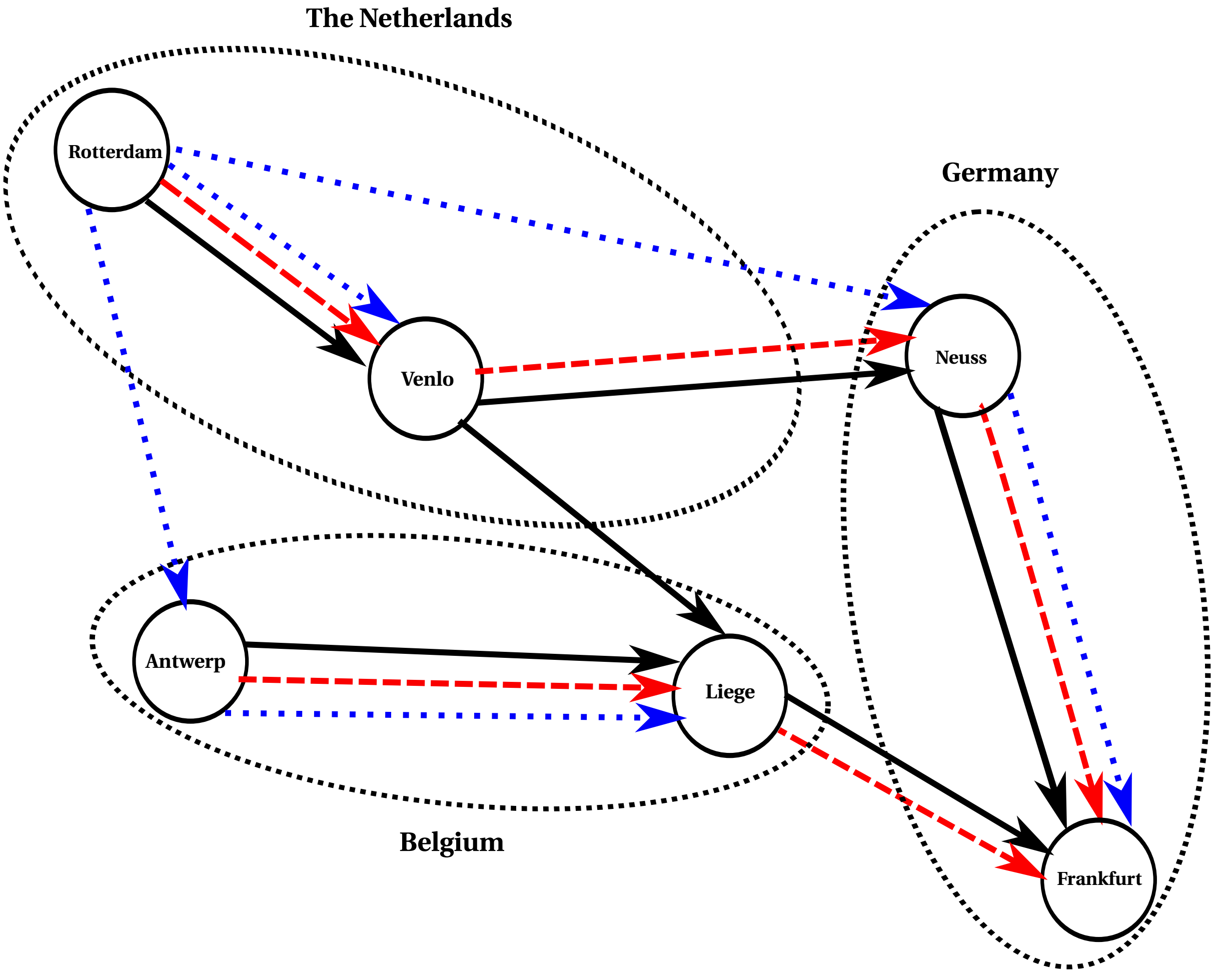

Figure 5.2: The topology of the multiple-region IFTN benchmark system between Rotterdam and Frankfurt. The solid black arcs, the dashed red arcs, and the dotted blue arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

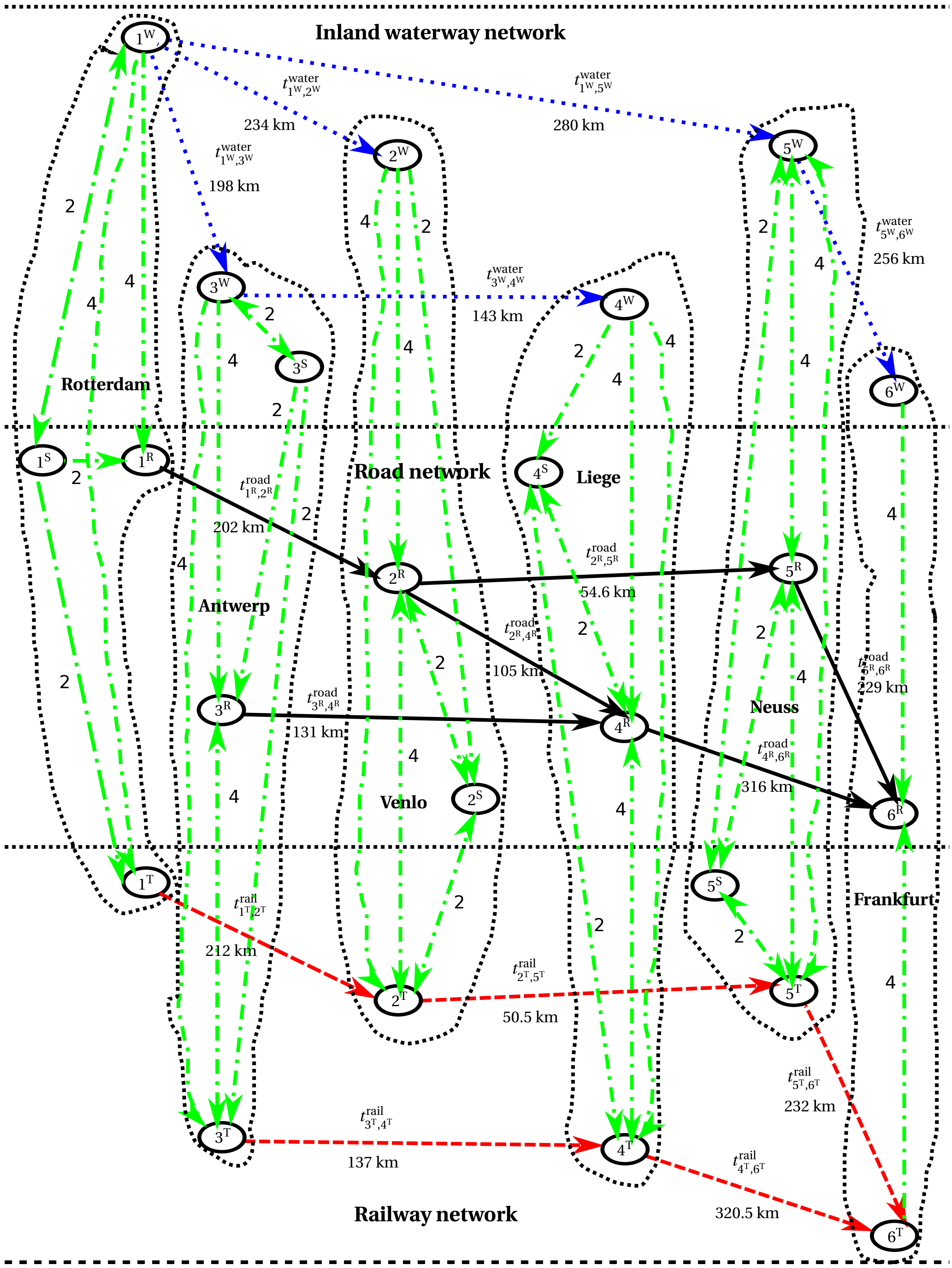

Figure 5.3: The corresponding virtual network representation of the network shown in Figure 5.2. Each double-headed arc in the figure represents two directed links with opposite directions.

Table 5.2: Densities of traffic flows on the freeway links.

Period (h)	0 – 8	9 – 20	21 – 32	33 – 40	41 – 48
$\rho^{\text{road,oth}}_{1^{\text{R}},2^{\text{R}}}, \rho^{\text{road,oth}}_{3^{\text{R}},4^{\text{R}}}$ (veh/km/lane)	35.0	45.0	35.0	30.0	30.0
$\rho^{\text{road,oth}}_{2^{\text{R}},4^{\text{R}}}, \rho^{\text{road,oth}}_{2^{\text{R}},5^{\text{R}}}, \rho^{\text{road,oth}}_{4^{\text{R}},6^{\text{R}}}, \rho^{\text{road,oth}}_{5^{\text{R}},6^{\text{R}}}$ (veh/km/lane)	20.0	45.0	20.0	45.0	20.0

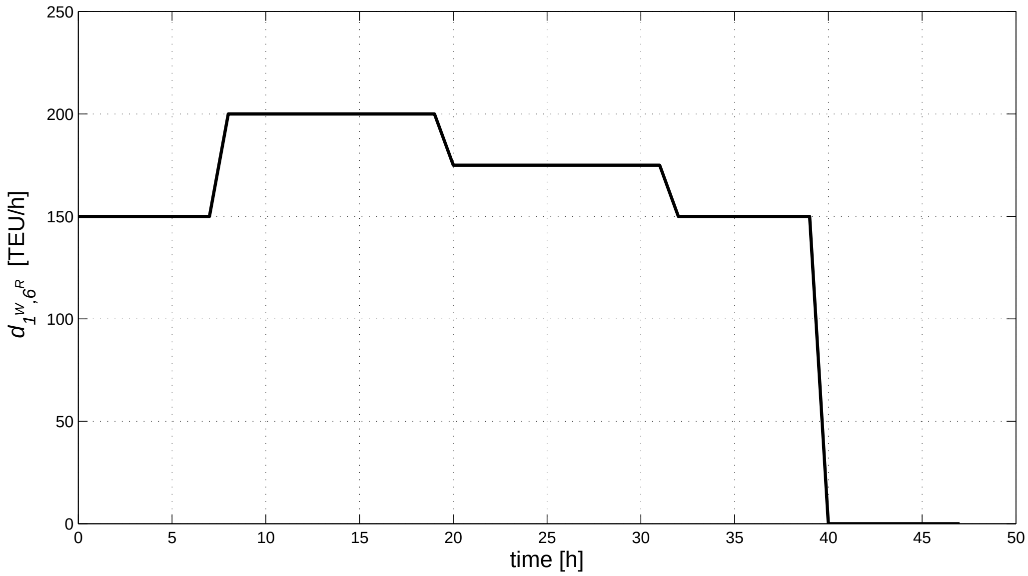

Figure 5.4: The transport demand, $d_{1^{\text{W}},6^{\text{R}}}$, over the planning period.

Controller and solver settings

In general the MPC controllers of different transport operators may require different prediction horizons to capture the dynamics of their own networks. This is because different transport networks may have different properties, e.g., size, physical capacity, and traffic condition. In this chapter, for the sake of simplicity[1] a common prediction horizon has been chosen for all three MPC controllers . The common prediction horizon should be large enough to cover the dynamic evolution of all subnetworks.

Based on initial empirical experiments carried out for this particular problem setting, the prediction horizon of individual operators is taken as $N_{\text{p}} = 16$. The empirical experiments are conducted in the same way as discussed in Section 4.5.2 when choosing the prediction horizon for the MPFC problem. In the simulation, we assume that the information of traffic density on freeway links and the transport demand in the prediction period $\left[kT_{\text{s}}, (k+N_{\text{p}})T_{\text{s}}\right)$ can be predicted accurately for time step k. The maximum allowed computation time for operators is $T_{\text{allowed}} = 30$ (min). The coordination parameters are taken as $\rho = 0.3$ and $b = 5\rho$ for the parallel DMPFC approach, and $\rho = 0.3$ for the other two DMPFC approaches. The iteration stopping threshold for the two ALR-based DMPFC approaches is set as $\varepsilon = 3 \times 10^{-3}$, while the threshold for the ADMM-based DMPFC approach is set as $\varepsilon = 1.5 \times 10^{-3}$. These iteration stopping thresholds are selected to make sure that an accuracy of $\varepsilon_{\text{variable}} = 10^{-2}$ on

[1]The DMPFC approaches presented in this chapter can be easily adapted to have different prediction horizons for different MPC controllers by only performing negotiation about the container flow information in the minimum prediction period of any two operators.

interconnecting constraints (5.7)-(5.8) is obtained for all the three DMPFC approaches.

We assume that a floating-point number is needed to transmit one interconnecting variable or one Lagrange multiplier from one operator to another. Therefore, the communication cost J_{com} can be calculated as $N_{\text{iteration}} I_{\text{iteration}}$, where $N_{\text{iteration}}$ is the total number of iterations during the whole simulation process and $I_{\text{iteration}}$ is the number of information exchanges per iteration.

For comparison purposes, a central operator is first assumed to be able to obtain all necessary planning information and to plan synchromodal freight transport in the whole network. Therefore, this central operator performs planning in a centralized way. The corresponding planning problem for the central operator is a linear programming optimization problem given by (5.9)–(5.12) and (5.16)–(5.17). This planning problem is solved using the simplex method implemented by the CPLEX solver of the TOMLAB Optimization Toolbox [81]. Next, three DMPFC approaches are applied for the coordinated synchromodal freight transport planning problem. The corresponding quadratic programming (QP) optimization problem in each DMPFC approach has a *positive semi-definite* quadratic matrix. Therefore, a regularization term is included in the objective functions (5.19), (5.20), and (5.23) to obtain a *positive definite* quadratic matrix in the QP optimization problem. Adding the regularization term might lead to a slightly increase in the value of the objective function, but can guarantee to have one unique solution for the corresponding QP optimization problem in each DMPFC approach considered in this chapter. The regularized QP optimization problems are solved with the barrier method implemented by the CPLEX Barrier QP solver of the TOMLAB Optimization Toolbox [81]. The simulation experiments are done with the use of a desktop computer with an Intel® Xeon(R) CPU W3690 with 3.47 GHz and 16 GB RAM.

5.4.2 DMPFC approach evaluations

This section illustrates the coordination process of the proposed DMPFC approaches and assesses their performance using the multiple-region IFTN benchmark system presented in Section 3.4.2 and the coordinated synchromodal freight transport planning problem defined in Section 5.4.1.

Coordination process illustration

We illustrate the coordination process of the three DMPFC approaches by presenting the evolution of the differences between particular interconnecting variables in the MPFC problems of two neighboring transport operators and the evolution of the associated Lagrangian multipliers for a particular time step. We choose two sets of interconnecting variables between the MPFC problem of operator 1 (providing transport services in The Netherlands) and the MPFC problem of operator 3 (providing transport services in Germany) for time step $k = 1$. These two sets of interconnecting variables are output interconnecting variables $w_{\text{out},3,1,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ and the corresponding input interconnecting variables $w_{\text{in},1,3,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ associated with the freeway link $l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}$ for $l = 1, 2, \ldots, N_{\text{p}}$.

For the *serial* ALR-based DMPFC approach, Figure 5.5 shows the coordination process on the values of $w_{\text{out},3,1,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ and the values of $w_{\text{in},1,3,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ between operator 1 and operator 3 at the first iteration of time step $k = 1$. At the first iteration, operator 1 first solves its MPFC problem and sends the preferred values of output interconnecting variables $w^1_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ (given in Figure 5.5(a)) to operator 3; then operator 3 computes its preferred values of input interconnecting variables $w^1_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ (by solving its MPFC problem with the values of $w^1_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ received from operator 1), and sends these preferred values (given in Figure 5.5(b)) to operator 1; finally, operator 3 updates the values of the associated Lagrange multipliers $\lambda^1_{w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ (presented in Figure 5.5(c)) and sends them to operator 1 to be used at the next iteration. The next iterations will repeat the same coordination process of the first iteration until the iterations are stopped. It is noteworthy that a negative value of a Lagrange multiplier $\lambda^1_{w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ implies that larger values of $w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ and smaller values of $w_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ are preferred in the next iteration by operator 3 and operator 1, respectively.

The evolution of the differences between $w^s_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ and $w^s_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ during the iteration process for time step $k=1$ in the *serial* ALR-based DMPFC approach are presented in Figure 5.6. Figure 5.7 presents the evolution of the values of the Lagrange multipliers $\lambda^s_{w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ associated with interconnecting variables $w_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ and $w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ for time step $k=1$ in the *serial* ALR-based DMPFC approach. In general, the coordination process between two operators involves multiple pairs of interconnecting variables and should be terminated when the absolute differences between the values of their associated Lagrange multipliers at two successive iterations are smaller than certain threshold, e.g., $\varepsilon = 3\times 10^{-3}$. The relation $\varepsilon = \rho\varepsilon_{\text{variable}}$ holds in the *serial* ALR-based DMPFC approach (see **Algorithm 5.2**). Terminating the iteration process with a threshold $\varepsilon = 3\times 10^{-3}$ will therefore guarantee that the absolute differences between the values of all pairs of interconnecting variables are not larger than $\varepsilon_{\text{variable}} = 10^{-2}$.

For the *parallel* ALR-based DMPFC approach, the coordination process on the values of $w_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ and the values of $w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ between operator 1 and operator 3 at the first iteration of time step $k=1$ is presented in Figure 5.8. This coordination process has the same execution sequence, (i.e., first solving optimization problems, and next updating Lagrange multipliers), as that of the coordination process of the *serial* ALR-based DMPFC approach given in Figure 5.5. The major difference is the sequence in which operator 1 and operator 3 solve their MPFC problems: for the *serial* ALR-based DMPFC approach, operator 1 first solves its MPFC problem (presented in Figure 5.5(a)), and next operator 3 solves its MPFC problem (presented in Figure 5.5(b)); for the *parallel* ALR-based DMPFC approach, operator 1 and operator 3 solve their MPFC problems simultaneously (presented in Figure 5.8(a)). The coordination process of the iterations in the *parallel* ALR-based DMPFC approach is similar to the coordination process of the *serial* ALR-based DMPFC approach shown in Figures 5.6 and 5.7.

For the ADMM-based DMPFC approach, Figure 5.9 shows the coordination process on the values of $w_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ and the values of $w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ between operator 1 and operator 3 at the first iteration of time step $k=1$. At the first iteration, operator 1 and operator 3 first solve their DMPFC problems in parallel and send their preferred values of the input interconnecting variables $w^1_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$, and $w^1_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ (see Figure

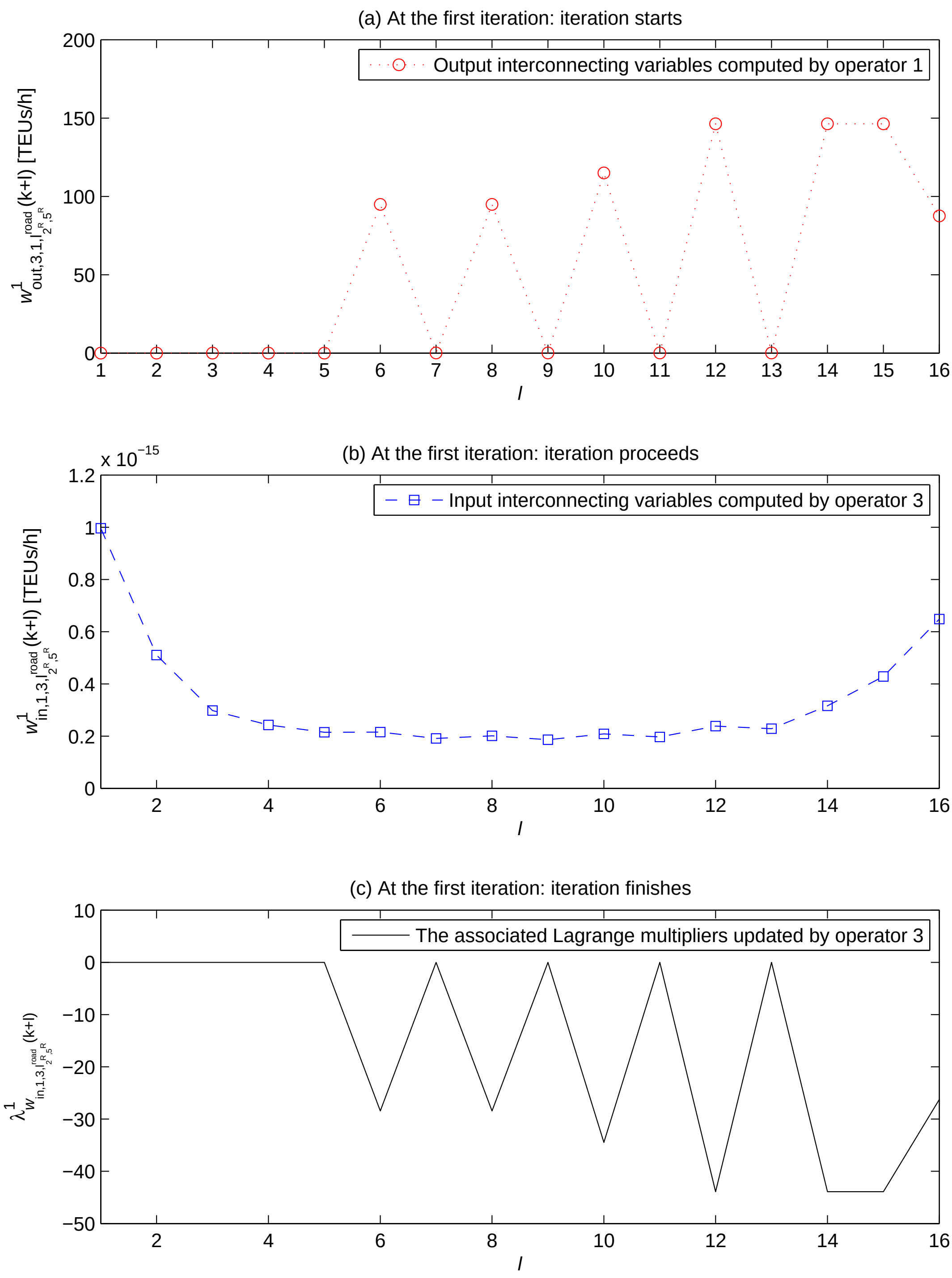

Figure 5.5: The coordination process on the values of interconnecting variables $w^1_{\text{out},3,1,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ and $w^1_{\text{in},1,3,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)$ over a prediction period of $N_{\text{p}} = 16$ time steps, hence, for $l = 1,2,\ldots,16$ between operator 1 and operator 3 at the first iteration of time step $k = 1$ in the serial ALR-based DMPFC approach. The associated Lagrange multipliers $\lambda^1_{w_{\text{in},1,3,l^{\text{road}}_{2^{\text{R}},5^{\text{R}}}}(k+l)}$ are shown in Figure 5.5(c).

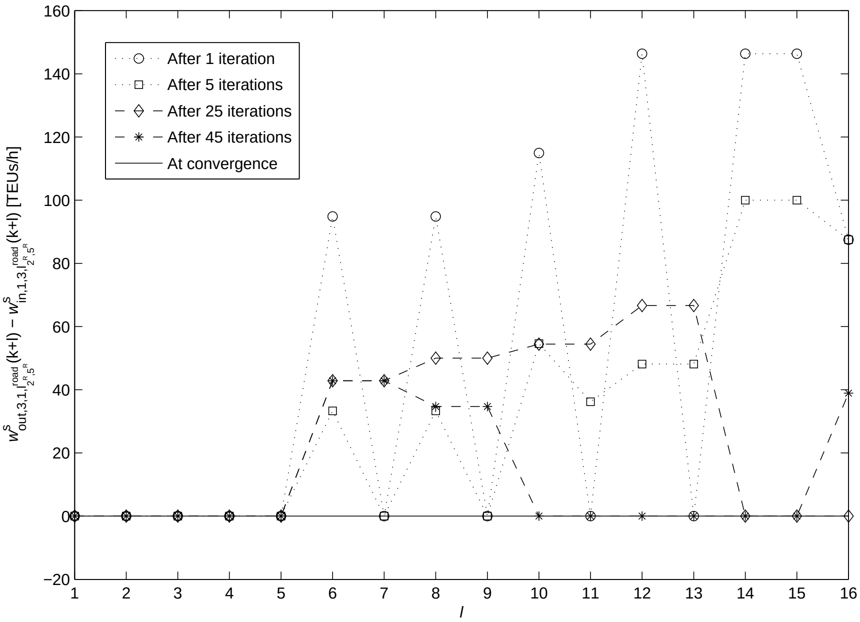

Figure 5.6: The evolution of the differences between the values of output interconnecting variable of the MPFC problem of operator 1, i.e., $w^{s}_{\mathrm{out},3,1,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)$, and the values of the corresponding input interconnecting variable of the MPFC problem of operator 3, i.e., $w^{s}_{\mathrm{in},1,3,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)$ in the serial ALR-based DMPFC approach, for the time step $k=1$ over a prediction period of $N_{\mathrm{p}}=16$ time steps, hence, for $l=1,2,\dots,16$.

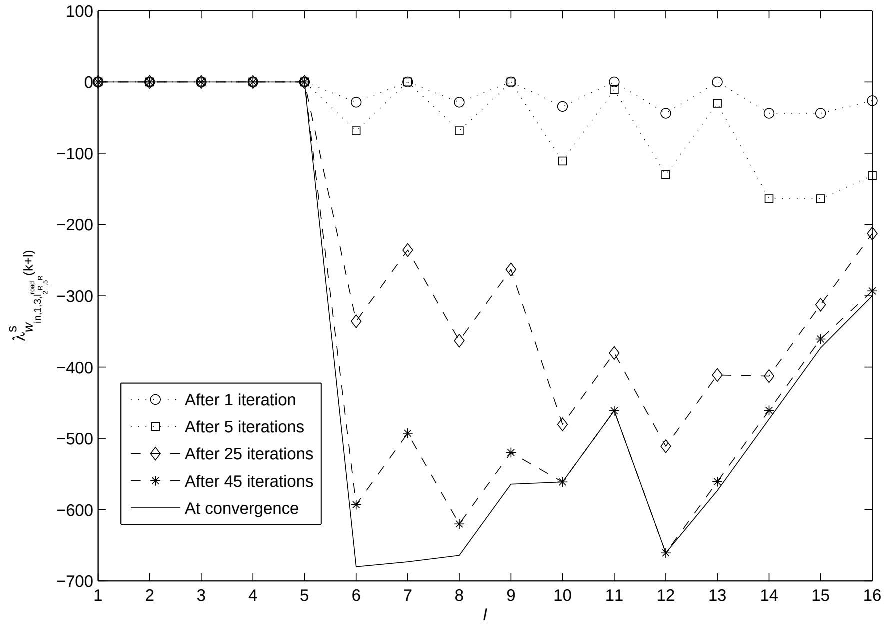

Figure 5.7: The evolution of the Lagrange multipliers $\lambda^s_{w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ *computed by operator 3 in the serial ALR-based DMPFC approach for the time step* $k = 1$ *over a prediction period of* $N_\text{p} = 16$ *time steps, hence, for* $l = 1, 2, \dots, 16$.

5.9(a)) to each other; next, each of two operators uses the values of $w^1_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ or $w^1_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)$ received from the other operator to update its own Lagrange multipliers $\lambda^1_{w_{\text{out},3,1,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ or $\lambda^1_{w_{\text{in},1,3,l^{\text{road}}_{2\text{R},5\text{R}}}(k+l)}$ (see Figure 5.9(b)). Each operator will keep the Lagrange multipliers updated by itself to be used in the next iteration. The next iterations will perform the same coordination process of the first iteration (Figure 5.9) until the stopping criteria are reached. Moreover, the coordination process of the iterations in the ADMM-based DMPFC approach differs from the coordination process of the *parallel* ALR-based DMPFC approach in terms of having locally updated and privately used Lagrange multipliers for operator 1 and operator 3, respectively.

Performance evaluation

The total delivery cost obtained by the central operator is 5.8627×10^6 (€). The planning performance of the three DMPFC approaches is presented in Table 5.3. As shown in Table 5.3 all three DMPFC approaches obtain the same total delivery cost, i.e., 5.8627×10^6 (€), the same as the total delivery cost attained by the central operator. The corresponding delivery costs of the three operators in their subnetworks are also the same for the three DMPFC approaches.

However, the corresponding performance of the DMPFC approaches is still different in terms of communication cost and actual computation time. In Table 5.3, the communication cost J_com and the actual computation time are calculated for all time steps of the whole simulation process. For the *parallel* ALR-based DMPFC approach and the

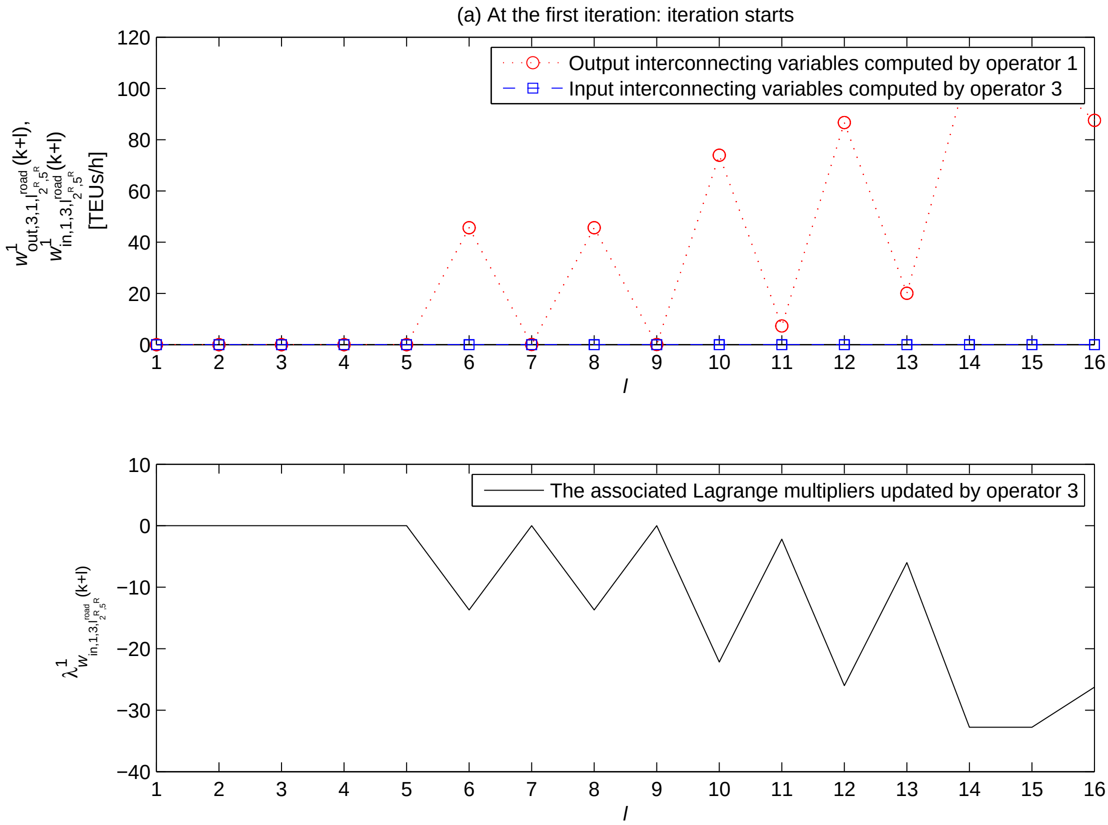

Figure 5.8: The coordination process on the values of interconnecting variables $w^1_{\text{out},3,1,l^{\text{road}}_{2^\text{R},5^\text{R}}}(k+l)$ and $w^1_{\text{in},1,3,l^{\text{road}}_{2^\text{R},5^\text{R}}}(k+l)$ over a prediction period of $N_\text{p} = 16$ time steps, hence, for $l = 1, 2, \ldots, 16$ associated with the freeway link $l^{\text{road}}_{2^\text{R},5^\text{R}}$ between operator 1 and operator 3 at the first iteration of time step $k = 1$ in the parallel ALR-based DMPFC approach. The associated Lagrange multipliers $\lambda^1_{w_{\text{in},1,3,l^{\text{road}}_{2^\text{R},5^\text{R}}}}(k+l)$ are shown in Figure 5.5(b).

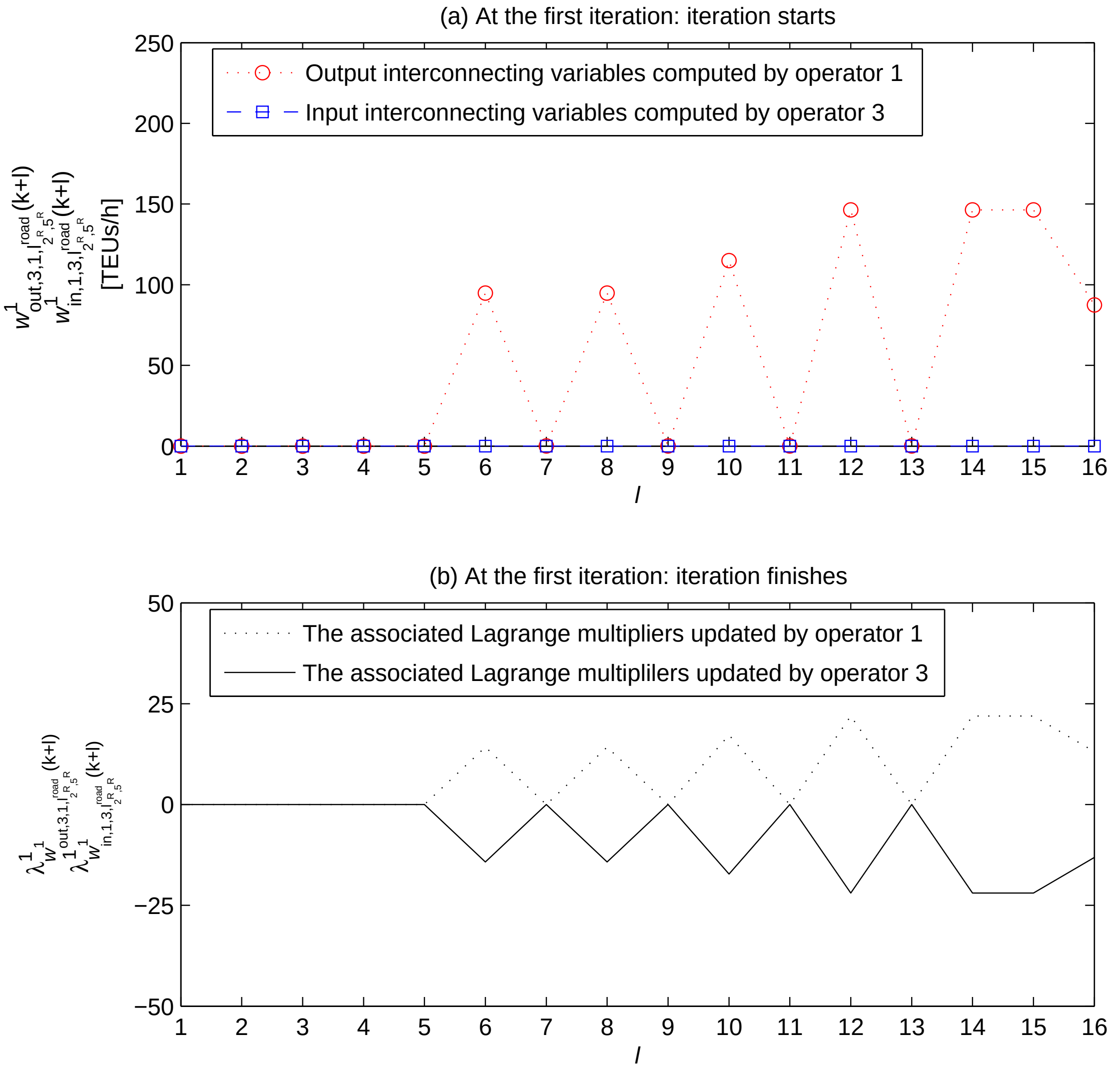

Figure 5.9: The coordination process on the values of interconnecting variables $w^1_{\mathrm{out},3,1,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)$ and $w^1_{\mathrm{in},1,3,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)$ over a prediction period of $N_{\mathrm{p}} = 16$ time steps, hence, for $l = 1, 2, \ldots, 16$ associated with the freeway link $l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}$ between operator 1 and operator 3 at the first iteration of time step $k = 1$ in the ADMM-based DMPFC approach. The associated Lagrange multipliers $\lambda^1_{w_{\mathrm{out},3,1,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)}$ and $\lambda^1_{w_{\mathrm{in},1,3,l^{\mathrm{road}}_{2^{\mathrm{R}},5^{\mathrm{R}}}}(k+l)}$ updated by two operators are shown in Figure 5.9(b).

Table 5.3: The performance of three DMPFC approaches. The lables 'sDMPFC', 'pDMPFC' and 'ADMM' in the 'DMPFC approaches' column stand for the serial *ALR-based DMPFC approach, the* parallel *ALR-based DMPFC approach, and the ADMM-based DMPFC approach, respectively.*

DMPFC approaches		Delivery cost	Communication cost			Computation time (min)
			$N_{\text{iteration}}$	$I_{\text{iteration}}$	J_{com} (floats)	
sDMPFC	Overall	5.8627×10^6	1840	336	618240	8.23
	Operator 1	3.9326×10^6		80	147200	2.85
	Operator 2	1.9076×10^6		96	176640	3.18
	Operator 3	2.2500×10^4		160	294400	2.21
pDMPFC	Overall	5.8627×10^6	5249	336	1763664	8.26
	Operator 1	3.9326×10^6		80	419920	7.86
	Operator 2	1.9076×10^6		96	503904	8.13
	Operator 3	2.2500×10^4		160	839840	5.98
ADMM	Overall	5.8627×10^6	4652	224	1042048	7.55
	Operator 1	3.9326×10^6		80	372160	6.78
	Operator 2	1.9076×10^6		64	297728	7.48
	Operator 3	2.2500×10^4		80	372160	5.01

ADMM-based DMPFC approach, the overall actual computation time for each time step is the maximum value of the actual computation times spent by the three operators during the same time step. For the *serial* ALR-based DMPFC approach, the overall actual computation time for each time step is summation of the actual computation times spent by the three operators during the same time step. The actual computation time for each time step is the maximum value of the actual computation times spent by the three operators for this time step. On the one side, the *serial* ALR-based DMPFC approach requires the minimum total number of iterations $N_{\text{iteration}} = 1840$ and also the lowest total communication cost $J_{\text{com}} = 618240$ (floats). The total communication cost of the *serial* ALR-based DMPFC approach accounts only for 35.1% and 59.3% of the total communication cost of the *parallel* ALR-based DMPFC approach and of the ADMM-based DMPFC approach, respectively. The distribution of the overall communication cost J_{com} among three operators changes when different DMPFC approaches are used. For example, the communication costs of operator 1, operator 2, and operator 3 for implementing the *serial* DMPFC approach are 147200 (floats), 176640 (floats), and 294400 (floats), respectively. On the other side, the ADMM-based DMPFC approach requires the lowest actual computation time, i.e., 7.55 (min) while that for the *serial* ALR-based DMPFC approach and the *parallel* ALR-based DMPFC approach is 8.23 (min), and 8.26 (min), respectively. The ADMM-based DMPFC approach is 8.3% and 8.6% faster than the *serial* ALR-based DMPFC approach and the *parallel* ALR-based DMPFC approach, respectively. It is worthwhile to note that even though the *serial* ALR-based DMPFC approach requires the least number of iterations, it actually requires more computation time than the ADMM-based DMPFC approach. This is because at each iteration multiple optimization problems are solved in a serial fashion in the *serial* ALR-based DMPFC approach, while the optimization problems are solved in parallel at each iteration of the ADMM-based DMPFC approach.

For the coordinated synchromodal freight transport planning problem considered in this section, it can be concluded that all three DMPFC approaches can attain the same coordination goal as that of the central operator. With respect to the other performance indicators and the properties of different DMPFC approaches listed in Section 5.3.3 two comments can be made: the ADMM-based DMPFC approach outperforms the *parallel* ALR-based DMPFC approach by exchanging fewer types of information and requiring fewer iterations and actual computation time; the *serial* ALR-based DMPFC approach takes fewer iterations than the ADMM-based DMPFC approach, but it requires to exchange more types of information and needs a larger actual computation time. It is noteworthy to point out that even though the *serial* ALR-based DMPFC approach requires more types of information exchanged than the ADMM-based DMPFC approach, it exchanges less floating-point numbers. In general, the implementation and performance of a DMPFC approach depends on the coordination mechanism, the required degree of confidentiality in information exchanges, the number of information exchanges, and the way in which the received information is used by operators. Therefore, for a particular coordinated synchromodal freight transport planning problem the appropriate DMPFC approach should be chosen considering the communication ability of transport operators, their accepted degree of confidentiality in information exchanges, and their preferences on performance indicators, e.g., less information exchanges or less computation time.

5.5 Summary

This chapter has investigated coordinated synchromodal freight transport planning among multiple transport operators in the hinterland haulage among deep-sea ports and inland terminals. Each operator is assumed to adopt a Model Predictive Control (MPC) approach for controlling container flows in one of the multiple interconnected subnetworks at the tactical flow level. This chapter has first formulated the Coordinated Model Predictive container Flow Control (CMPFC) problem in coordinated synchromodal freight transport by introducing interconnecting variables and interconnecting constraints among the planning problems of each of the operators. Three Distributed Model Predictive container Flow Control (DMPFC) approaches have been proposed to solve the CMPFC problem in a distributed way, adopting the auxiliary problem principle, or block coordinate descent, or the alternative direction of multiplier method to decouple the interconnecting constraints. When implementing these three DMPFC approaches for the multiple-region IFTN benchmark system, all of them obtain the same total delivery cost as the total delivery cost of the central operator. Meanwhile, the simulation results also indicate that for the given case study the ADMM based-DMPFC approach takes the smallest actual computation time (8.3% and 8.6% faster than the two ALR-based DMPFC approaches) while the *serial* ALR-based DMPFC approach requires the least iterations and information exchange (only 35.1% and 59.3% of the total communication cost of the *parallel* ALR-based DMPFC approach and the ADMM-based DMPFC approach, respectively) in the coordination process.

In this chapter we use a coordinated planning problem setting when evaluating the performance of the proposed DMPFC approach. Future research requires to conduct further performance evaluations under different transport demand scenarios and under different prediction error levels on the transport demand and traffic conditions in the network. In this chapter a common prediction horizon is used for the MPC controllers of all transport operators in the coordinated planning. It is interesting to investigate the influence of using different prediction horizons for the MPC controllers on the complexity of and the performance of the DMPFC approaches. Moreover, this chapter considers the coordinated planning among multiple intermodal freight transport operators. Future research can investigate other organizational structures of coordinated planning, e.g., the coordinated planning among multiple different unimodal freight transport operators (e.g., truck operators, train operators, and barge operators.) for jointly providing synchromodal container transport services.

Chapter 6

Conclusions and future research

This thesis has investigated network models and container flow control approaches for synchromodal freight transport planning among deep-sea terminals and inland terminals for a single intermodal freight transport operator, and for coordinated synchromodal freight transport planning among multiple transport operators. This chapter presents the main conclusions of the work conducted in this thesis, and points out directions for future research.

6.1 Main Contributions and Conclusions

In this thesis, we have addressed the problem of determining *how to control and coordinate container flows for synchromodal freight transport at the tactical container flow level for intermodal freight transport operators*. Our solution relies on deploying a systems and control perspective on container flow planning in synchromodal freight transport.

The main contributions of this thesis are as follows:

- We have proposed two discrete-time intermodal freight transport network (IFTN) models that are capable of representing the key characteristics of the intermodal freight transport systems at the tactical container flow level.
- We have proposed a model predictive container flow control (MPFC) approach for addressing the dynamic transport demand and dynamic traffic conditions in the network for synchromodal freight transport planning of a single transport operator. A multi-start Iterative Linear Programming (ILP) optimization approach has been proposed to efficiently solve the nonlinear and non-convex MPFC problem with a load-dependent IFTN model.
- We have proposed three distributed model predictive container flow control (DMPFC) approaches for coordinated planning among multiple transport operators based on the Augmented Lagrangian Relaxation (ALR) method and the Alternating Direction Method of Multipliers (ADMM) algorithm.

More specifically, three key research questions formulated in Chapter 1 are answered as follows:

- What are the key characteristics of intermodal freight transport systems and what intermodal freight transport network models can be developed to capture these characteristics adequately at the tactical container flow level?

For the flow control problem in synchromodal freight transport planning, key characteristics of intermodal freight transport systems are modality changes at intermodal terminals, time-dependent transport times on freeway links, timetables for trains and barges, and limited physical capacity constraints on the network. Chapter 3 has proposed two IFTN models. The first linear IFTN model captures the above key characteristics at the tactical container flow level. The second load-dependent IFTN model extends the linear IFTN model to include the impact of freight trucks operated by the transport operator on the freeway transport times with a multi-class version of the nonlinear and non-convex speed-density relation model. Moreover, a single-region IFTN benchmark system and a multiple-region IFTN benchmark system have been presented to demonstrate the usage of the proposed network modeling approach. These benchmark systems have been successfully used for evaluating the container flow control approaches in Chapters 4 and 5.

- How can a single intermodal freight transport operator control container flows for synchromodal freight transport planning with the dynamic transport demand and dynamic traffic conditions in an intermodal freight transport network?

  The synchromodal freight transport planning problem among deep-sea terminals and inland terminals for a single intermodal freight transport operator has been investigated from a systems and control perspective in Chapter 4. We have proposed a Model Predictive container Flow Control (MPFC) approach to simultaneously determine both route selection and flow assignment in a receding horizon way for synchromodal freight transport planning considering the dynamic transport demand and traffic conditions in the network.

  For the linear IFTN model, the MPFC approach involves solving linear programming problems and is suited for computationally planning synchromodal freight transport in large-sized networks. For the given case study in the single-region IFTN benchmark system, the MPFC approach with a prediction horizon of 12 hours obtains a 20.18% reduction of the total delivery cost compared with a greedy all-or-nothing approach.

  For the load-dependent IFTN model, we have proposed a multi-start Iterative Linear Programming (ILP) method using the stopping window method to efficiently solve the nonlinear and non-convex MPFC optimization problem for each time step. Two solutions methods, i.e., the proposed multi-start ILP method and the multi-start Sequential Quadratic Programming (SQP) method, have been used in the simulation study on the single-region IFTN benchmark system. For the MPFC approach with a prediction horizon of 10 hours, the multi-start ILP method achieves a planning performance that is comparable with that of the multi-start SQP method, while it significantly reduces the computation time.

  Moreover, simulation results also show that the MPFC approach with either the linear IFTN model or the load-dependent IFTN model achieves good planning performance in a consistent manner under different demand scenarios and prediction error levels.

- How can multiple intermodal freight transport operators coordinate their container flow control actions for coordinated synchromodal freight transport planning in different but interconnected service areas?

We have investigated coordinated synchromodal freight transport planning among multiple intermodal freight transport operators in different but interconnected service areas in Chapter 5. The coordination goal is to minimize the total freight delivery cost for serving the transport demand. Based on the Augmented Lagrangian Relaxation (ALR) method and the Alternating Direction Method of Multipliers (ADMM) method, we have proposed three Distributed Model Predictive container Flow Control (DMPFC) approaches for the coordinated synchromodal freight transport planning problem: the *parallel* ALR-based DMPFC approach, the *serial* ALR-based DMPFC approach, and the ADMM-based DMPFC approach.

The performance of these three DMPFC approaches has been analyzed and evaluated considering the coordinated synchromodal freight transport planning problem for the multiple-region IFTN benchmark system with the linear IFTN model. In the simulation, all of these three DMPFC approaches obtain the same total delivery cost as the total delivery cost of a central operator. This central operator is introduced for comparison purposes, and is assumed to be able to obtain all necessary planning information and to plan synchromodal freight transport in the whole network in a centralized way. Meanwhile, the simulation results also indicate that for the given case study the ADMM based-DMPFC approach requires the smallest actual computation time (it is 8.3% and 8.6% faster than the two ALR-based DMPFC approaches) while the *serial* ALR-based DMPFC approach requires the least iterations and information exchanges (only 35.1% and 59.3% of the total communication cost of the *parallel* ALR-based DMPFC approach and the ADMM-based DMPFC approach, respectively) in the coordination process.

The work of this thesis is presented at three journal papers [95, 97, 99] and five international conference papers [92–94, 96, 98].

6.2 Recommendation for future research

The network models and planning approaches for synchromodal freight transport planning have been investigated at the tactical flow level in this thesis. Future research directions are presented and discussed in two aspects: network modeling and solution approaches. Moreover, since the network models and planning approaches proposed in this thesis need to be used in the multi-level freight transport planning framework presented in Chapter 1, research directions for the implementation of this multi-level planning framework are also discussed. Below we discuss possible future research directions in synchromodal freight transport planning.

Network modeling

- Environmental issues, e.g., reducing CO_2 emission, are receiving increasing attention from both researchers and practitioners in freight transport. Although the planning objective (4.1) used in this thesis can capture the environmental aspects with a generic term, i.e., “transport cost", it is still important to explicitly capture environmental aspects in the network model and the planning objective. Emission models have been developed for both single modalities and for a combination of multiple modalities in the literature. The challenge is to integrate appropriate emission models (for the considered synchromodal freight transport problems) into the IFTN models presented in this thesis. Moreover, it is also essential to make an appropriate trade-off between model accuracy and the computational tractability of the planning problems.

- The issue of empty container repositioning has not been explicitly considered in this thesis. Therefore, future research can extend the work presented in this thesis to capture different empty repositioning strategies, such as reusing empty containers [21, 47], and to investigate their effects on the performance of the presented MPFC approach in this thesis.

- The issue of timetables is crucial for railway and inland waterway freight transport. Three aspects are important when modeling the network, i.e., whether timetables are predetermined for barges and trains, whether the predetermined timetables can be accurately implemented, and whether the predetermined timetables can be updated according to the newly arrived logistic information. In this thesis we assumed that timetables are predetermined for barges and trains and can be accurately implemented. However, delays can occur on barges and trains due to unexpected events at deep-sea ports, e.g., the late arrival of deep-sea vessels, or equipment failures at the container terminal. To address the issue of delays, it is important to analyze their characteristics and to search for appropriate approaches to capture these characteristics in the network model. Moreover, the case of barge transport without fixed schedules needs further investigation. For instance, instead of at a particular time instant a container barge might departure from a terminal within a time slot when a certain level of capacity utilization is reached.

- This thesis assumes that timetables for trains are predetermined in such a way that only one train can be loaded with containers at a specific time for each link of the railway network. There are, however, also cases in which multiple trains with overlapping container loading times are scheduled at the origin terminal of a link. The model for the dynamics of railway links formulated in Chapter 3.2.4 will then need to be extended accordingly. An option is to introduce additional virtual links for representing the loading operation of each of these multiple trains simultaneously.

- The topic of modal split targeting has received significant research attention in freight transport. As a new trend, transport regulators are currently interested in suggesting or even imposing modal split targets on terminal operations and hinterland transport for environmental concerns and efficient planning [44, 126]. The Port of Rotterdam Authority signed contracts with terminal operators on the newly constructed Maasvlakte 2, in which terminal operators committed to reduce the share of trucks in the modal split by using more barges and trains. Motivated by this practice, a model predictive approach was proposed for cargo assignment with the inclusion of a modal split constraint from a perspective intermodal terminal operator in [119]. In this thesis, we have not included modal split targets in the optimization problems for synchromodal freight transport planning of transport operators. Therefore, future research could explicitly include the modal split target as either hard or soft planning constraints in the synchromodal freight transport planning, and to tackle the challenge of coordinating actions of terminal operators and transport operators for achieving their modal split targets.

- The issue of modal split targeting in freight transport has been investigated with static models for policy making at the strategic level. Two reccent papers [59, 60] use a dynamic modal split model, which considers a dynamic relationship between average transport cost and freight flow, named dynamic cost function, for each modalities. The modal split evolution can evolve towards a unique stable, a periodic, or a chaotic equilibrium, and the conditions for the occurrence of a particular type of equilibrium and the characteristics of the corresponding transition phases have been investigated in [60]. Directions for future research are to analyze the effect of various measures (e.g., increasing CO_2 price, and making investments on new infrastructures) on the modal split evolution with the model proposed in [59, 60], and to investigate what policy packages should be deployed in order to achieve a modal split target. An implementation of the determined policy packages will influence the values of the cost parameters in the network models presented in this thesis and model extensions might also be required to capture possibly new phenomena emerged.

Solution approaches

- The computational complexity issue hinders the load-dependent IFTN model presented in Chapter 3.3 from being used in large-scale transport networks. This thesis has proposed an iterative linear programming approach to solve the corresponding nonlinear and non-convex planning problem through an iterative process. An alternative approach is to approximate the nonlinear and non-convex relations in the load-dependent IFTN model using the Piecewise Affine (PWA) functions. The resulting PWA network model can then be formulated as a Mixed Logical Dynamic (MLD) model by applying certain transformations [171]. Correspondingly, the original synchromodal freight transport planning problem, with the MLD model, can be recast as a Mixed Integer Linear Programming (MILP) optimization problem, for which efficient solvers are available [4, 101]. The PWA approximation method could be suited for obtaining a fast optimization approach for solving the MPFC problem with the load-dependent IFTN model.

- The MPC approach requires to calculate container flow control actions for each time step of the transport planning process. This regular calculation takes more computation efforts and is not always necessary since the freight planning situations might not vary a lot between two successive planning time intervals. An event-triggered strategy has been used for reducing the computational complexity of the MPC approach in various applications, e.g., freeway traffic control [57], container terminal operations [174], and a hybrid power plant with both solar panels and a gas microturbine [51]. An event-triggered MPFC approach can be developed to reduce the computational complexity of the MPFC approach proposed in this thesis by avoiding the possibly unnecessary computations of flow control actions at some time steps of the synchromodal freight transport planning process.

- The MPFC approach has been essentially proposed for deterministic synchromodal freight transport planning settings in Chapter 4. Its performance under the existing of errors (or uncertainties) on system disturbances (i.e., the transport demand, and the traffic conditions in the network) has been evaluated with the statistic values of the total delivery cost, and the computation time in multiple simulation tests. Robust MPC approaches (e.g., min-max MPC approaches [22, 73], and scenario-based MPC approach [10, 143]) can be developed to take into account the effect of having prediction errors on system disturbances while determining container flow control actions in the network.

- The DMPC methodology can be used for controlling container flows in coordinated synchromodal freight transport planning. This thesis focuses in particular on the ALR-based DMPC approaches and the ADMM-based DMPC approach. In order to explore new coordination mechanisms that are more efficient (in terms of computation speeds, and/or communication costs) than the DMPFC approaches used in this thesis, it is interesting to investigate the application of other DMPC approaches, (e.g., price-driven DMPC approach [29, 110], and bargaining game based DMPC approach [107]), in synchromodal freight transport planning. Moreover, it is challenging to carry out fundamental research on new DMPC approaches by either exploring the characteristic properties of certain optimization problems, or developing new distributed optimization algorithms.

Implementation

- The Operation Research (OR) literature on routing and scheduling of individual vehicles or containers in freight transport is very rich, and it includes, e.g., vehicle routing problems [153], and pickup and delivery problems [9, 52]. The network models and solutions approaches developed in this literature will be the basis for investigating synchromodal freight transport planning problems at the individual container planning level. Meanwhile, additional constraints need be introduced to fulfill the synchronization requirements, e.g., synchronizing container transport schedules and transport resource allocation plans.

- A challenging issue for the implementation of the multi-level freight transport planning approach presented in this thesis is to develop appropriate information mapping approaches for efficiently aggregating or disaggregating transport information between the flow planning level and the container planning level. Solution approaches can come from other domains in which a multi-level approach has been considered before, e.g., power systems [128], intelligent vehicle highway systems [7], and urban traffic networks [100].

- Pricing synchromodal freight transport services involves determining how much customers should be charged for each service with particular service-related characteristics i.e., origin, destination, the number of containers that have to be transported, and the due time for completing the movement. The pricing strategy will greatly affect the competitiveness of synchromodal freight transport services, and consequently the wide-spread implementation of the concept of synchromodality. We have proposed a cost-plus-pricing strategy in [98] by extending the work presented in this thesis. The revenue management approach is an alternative way to design pricing mechanisims for synchromodal freight transport services.

Appendix A

Fundamental Diagram

In literature, the fundamental diagram of traffic flows on freeways represents the steady-state relation between two out of three aggregated variables: the mean traffic flow q (veh/h), the mean traffic density ρ (veh/km/lane), and the mean speed v (km/h). The fundamental equation of traffic flow captures the relationship among these three variables [40, 112, 129]:

$$q = \lambda \rho v. \tag{A.1}$$

In (A.1), λ is the number of lanes on the freeway. The fundamental diagram has three variants: the speed-density fundamental diagram, the flow-density fundamental diagram, and the flow-speed fundamental diagram. These three types of fundamental diagram can easily be transformed from one type to another type based on the fundamental equation of traffic flow (A.1).

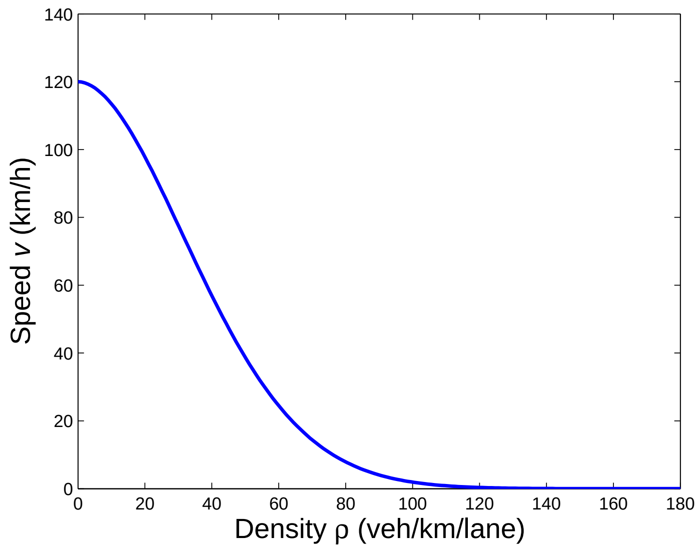

Figure A.1: The speed-density fundamental diagram.

An empirical formula of the speed(v)-density(ρ) relation can be represented as:

$$v(\rho) = v_{\text{free}} \exp\left[-\frac{1}{a}\left(\frac{\rho}{\rho_{\text{crit}}}\right)^{a}\right], \tag{A.2}$$

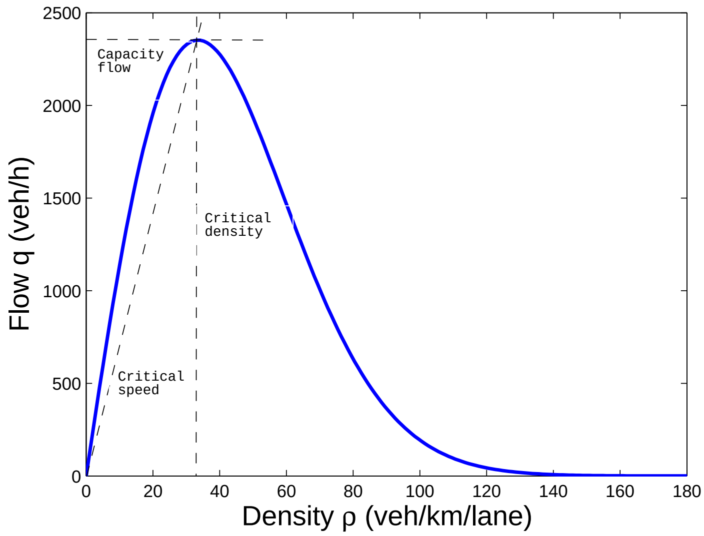

Figure A.2: The flow-density fundamental diagram.

where v_{free} is the free-flow speed, ρ_{crit} is the critical density (corresponding to the maximum traffic flow), and a is a parameter of the model [129]. Figures A.1 and A.2 show the speed-density fundamental diagram and the flow-density fundamental diagram for a freeway with a single lane, respectively. In these two figures the values of the model parameters are taken as $v_{\text{free}} = 120$ km/h, $\rho_{\text{crit}} = 33.5$ veh/km/lane, and $a = 1.867$ [78, 89].

Bibliography

[1] A. Alessandri, S. Sacone, and S. Siri. Modelling and optimal receding-horizon control of maritime container terminals. *Journal of Mathematical Modelling and Algorithms*, 6(1):109–133, 2007.

[2] I. Alvarado, D. Limon, D.M. de la Peña, J.M. Maestre, M.A. Ridao, H. Scheu, W. Marquardt, R.R. Negenborn, B. De Schutter, F. Valencia, and J. Espinosa. A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark. *Journal of Process Control*, 21(5):800–815, 2011.

[3] Ó. Álvarez-SanJaime, P. Cantos-Sánchez, R. Moner-Colonques, and J.J. Sempere-Monerris. The impact on port competition of the integration of port and inland transport services. *Transportation Research Part B: Methodological*, 80:291–302, 2015.

[4] A. Atamtürk and M.W.P. Savelsbergh. Integer-programming software systems. *Annals of Operations Research*, 140(1):67–124, 2005.

[5] H. Ayed, Z. Habas, D. Khadraoui, and C. Galvez-Fernandez. A parallel algorithm for solving time dependent multimodal transport problem. In *Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems (ITSC 2011)*, pages 722–727, Washington, DC, USA, October 2011.

[6] C. Barnhart and H.D. Ratliff. Modeling intermodal routing. *Journal of Business Logistics*, 14(1):205–223, 1993.

[7] L.D. Baskar. *Traffic Management and Control in Intelligent Vehicle Highway Systems.* Ph.D thesis, Delft University of Technology, Delft, The Netherlands, November 2009.

[8] B. Behdani, Y. Fan, B. Wiegmans, and R.A. Zuidwijk. Multimodal schedule design for synchromodal freight transport systems. *Available at SSRN: http://ssrn.com/abstract=2438851 or http://dx.doi.org/10.2139/ssrn.2438851*, May 2014.

[9] G. Berbeglia, J.-F. Cordeau, and G. Laporte. Dynamic pickup and delivery problems. *European Journal of Operational Research*, 202(1):8–15, 2010.

[10] D. Bernardini and A. Bemporad. Scenario-based model predictive control of stochastic constrained linear systems. In *Proceedings of the IEEE Conference on Decision and Control*, Shanghai, China.

[11] D.P. Bertsekas. *Constrained Optimization and Lagrange Multiplier Methods.* Academic Press, London, UK, 1982.

[12] D.P. Bertsekas and J.N. Tsitsiklis. *Parallel and Distributed Computation: Numerical Methods*. Athena Scientific, Englewood Cliffs, New Jersey, 1997.

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

[14] B.S. Boardman, E.M. Malstrom, D.P. Butler, and M.H. Cole. Computer assisted routing of intermodal shipments. *Computers and Industrial Engineering*, 33(1-2):311–314, 1997.

[15] S. Bock. Real-time control of freight forwarder transportation networks by integrating multimodal transport chains. *European Journal of Operational Research*, 200(3):733–746, 2010.

[16] P.T. Boggs and J.W. Tolle. Sequential quadratic programming. *Acta numerica*, 4:1–51, January 1995.

[17] P.T. Boggs and J.W. Tolle. Sequential quadratic programming for large-scale nonlinear optimization. *Journal of Computational and Applied Mathematics*, 124(1–2):123–137, 2000.

[18] J.F. Bonnans, J.C. Gilbert, C. Lemaréchal, and C.A. Sagastizábal. *Numerical optimization: theoretical and practical aspects*. Springer Science & Business Media, USA, 2nd edition, 2006.

[19] S. Boyd and L. Vandenberghe. *Convex Optimization*. Cambridge University Press, Cambridge, UK, 2004.

[20] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein. Distributed optimization and statistical learning via the alternating direction method of multipliers. *Foundations and Trends in Machine Learning*, 3(1):1–122, 2010.

[21] K. Braekers, G.K. Janssens, and A. Caris. Challenges in managing empty container movements at multiple planning levels. *Transport Reviews*, 31(6):681–708, 2011.

[22] P.J. Campo and M. Morari. Robust model predictive control. In *Proceedings of the American Control Conference*, pages 1021–1026, Minneapolis, Minnesota, 1987.

[23] E. Camponogara, D. Jia, B.H. Krogh, and S. Talukdar. Distributed model predictive control. *IEEE Control Systems Magazine*, 22(1):44–52, 2002.

[24] A. Caris, C. Macharis, and G.K. Janssens. Planning problems in intermodal freight transport: accomplishments and prospects. *Transportation Planning and Technology*, 31(3):277–302, 2008.

[25] A. Caris, C. Macharis, and G.K. Janssens. Decision support in intermodal transport: A new research agenda. *Computers in Industry*, 64(2):105–112, 2013.

[26] M.J. Cassidy, K. Jang, and C.F. Daganzo. Macroscopic fundamental diagrams for freeway networks: Theory and observation. *Transportation Research Record*, 2260:8–15, 2011.

[27] CEC. *'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, Belgium, 2006.

[28] T.-S. Chang. Best routes selection in international intermodal networks. *Computers and Operations Research*, 35(9):2877–2891, 2008.

[29] R. Cheng, J.F. Forbes, and W.S. Yip. Price-driven coordination method for solving plant-wide MPC problems. *Journal of Process Control*, 17(5 SPEC. ISS.):429–438, 2007.

[30] J.H. Cho, H.S. Kim, and H.R. Choi. An intermodal transport network planning algorithm using dynamic programming - A case study: From Busan to Rotterdam in intermodal freight routing. *Applied Intelligence*, 36(3):529–541, 2012.

[31] A.H.F. Chow. Generalized network fundamental diagram for motorway traffic management. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 1016–1021, The Hague, The Netherlands, October 2013.

[32] P.D. Christofides, R. Scattolini, D.M. de la Peña, and J. Liu. Distributed model predictive control: A tutorial review and future research directions. *Computers & Chemical Engineering*, 51:21–41, 2013.

[33] C. Clott and B.C. Hartman. Supply chain integration, landside operations and port accessibility in metropolitan Chicago. *Journal of Transport Geography*, 51:130–139, 2016.

[34] C. Conte, T. Summers, M.N. Zeilinger, M. Morari, and C.N. Jones. Computational aspects of distributed optimization in model predictive control. In *Proceedings of the IEEE Conference on Decision and Control*, pages 6819–6824, Hawaii, USA, December 2012.

[35] R. Costa, J. Lemos, J.F.C. Mota, and J.M.F. Xavier. D-ADMM based distributed MPC with input-output models. In *Proceedings of the 2014 IEEE Multi-Conference on Systems and Control*, pages 699–704, Antibes, France, October 2014.

[36] T.G. Crainic. Service network design in freight transportation. *European Journal of Operational Research*, 122(2):272–288, 2000.

[37] T.G. Crainic and K.H. Kim. Intermodal transportation. In C. Barnhart and G. Laporte, editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, chapter 8, pages 467–537. Elsevier, 2007.

[38] T.G. Crainic and G. Laporte. Planning models for freight transportation. *European Journal of Operational Research*, 97(3):409–438, 1997.

[39] T.G. Crainic, M. Florian, J. Guélat, and H. Spiess. Strategic planning of freight transportation: STAN, an interactive graphic systems. *Transportation Research Record*, 1283:97–124, 1990.

[40] C.F. Daganzo. *Fundementals of Transportation and Traffic Operations.* Pergamon, 1997.

[41] C.F. Daganzo. Urban gridlock: Macroscopic modeling and mitigation approaches. *Transportation Research Part B: Methodological*, 41(1):49–62, 2007.

[42] C.F. Daganzo and N. Geroliminis. An analytical approximation for the macroscopic fundamental diagram of urban traffic. *Transportation Research Part B: Methodological*, 42(9):771–781, 2008.

[43] DB Netz AG. Interactive map. July 2014. URL http://stredax.dbnetze.com/ISRViewer/public_html_en/svg/index.html.

[44] P.W. de Langen, R. van den Berg, and A. Willeumier. A new approach to granting terminal concessions: The case of the rotterdam world gateway terminal. *Maritime Policy and Management*, 39(1):79–90, 2012.

[45] L.B. de Oliveira and E. Camponogara. Multi-agent model predictive control of signaling split in urban traffic networks. *Transportation Research Part C: Emerging Technologies*, 18(1):120–139, 2010.

[46] F.A. De Souza, E. Camponogara, W.K. Junior, and V.B. Peccin. Distributed MPC for urban traffic networks: A simulation-based performance analysis. *Optimal Control Applications and Methods*, 36(3):353–368, 2015.

[47] P.J. Dejax and T.G. Crainic. Review of empty flows and fleet management models in freight transportation. *Transportation Science*, 21(4):227–247, 1987.

[48] A.J. del Real, A. Arce, and C. Bordons. An integrated framework for distributed model predictive control of large-scale power networks. *IEEE Transactions on Industrial Informatics*, 10(1):197–209, February 2014.

[49] P. Deo, B. De Schutter, and A. Hegyi. Model predictive control for multi-class traffic flows. In *Proceedings of the 12th IFAC Symposium on Transportation Systems*, pages 25–30, Redondo Beach, California, September 2009.

[50] A. Di Febbraro, N. Sacco, and M. Saeednia. A cooperative framework for freight distribution in multimodal corridors. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 949–954, October 2013.

[51] J.-Y. Dieulot, F. Colas, L. Chalal, and G. Dauphin-Tanguy. Event-triggered variable horizon supervisory predictive control of hybrid power plants. *Control Engineering Practice*, 34:61–67, 2015.

[52] Y. Dumas, J. Desrosiers, and F. Soumis. The pickup and delivery problem with time windows. *European Journal of Operational Research*, 54(1):7–22, 1991.

[53] Europe Container Terminal. *The future of freight transport.* Europe Container Terminal, Rotterdam, The Netherlands, October 2011. URL http://www.ect.nl/en/content/future-freight-transport.

[54] Europe Container Terminal. *Fast Forward: Synchromodality.* Europe Container Terminal, Rotterdam, The Netherlands, December 2011.

[55] Europe Container Terminal. *Synchromodaal vervoer in 2020.* Europe Container Terminal, Rotterdam, The Netherlands, July 2012.

[56] F. Farokhi, I. Shames, and K.H. Johansson. Distributed MPC via dual decomposition and alternative direction method of multipliers. In J.M. Maestre and R.R. Negenborn, editors, *Distributed Model Predictive Control Made Easy*, volume 69 of *Intelligent Systems, Control and Automation: Science and Engineering*, pages 115–131. Springer, 2014.

[57] A. Ferrara, S. Sacone, and S. Siri. Event-triggered model predictive schemes for freeway traffic control. *Transportation Research Part C: Emerging Technologies*, 58:554–567, 2015.

[58] C. Ferrari, F. Parola, and E. Gattorna. Measuring the quality of port hinterland accessibility: The ligurian case. *Transport Policy*, 18(2):382–391, 2011.

[59] P. Ferrari. The dynamics of modal split for freight transport. *Transportation Research Part E: Logistics and Transportation Review*, 70(1):163–176, 2014.

[60] P. Ferrari. Dynamic cost functions and freight transport modal split evolution. *Transportation Research Part E: Logistics and Transportation Review*, 77:115–134, 2015.

[61] J.R.D. Frejo and E.F. Camacho. Global versus local MPC algorithms in freeway traffic control with ramp metering and variable speed limits. *IEEE Transactions on Intelligent Transportation Systems*, 13(4):1556–1565, 2012.

[62] D. Gabay and B. Mercier. A dual algorithm for the solution of nonlinear variational problems via finite element approximation. *Computers and Mathematics with Applications*, 2(1):17–40, 1976.

[63] C.E. García, D.M. Prett, and M. Morari. Model predictive control: theory and practice - A survey. *Automatica*, 25(3):335–348, 1989.

[64] N. Geroliminis and C.F. Daganzo. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological*, 42(9):759–770, 2008.

[65] N. Geroliminis and J. Sun. Properties of a well-defined macroscopic fundamental diagram for urban traffic. *Transportation Research Part B: Methodological*, 45(3):605–617, 2011.

[66] N. Geroliminis and J. Sun. Hysteresis phenomena of a macroscopic fundamental diagram in freeway networks. *Transportation Research Part A: Policy and Practice*, 45 (9):966–979, 2011.

[67] A.H. Ghods, L. Fu, and A. Rahimi-Kian. An efficient optimization approach to real-time coordinated and integrated freeway traffic control. *IEEE Transactions on Intelligent Transportation Systems*, 11(4):873–884, 2010.

[68] R. Glowinski and A. Marroco. Sur l'approximation, par éléments finis d'ordre un, et la résolution, par pénalisation-dualité d'une classe de problèmes de Dirichlet non linéaires. *ESAIM: Mathematical Modelling and Numerical Analysis-Modélisation Mathématique et Analyse Numérique*, 9(R2):41–76, 1975.

[69] A. Goel. The value of in-transit visibility for supply chains with multiple modes of transport. *International Journal of Logistics Research and Applications*, 13(6):475–492, 2010.

[70] G.H. Golub and C.F. van Loan. *Matrix Computations*. The Johns Hopkins University Press, Baltimore, Maryland, 3rd edition, 1996.

[71] S.E. Grasman. Dynamic approach to stratigic and operational multimodal routing decisions. *International Journal of Logistics Systems and Management*, 2(1):96–106, 2006.

[72] T. Groen, T. Groen, W. Hofman, R. Janssen, J. Van Meijeren, M. Oonk, and et al. *Implementatieroadmap Synchromodaliteit*. TNO, Connekt & Dinalog commissioned by the Ministry of Infrastructure and Environment, The Netherlands, 2011.

[73] J.K. Gruber, D.R. Ramirez, D. Limon, and T. Alamo. Computationally efficient nonlinear min-max model predictive control based on volterra series models - Application to a pilot plant. *Journal of Process Control*, 23(4):543–560, 2013.

[74] J. Haddad, M. Ramezani, and N. Geroliminis. Cooperative traffic control of a mixed network with two urban regions and a freeway. *Transportation Research Part B: Methodological*, 54:17–36, 2013.

[75] P.T. Harker. *Predicting intercity freight flows*. VNU Science Press, Utrecht, The Netherlands, 1987.

[76] I. Harris, Y. Wang, and H. Wang. ICT in multimodal transport and technological trends: Unleashing potential for the future. *International Journal of Production Economics*, 159:88–103, 2015.

[77] A. Hegyi. *Model predictive control for integrating traffic control measures*. Ph.D thesis, Delft University of Technology, Delft, The Netherlands, February 2004.

[78] A. Hegyi, B. De Schutter, and H. Hellendoorn. Model predictive control for optimal coordination of ramp metering and variable speed limits. *Transportation Research Part C: Emerging Technologies*, 13(3):185 – 209, 2005.

[79] S. Hernández, S. Peeta, and G. Kalafatas. A less-than-truckload carrier collaboration planning problem under dynamic capacities. *Transportation Research Part E: Logistics and Transportation Review*, 47(6):933–946, 2011.

[80] K. Holmström, A.O. Göran, and M.M. Edvall. *User's guide for TOMLAB/SNOPT*. Tomlab Optimization Inc., 2008.

[81] Tomlab Optimization Inc. *TOMLAB Release 8.0*. Tomlab Optimization, Inc., Seattle, Washington, USA, 2014.

[82] Infrabel. Network statement – C.1 map of the Belgian railway infrastructure. July 2014. URL http://www.infrabel.be/en/documents/c-maps/c1-map-belgian-railway-infrastructure.

[83] Infrabel. Network statement – E.1 distances between stations and crossings. June 2014. URL http://www.infrabel.be/en/documents/e-technical-documents/e1-distances-between-stations-and-crossings.

[84] I. Jarzemskiene. The evolution of intermodal transport research and its development issues. *Transport*, 22(4):296–306, 2007.

[85] B. Jourquin. A multi-flow multi-modal assignment procedure on large freight transportation networks. *Studies in Regional Science*, 35(4):929–945, 2006.

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

[87] M. Kögel and R. Findeisen. Cooperative distributed MPC using the alternating direction multiplier method. In *Proceedings of the 8th IFAC Symposium on Advanced Control of Chemical Processes*, pages 445–450, Singapore, July 2012.

[88] A. Kotsialos, M. Papageorgiou, M. Mangeas, and H. Haj-Salem. Coordinated and integrated control of motorway networks via non-linear optimal control. *Transportation Research Part C: Emerging Technologies*, 10(1):65–84, 2002.

[89] A. Kotsialos, M. Papageorgiou, and A. Messmer. Optimal coordinated and integrated motorway network traffic control. In *Proceedings of 14th International Symposium on transportation and Traffic Theory*, pages 621–644, Jerusalem, Israel, 1999.

[90] M.A. Krajewska, H. Kopfer, G. Laporte, S. Ropke, and G. Zaccour. Horizontal cooperation among freight carriers: Request allocation and profit sharing. *Journal of the Operational Research Society*, 59(11):1483–1491, 2008.

[91] S. Leirens, C. Zamora, R.R. Negenborn, and B. De Schutter. Coordination in urban water supply networks using distributed model predictive control. In *Proceedings of the 2010 American Control Conference (ACC 2010)*, pages 3957–3962, Baltimore, MD, June 2010.

[92] L. Li, R.R. Negenborn, and B. De Schutter. A general framework for modeling intermodal transport networks. In *Proceedings of the 10th IEEE International Conference on Networking, Sensing and Control (ICNSC 2013)*, pages 579–585, Paris, France, April 2013.

[93] L. Li, R.R. Negenborn, and B. De Schutter. A sequential linear programming approach for flow assignment in intermodal freight transport. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 1124–1230, The Hague, The Netherlands, October 2013.

[94] L. Li, R.R. Negenborn, and B. De Schutter. A receding horizon approach for container flow assignment in intermodal freight transport. In *Proceedings of the 93rd Annual Meeting of the Transportation Research Board*, Washington, DC, January 2014.

[95] L. Li, R.R. Negenborn, and B. De Schutter. Receding horizon approach for container flow assignment in intermodal freight transport. *Transportation Research Record*, 2410:132–140, 2014.

[96] L. Li, R.R. Negenborn, and B. De Schutter. Multi-agent cooperative transport planning of intermodal freight transport. In *Proceedings of the 17th IEEE International Conference on Intelligent Transport Systems (ITSC 2014)*, pages 2465–2471, Qingdao, China, October 2014.

[97] L. Li, R.R. Negenborn, and B. De Schutter. Intermodal freight transport planning – A receding horizon control approach. *Transportation Research Part C: Emerging Technologies*, 60:77–95, 2015.

[98] L. Li, R.R. Negenborn, and B. De Schutter. Pricing intermodal freight transport services: A cost-plus-pricing strategy. In *Proceedings of the 6th International Conference on Computational Logistics (ICCL'15)*, pages 541–556, Delft, The Netherlands, September 2015.

[99] L. Li, R.R. Negenborn, and B. De Schutter. Distributed model predictive control for cooperative synchromodal container transport. April 2016. Submitted to Transportation Research Part E: Logistics and Transportation review, under second review.

[100] S. Lin, T. Ling, and Y. Xi. Model predictive control for large-scale urban traffic networks with a multi-level hierarchy. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 211–216, The Hague, The Netherlands, October 2013.

[101] J. Linderoth and T. Ralphs. *Noncommercial software for mixed-integer linear programming*. Optimization Online, 2005.

[102] J. Liu, D.M. De La Peña, and P.D. Christofides. Distributed model predictive control of nonlinear process systems. *AIChE Journal*, 55(5):1171–1184, 2009.

[103] S. Logghe. *Dynamic modelling of heterogeneous vehicular traffic*. Ph.D thesis, University of Leuven, Heverlee, Belgium, June 2003.

[104] I.M.P.J. Lucassen and I. Dogger. *Synchromodality pilot study – Identifiction of bottlenecks and possibilities for a network between Rotterdam, Moerdijk and Tilburg*. TNO, The Netherlands, 2013.

[105] C. Macharis and Y.M. Bontekoning. Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research*, 153(2):400–416, 2004.

[106] J. Maciejowski. *Predictive control with constraints*. Prentice-Hall, Harlow, UK, 2002.

[107] J.M. Maestre and R.R. Negenborn, editors. *Distributed Model Predictive Control Made Easy*. Springer, 2014.

[108] J.M. Maestre, D.M. de la Peña, and E.F. Camacho. Distributed MPC: A supply chain case study. In *Proceedings of the 48th IEEE Conference on Decision and Control*, pages 7099–7104, Shanghai, China, December 2009.

[109] L.C. Maia and A.F. do Couto. An innovative freight traffic assignment model for multimodal networks. *Computers in Industry*, 64(2):121–127, 2013.

[110] N.I. Marcos, J.F. Forbes, and M. Guay. Price-driven coordination of distributed MPC controllers for constrained dynamic systems. *Industrial and Engineering Chemistry Research*, 52(49):17451–17464, 2013.

[111] R. Martí. Advanced multi-start methods. International Series in Operations Research & Management Science: Handbook of Metaheuristics, chapter 9, pages 265–281. Elsevier, New York, USA, 2010.

[112] A.D. May. *Traffic flow fundamentals*. Prentice Hall, Englewood Cliffs, New Jersey, 1990.

[113] P. Mc Namara, R.R. Negenborn, B. De Schutter, and G. Lightbody. Optimal coordination of a multiple HVDC link system using centralized and distributed control. *IEEE Transactions on Control Systems Technology*, 21(2):302–314, 2013.

[114] R. McFedries. Maasvlakte 2 to become bustling sustainable business centre. *Maritime by Holland*, 60(7):72–74, 2011.

[115] M.R.K. Mes and M.-E. Iacob. Synchromodal transport planning at a logistics service provider. In H. Zijm, M. Klumpp, U. Clausen, and M.t. Hompel, editors, *Logistics and Supply Chain Innovation*, Lecture Notes in Logistics, pages 23–36. Springer International Publishing, 2016.

[116] J.F.C. Mota, J.M.F. Xavier, P.M.Q. Aguiar, and M. Puschel. Distributed ADMM for model predictive control and congestion control. In *Proceedings of the 51st IEEE Conference on Decision and Control*, pages 5110–5115, Hawaii, USA, December 2012.

[117] J.L. Nabais, R.R. Negenborn, R.B.C. Benitez, and M.A. Botto. Setting cooperative relations among terminals at seaports using a multi-agent system. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 1731–1736, The Hague, The Netherlands, October 2013.

[118] J.L. Nabais, R.R. Negenborn, and M.A. Botto. Hierarchical model predictive control for optimizing intermodal container terminal operations. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 708–713, The Hague, The Netherlands, October 2013.

[119] J.L. Nabais, R.R. Negenborn, R.B. Carmona Benítez, and M.A. Botto. Achieving transport modal split targets at intermodal freight hubs using a model predictive approach. *Transportation Research Part C: Emerging Technologies*, 60:278–297, 2015.

[120] NEA. *Vergelijkingskader modaliteiten*. Rijswijk, The Netherlands, 2011.

[121] R.R. Negenborn. *Multi-agent model predictive control with applications to power networks.* Ph.D thesis, Delft University of Technology, Delft, The Netherlands, December 2007.

[122] R.R. Negenborn, B. De Schutter, and J. Hellendoorn. Multi-agent model predictive control for transportation networks: Serial versus parallel schemes. *Engineering Applications of Artificial Intelligence*, 21(3):353–366, 2008.

[123] R.R. Negenborn, P.-J. van Overloop, T. Keviczky, and B. De Schutter. Distributed model predictive control of irrigation canals. *Networks and Heterogeneous Media*, 4(2):359–380, 2009.

[124] T.E. Notteboom. Container shipping and ports: An overview. *Review of Network Economics*, 3(2):86–106, 2004.

[125] T.E. Notteboom and J.-P. Rodrigue. Containerisation, box logistics and global supply chains: The integration of ports and liner shipping networks. *Maritime Economics and Logistics*, 10(1-2):152–174, 2008.

[126] T.E. Notteboom and P. Verhoeven. The awarding of seaport terminals to private operators: European practices and policy implications. *European Transport - Trasporti Europei*, (45):83–101, 2010.

[127] Technical University of Crete and A. Messmer. *METANET – A simulation program for motorway networks.* Technical University of Crete, Dynamic Systems and Simulation Laboratory and A. Messmer, November 2013.

[128] S.K. Pandey, S.R. Mohanty, and N. Kishor. A literature survey on load-frequency control for conventional and distribution generation power systems. *Renewable and Sustainable Energy Reviews*, 25:318–334, 2013.

[129] M. Papageorgiou, J.-M. Blosseville, and H. Hadj-Salem. Macroscopic modelling of traffic flow on the Boulevard Périphérique in Paris. *Transportation Research Part B: Methodological*, 23(1):29–47, 1989.

[130] P.M. Pardalos and M.G.C. Resende, editors. *Handbook of Applied Optimization.* Oxford University Press, Oxford, UK, 2002.

[131] Port of Rotterdam Authority. Port vision 2030: Port compass. December 2011. URL http://www.portofrotterdam.com/en/Port/port-in-general/port-vision-2030/Documents/Port-Vision-2030.pdf.

[132] ProRail. Network statement 2014 combined network – version 1.2. August 2013. URL http://www.prorail.nl/sites/default/files/2782585_v1.5_nv2013_gemengde_net_9aug2013.pdf.

[133] C. Puettmann and H. Stadtler. A collaborative planning approach for intermodal freight transportation. *OR Spectrum*, 32(3):809–830, 2010.

[134] W. Qi, J. Liu, and P.D. Christofides. A distributed control framework for smart grid development: Energy/water system optimal operation and electric grid integration. *Journal of Process Control*, 21(10):1504–1516, 2011.

[135] W. Qi, J. Liu, and P.D. Christofides. Distributed supervisory predictive control of distributed wind and solar energy systems. *IEEE Transactions on Control Systems Technology*, 21(2):504–512, 2013.

[136] J. Rawlings and D. Mayne. *Model Predictive Control: Theory and Design*. Nob Hill, Madison, Wisconsin, 2009.

[137] V. Reis. Should we keep on renaming a +35-year-old baby? *Journal of Transport Geography*, 46:173–179, 2015.

[138] C.B. Royo. *Generalized Unit Commitment by The Radar Multiplier Method*. Ph.D thesis, Technical University of Catalonia, Barcelona, Spain, July 2001.

[139] N. Saeed. Cooperation among freight forwarders: Mode choice and intermodal freight transport. *Research in Transportation Economics*, 42(1):77–86, 2013.

[140] N. Saeed and O.I. Larsen. An application of cooperative game among container terminals of one port. *European Journal of Operational Research*, 203(2):393–403, 2010.

[141] H. Sarimveis, P. Patrinos, C.D. Tarantilis, and C.T. Kiranoudis. Dynamic modeling and control of supply chain systems: A review. *Computers and Operations Research*, 35(11): 3530–3561, 2008.

[142] R. Scattolini. Architectures for distributed and hierarchical model predictive control – A review. 19(5):723–731, May 2009.

[143] G. Schildbach and M. Morari. Scenario-based model predictive control for multi-echelon supply chain management. *European Journal of Operational Research*, 252 (2):540–549, 2016.

[144] K. Sharypova. *Optimization of hinterland intermodal container transportation*. Ph.D thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, January 2014.

[145] Y. Sheffi. *Urban Transportation networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice-Hall, Englewood Cliffs, New Jersey, 1985.

[146] V. Spudić, C. Conte, M. Baotić, and M. Morari. Cooperative distributed model predictive control for wind farms. *Optimal Control Applications and Methods*, 36(3): 333–352, 2015.

[147] M. SteadieSeifi, N.P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi. Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233(1):1–15, 2014.

[148] T.H. Summers and J. Lygeros. Distributed model predictive consensus via the alternating direction method of multipliers. In *Proceedings of the 50th Annual Allerton Conference on Communication, Control, and Computing*, pages 79–84, Illinois, USA, October 2012.

[149] L. Tavasszy and G. De Jong, editors. *Modelling Freight Transport*. Elsevier, London, UK, 2013.

[150] L. Tavasszy, B. Behdani, and R. Konings. Intermodality and synchromodality. *Available at SSRN: http://ssrn.com/abstract=2592888 or http://dx.doi.org/10.2139/ssrn.2592888*, April 2015.

[151] F. Tazelaar and H. Peters. APM terminals Maasvlakte II: The next big step in fully automated container terminals. *Maritime by Holland*, 61(3):69–71, 2012.

[152] TKI DINALOG. *Synchromodal Transport*. Breda, The Netherlands, December 2015. URL http://www.dinalog.nl/en/themes/synchromodal/.

[153] P. Toth and D. Vigo. *The vehicle routing problem*. Society for Industrial and Applied Mathematics, Philadelphia, Pennsylvania, 2001.

[154] UNCTAD. Review of maritime transportation. Paper presented at the united nations conference on trade and development. October 2015. URL http://unctad.org/en/PublicationsLibrary/rmt2015_en.pdf.

[155] UN/ECE. *'Terminology on Combined Goods'*. United Nations, New York and Geneva, 2001.

[156] M. van den Driest. *Reducing CO2-emission of container transport in The Netherlands*. MSc thesis, Delft University of Technology, Delft, The Netherlands, October 2010.

[157] M.R. van der Horst and P.W. de Langen. Coordination in hinterland transport chains: A major challenge for the seaport community. *Maritime Economics and Logistics*, 10 (1-2):108–129, 2008.

[158] M.R. van der Horst and L.M. van der Lugt. Coordination mechanisms in improving hinterland accessibility: Empirical analysis in the port of rotterdam. *Maritime Policy and Management*, 38(4):415–435, 2011.

[159] P.-J. van Overloop, R.R. Negenborn, B. De Schutter, and N.C. van de Giesen. Predictive control for national water flow optimization in The Netherlands. In R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, editors, *Intelligent Infrastructures*, volume 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, chapter 17, pages 439–461. Springer Netherlands, 2010.

[160] B. van Riessen. *Planning of hinterland transportation in the EGS network*. MSc thesis, Delft University of Technology, Delft, The Netherlands, February 2013.

[161] B. van Riessen, R.R. Negenborn, and R. Dekker. Synchromodal container transportation: An overview of current topics and research opportunities. In *Proceedings of the 6th International Conference on Computational Logistics (ICCL'15)*, pages 386–397, Delft, The Netherlands, September 2015.

[162] B. van Riessen, R.R. Negenborn, R. Dekker, and G. Lodewijks. Service network design for an intermodal container network with flexible transit times and the possibility of using subcontracted transport. *International Journal of Shipping and Transport Logistics*, 7(4):457–478, 2015.

[163] B. van Riessen, R.R. Negenborn, G. Lodewijks, and R. Dekker. Impact and relevance of transit disturbances on planning in intermodal container networks using disturbance cost analysis. *Maritime Economics and Logistics*, 17(4):440–463, 2015.

[164] A.W. Veenstra, R.A. Zuidwijk, and E. van Asperen. The extended gate concept for container terminals: Expanding the notion of dry ports. *Maritime Economics and Logistics*, 14(1):14–32, 2012.

[165] A.N. Venkat, I.A. Hiskens, J.B. Rawlings, and S.J. Wright. Distributed MPC strategies with application to power system automatic generation control. *IEEE Transactions on Control Systems Technology*, 16(6):1192–1206, 2008.

[166] L. Verdonck, A.N. Caris, K. Ramaekers, and G.K. Janssens. Collaborative logistics from the perspective of road transportation companies. *Transport Reviews*, 33(6):700–719, 2013.

[167] K. Verweij. 'synchronic modalities – critical success factors'. In P.J. van der Sterre, editor, *EVO's Logistics Yearbook 2011*, pages 75–88. Rotterdam, The Netherlands, 2011.

[168] Y. Wan, A. Zhang, and A.C.L. Yuen. Urban road congestion, capacity expansion and port competition: Empirical analysis of US container ports. *Maritime Policy and Management*, 40(5):417–438, 2013.

[169] W. Wang and D.E. Rivera. Model predictive control for tactical decision-making in semiconductor manufacturing supply chain management. *IEEE Transactions on Control Systems Technology*, 16(5):841–855, 2008.

[170] X. Wang, H. Kopfer, and M. Gendreau. Operational transportation planning of freight forwarding companies in horizontal coalitions. *European Journal of Operational Research*, 237(3):1133–1141, 2014.

[171] H.P. Williams. *Model Building in Mathematical Programming*. John Wiley & Sons, Chichester, England, 4th edition, 1999.

[172] J. Xin, R.R. Negenborn, and G. Lodewijks. Hybrid MPC for balancing throughput and energy consumption in an automated container terminal. In *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, pages 1238–1244, The Hague, The Netherlands, October 2013.

[173] J. Xin, R.R. Negenborn, and G. Lodewijks. Energy-efficient container handling using hybrid model predictive control. *International Journal of Control*, 88(11):2327–2346, 2015.

[174] J. Xin, R.R. Negenborn, and G. Lodewijks. Event-driven receding horizon control for energy-efficient container handling. *Control Engineering Practice*, 39:45–55, 2015.

[175] Y.-C. Yang and S.-L. Chen. Determinants of global logistics hub ports: Comparison of the port development policies of Taiwan, Korea, and Japan. *Transport Policy*, 45: 179–189, 2016.

[176] G.-T. Yeo, M. Roe, and J. Dinwoodie. Evaluating the competitiveness of container ports in Korea and China. *Transportation Research Part A: Policy and Practice*, 42(6):910–921, 2008.

[177] I. Yperman. *The link transmission model for dynamic network loading.* Ph.D thesis, Katholieke Universiteit Leuven, Leuven, Belgium, June 2007.

[178] H. Zheng, R.R. Negenborn, and G. Lodewijks. Predictive path following with arrival time awareness for waterborne AGVs. *Transportation Research Part C: Emerging Technologies*, 2015.

[179] Z. Zhou, B. De Schutter, S. Lin, and Y. Xi. Multi-agent model-based predictive control for large-scale urban traffic networks using a serial scheme. *IET Control Theory and Applications*, 9(3):475–484, 2015.

[180] A. Ziliaskopoulos and W. Wardell. An intermodal optimum path algorithm for multimodal networks with dynamic arc travel times and switching delays. *European Journal of Operational Research*, 125(3):486–502, 2000.

Glossary

List of symbols and notations

Below follows a list of the most frequently used symbols and notations in this thesis.

$a_{i,j}^{\text{road}}$	model parameter of the speed-density relation model for link $l_{i,j}^{\text{road}}$
$a_{i,j}^{\text{road,truck}}$	model parameter of the multi-class version of the speed-density relation model for link $l_{i,j}^{\text{road}}$
b	positive scalar
$c_{i,d}$	typical transport cost from node i to destination node d
$c_{i,\text{store}}(k)$	container storage cost at node i for time step k
$c_{i,j}^{m,d}$	typical transport cost from link $l_{i,j}^{m}$ to destination node d
$c_{i,j,\text{distance}}^{m}(k)$	distance-dependent vehicle transport or modality change cost on link $l_{i,j}^{m}$ for time step k
$c_{i,j,\text{time}}^{m}(k)$	time-dependent vehicle transport or modality change costs on link $l_{i,j}^{m}$ for time step k
$C_{i,j}^{m,\text{in}}(k)$	maximum entering container flow of link $l_{i,j}^{m}$ for time step k
$C_{i,j}^{\text{rail,in}}(k)$	maximum entering container flow of link $l_{i,j}^{\text{rail}}$ for time step k
$C_{i,j}^{\text{water,in}}(k)$	maximum entering container flow of link $l_{i,j}^{\text{water}}$ for time step k
d	destination node indices
$d_{o,d}(k)$	volume of the transport demand with origin and destination pair (o,d) during time step k
$d_{i,o,d}^{\text{in}}(k)$	volume of the container flow corresponding to the transport demand with origin and destination pair (o,d), entering node $i=o$ from the outside of the network during time step k
$d_{i,o,d}^{\text{out}}(k)$	volume of the container flow corresponding to the transport demand with origin and destination pair (o,d), arriving at the final destination node $i=d$ during time step k
$\mathbf{d}(k)$	disturbances for time step k
$\tilde{\mathbf{d}}(k)$	disturbances for a prediction period $\left[kT_{\text{s}}, \left(k+N_{\text{p}}\right)T_{\text{s}}\right)$
$\bar{\mathbf{d}}$	disturbances for a planning period $\left[0, N_{\text{planning}}T_{\text{s}}\right)$
$\mathscr{G}(\mathscr{V},\mathscr{E},\mathscr{M})$	directed graph with node set $\mathscr{V}$, link set $\mathscr{E}$, and transport mode

	and modality change set $\mathcal{M}$
$\mathcal{G}_n(\mathcal{V}_n, \mathcal{E}_n, \mathcal{M}_n)$	directed graph with node set $\mathcal{V}_n$, link set $\mathcal{E}_n$, and transport mode and modality change set $\mathcal{M}_n$
h_i^{in}	maximal container loading rates of the equipment at node i
h_i^{out}	maximal container unloading rates of the equipment at node i
$h_{i,j,s}^{\text{rail}}$	container loading capacity of equipment at terminal i for serving train s that is scheduled to travel on link $l_{i,j}^{\text{rail}}$
$h_{i,j,s}^{\text{water}}$	container loading capacity of equipment at terminal i for serving barge s that is scheduled to travel on link $l_{i,j}^{\text{water}}$
i	node indices
j	node indices
J	total delivery cost
J_{com}	total number of floating-point numbers exchanged
$J_{\text{window}}^{\max}$	maximum value of the objective functions within a stopping time window
$J_{\text{window}}^{\text{mean}}$	mean value of the objective functions within a stopping time window
$J_{\text{window}}^{\min}$	minimum value of the objective functions within a stopping time window
J_{total}	total delivery cost of all operators
k	time step indices
k_{e}	time step indices
$\mathcal{K}_{\text{e}}(k)$	set of all time steps k_{e} satisfying $k_{\text{e}} \geq k - t_{i,j}^{m,\max}$ and $k_{\text{e}} \leq k-1$, at which if container flows enter link $l_{i,j}^{m}$, these container flows will leave this link during time step k
$k_{i,j,s}^{\text{rail,available}}$	index of time instant $k_{i,j,s}^{\text{rail,available}} T_{\text{s}}$, at which scheduled train s on railway link $l_{i,j}^{\text{rail}}$ becomes available at terminal i
$k_{i,j,s}^{\text{rail,arrival}}$	index of the time instant $k_{i,j,s}^{\text{rail,arrival}} T_{\text{s}}$, at which scheduled train s on railway link $l_{i,j}^{\text{rail}}$ arrives at terminal j
$k_{i,j,s}^{\text{rail,departure}}$	index of the time instant $k_{i,j,s}^{\text{rail,departure}} T_{\text{s}}$, at which scheduled train s on railway link $l_{i,j}^{\text{rail}}$ departures from terminal i
$k_{i,j,s}^{\text{water,available}}$	index of the time instant $k_{i,j,s}^{\text{water,available}} T_{\text{s}}$, at which scheduled barge s on inland waterway link $l_{i,j}^{\text{rail}}$ becomes available at terminal i
$k_{i,j,s}^{\text{water,arrival}}$	index of the time instant $k_{i,j,s}^{\text{water,arrival}} T_{\text{s}}$, at which scheduled barge s on inland waterway link $l_{i,j}^{\text{water}}$ arrives at terminal j
$k_{i,j,s}^{\text{water,departure}}$	index of the time instant $k_{i,j,s}^{\text{water,departure}} T_{\text{s}}$, at which scheduled barge s on inland waterway link $l_{i,j}^{\text{water}}$ departures from terminal i
$\mathbf{K}_n$	interconnecting output selection matrix of operator n for a single time step

$\tilde{\mathbf{K}}_n$	interconnecting output selection matrix of operator n for a prediction period
l	indices of steps for MPC controller
$l_{i,j}^m$	link from node i to node j with modality m
$l_{i,j}^{\text{road}}$	freeway link from node i to node j
$l_{i,j}^{\text{rail}}$	railway link from node i to node j
$l_{i,j}^{\text{water}}$	inland waterway link from node i to node j
$L_{i,j}^{\text{road}}$	length of freeway link $l_{i,j}^{\text{road}}$
L_{other}	typical length of other vehicles on freeways
L_{truck}	typical length of freight trucks on freeways
m	modality indices, or operator/subnetwork indices
$\max(N_1, N_2)$	maximum number of the two numbers, i.e., N_1 and N_2
$\min(N_1, N_2)$	minimum number of the two numbers, i.e., N_1 and N_2
$\min J(\cdot)$	minimum value of the function $J(\cdot)$
$\mathscr{M}_1$	set of modalities
$\mathscr{M}_2$	set of modality changes
n	operator/subnetwork indeces
$N_{\text{iteration}}^{\max}$	maximum iteration number
N_{link}	cardinality of the link set
$N_{\text{link}}^{\text{road}}$	cardinality of the freeway link set
$N_{\text{link}}^{\text{rail}}$	cardinality of the railway link set
$N_{\text{link}}^{\text{water}}$	cardinality of the inland waterway link set
N_{node}	cardinality of the node set
N_{od}	cardinality of the origin destination pair set of the transport demand
N_{p}	prediction horizon
N_{planning}	number of time steps in a planning period
N_{rail}	cardinality of the train node set
N_{road}	cardinality of the truck node set
N_{store}	cardinality of the storage yard node set
N_{sub}	number of transport operators/subnetworks
N_{water}	cardinality of the barge node set
N_{window}	number of iterations in the stopping window
$\mathscr{N}_i^{\text{in}}$	set of incoming links of node i
$\mathscr{N}_i^{\text{out}}$	set of outgoing links of node i
$\mathscr{N}_n^{\text{nei}}$	set of all neighboring operators/subnetworks of operator/subnetwork n
o	origin node indices
$\mathscr{O}_{\text{od}}$	set of all origin and destination pairs of the transport demand
$q_{i,j,o,d}^{m,\text{in}}(k)$	volume of the container flow corresponding to the transport demand with origin and destination pair (o,d), entering link $l_{i,j}^m$ for time step k

$q_{i,j,o,d}^{m,\text{out}}(k)$	volume of the container flow corresponding to the transport demand with origin and destination pair (o,d), leaving link $l_{i,j}^{m}$ for time step k
$r_{i,d}$	typical transport time from node i to destination node d
$r_{i,j}^{m,d}$	typical transport time from link $l_{i,j}^{m}$ to destination node d
round$(N1)$	nearest integer of the number N1
s	train and barge indices, or iteration indices
$s^{'}$	train and barge indices
S_i	storage capacity at node i
$S_{i,j,s}^{\text{rail}}$	capacity of train s that is scheduled to travel on link $l_{i,j}^{\text{rail}}$
$S_{i,j,s}^{\text{water}}$	capacity of barge s that is scheduled to travel on link $l_{i,j}^{\text{water}}$
$\mathscr{S}_{i,j}^{\text{rail}}$	set of trains that are scheduled to travel on link $l_{i,j}^{\text{rail}}$
$\mathscr{S}_{i,j}^{\text{water}}$	set of barges that are scheduled to travel on link $l_{i,j}^{\text{water}}$
$t_{i,j}^{m}(k)$	number of time steps contained in the transport time on link $l_{i,j}^{m}$ at time kT_{s}
$t_{i,j}^{\text{rail}}(k)$	number of time steps contained in the transport time on railway link $l_{i,j}^{\text{rail}}$ at time kT_{s}
$t_{i,j}^{\text{road}}(k)$	number of time steps contained in the transport time on freeway link $l_{i,j}^{\text{road}}$ at time kT_{s}
$t_{i,j}^{\text{water}}(k)$	number of time steps contained in the transport time on inland waterway link $l_{i,j}^{\text{water}}$ at time kT_{s}
$t_{i,j}^{m,\max}$	number of time steps contained in the maximum transport time on link $l_{i,j}^{m}$
$t_{i,j}^{\text{rail},\max}$	number of time steps contained in the maximum transport time on railway link $l_{i,j}^{\text{rail}}$
$t_{i,j}^{\text{road},\max}$	number of time steps contained in the maximum transport time on freeway link $l_{i,j}^{\text{road}}$
$t_{i,j}^{\text{water},\max}$	number of time steps contained in the maximum transport time on inland waterway link $l_{i,j}^{\text{water}}$
$t_{i,j,\text{traveling}}^{\text{rail}}(k)$	number of time steps that container flows will move on railway link $l_{i,j}^{\text{rail}}$, if they enter this link during time step k
$t_{i,j,\text{waiting}}^{\text{rail}}(k)$	number of time steps that container flows will spend waiting for leaving terminal i, if they enter railway link $l_{i,j}^{\text{rail}}$ during time step k
$t_{i,j,\text{traveling}}^{\text{water}}(k)$	number of time steps that container flows will move on inland waterway link $l_{i,j}^{\text{water}}$, if they enter this link during time step k
$t_{i,j,\text{waiting}}^{\text{water}}(k)$	number of time steps that container flows will spend waiting for leaving terminal i, if they enter inland waterway link $l_{i,j}^{\text{water}}$ during time step k
T_{allowed}	maximum allowed computation time for a single time step
T_{com}	total amount of time taken by operators to perform coordinated

	planning in the whole planning period
$T_{i,j}^{m}(k)$	transport time on link $l_{i,j}^{m}$ at time kT_{s}
T_{s}	length of time step
$\mathbf{t}^{\mathrm{road}}(k)$	number of time steps contained in the transport times of links in the road network for time step k
$\mathbf{t}_{\mathrm{fixed}}^{\mathrm{truck}}(k)$	fixed transport times on freeway links for time step k
$\mathbf{t}_{\mathrm{initial}}^{\mathrm{truck}}(k)$	initial transport times on freeway links for time step k
$\mathbf{t}_{\mathrm{typical}}^{\mathrm{truck}}(k)$	typical transport times on freeway links for time step k
$u_{i,j,o,d}^{m}(k)$	container flow corresponding to the transport demand with origin and destination pair (o,d), leaving node i through link $l_{i,j}^{m}$ during time step k
$\mathbf{u}(k)$	control actions for time step k
$\tilde{\mathbf{u}}(k)$	control actions for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\bar{\mathbf{u}}$	control actions for a planning period $\left[0,N_{\mathrm{planning}}T_{\mathrm{s}}\right)$
$v_{i,j}^{\mathrm{road}}(k)$	average speed on link $l_{i,j}^{\mathrm{road}}$ for time step k
$v_{i,j}^{\mathrm{road,truck}}(k)$	average speed of the freight truck flows on link $l_{i,j}^{\mathrm{road}}$ for time step k
$v_{i,j,\mathrm{free}}^{\mathrm{road}}$	free flow speed on link $l_{i,j}^{\mathrm{road}}$
$v_{i,j,\mathrm{free}}^{\mathrm{road,truck}}$	free flow speed of the freight truck flows on link $l_{i,j}^{\mathrm{road}}$
$v_{i,j,\mathrm{min}}^{\mathrm{road}}$	minimum speed on link $l_{i,j}^{\mathrm{road}}$
$\mathcal{V}_{\mathrm{road}}$	set of truck nodes
$\mathcal{V}_{\mathrm{rail}}$	set of train nodes
$\mathcal{V}_{\mathrm{water}}$	set of barge nodes
$\mathcal{V}_{\mathrm{store}}$	set of storage yard nodes
$\mathbf{v}_{n}(k)$	remaining variables influencing the dynamics of subnetwork n for time step k
$\tilde{\mathbf{v}}_{n}(k)$	remaining variables influencing the dynamics of subnetwork n for prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\mathbf{w}_{\mathrm{in},n}(k)$	input interconnecting variables of operator n for time step k
$\mathbf{w}_{\mathrm{out},n}(k)$	output interconnecting variables of operator n for time step k
$\mathbf{w}_{\mathrm{in},m,n}(k)$	input interconnecting variables of operator n to its neighboring operator m for time step k
$\mathbf{w}_{\mathrm{out},m,n}(k)$	output interconnecting variables of operator n to its neighboring operator m for time step k
$\tilde{\mathbf{w}}_{\mathrm{in},n}(k)$	input interconnecting variables of operator n for a prediction horizon $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\tilde{\mathbf{w}}_{\mathrm{out},n}(k)$	output interconnecting variables of operator n for a prediction horizon $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\tilde{\mathbf{w}}_{\mathrm{in},m,n}(k)$	input interconnecting variables of operator n to its neighboring operator m for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\tilde{\mathbf{w}}_{\mathrm{out},m,n}(k)$	output interconnecting variables of operator n to its neighboring operator m for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$

$\tilde{\mathbf{w}}^{s}_{\mathrm{in},m,n}(k)$	input interconnecting variables of operator n to its neighboring operator m for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$ at iteration s
$\tilde{\mathbf{w}}^{s}_{\mathrm{out},m,n}(k)$	output interconnecting variables of operator n to its neighboring operator m for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$ at iteration s
$x_{i,o,d}(k)$	number of containers corresponding to the transport demand with origin and destination pair (o,d), and staying at node i at time kT_{s}
$x^{m}_{i,j,o,d}(k)$	number of containers corresponding to the transport demand with origin and destination pair (o,d), traveling on link $l^{m}_{i,j}$ at time kT_{s}
$\mathbf{x}(k)$	system states for time step k
$\tilde{\mathbf{x}}(k)$	system states for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\bar{\mathbf{x}}$	system states for a planning period $\left[0,N_{\mathrm{planning}}T_{\mathrm{s}}\right)$
$y^{m}_{j,i,o,d}(k)$	container flow corresponding to the transport demand with origin and destination pair (o,d), entering node i through link $l^{m}_{j,i}$ during time step k
$\mathbf{y}(k)$	system outputs for time step k
$\tilde{\mathbf{y}}(k)$	system outputs for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\bar{\mathbf{y}}$	system outputs for a planning period $\left[0,N_{\mathrm{planning}}T_{\mathrm{s}}\right)$
$\tilde{\mathbf{z}}(k)$	global optimization variables for a prediction period $\left[kT_{\mathrm{s}},\left(k+N_{\mathrm{p}}\right)T_{\mathrm{s}}\right)$
$\tilde{\mathbf{z}}_{n}(k)$	operator n's local copies of some components of $\tilde{\mathbf{z}}(k)$
$\tilde{\mathbf{z}}_{n,m}(k)$	operator n's local copies of some components of $\tilde{\mathbf{z}}(k)$ shared with operator m
$\tilde{\mathbf{z}}^{s}_{n}(k)$	operator n's local copies of some components of $\tilde{\mathbf{z}}(k)$ at iteration s
α	value of time
ρ	penalty parameter
$\rho^{\mathrm{road}}_{i,j}(k)$	traffic density on freeway link $l^{\mathrm{road}}_{i,j}$
$\rho^{\mathrm{road}}_{i,j,\mathrm{crit}}$	critical density on freeway link $l^{\mathrm{road}}_{i,j}$
$\rho^{\mathrm{road,max}}_{i,j}$	maximum allowed traffic density on link $l^{\mathrm{road}}_{i,j}$
$\rho^{\mathrm{road,other}}_{i,j}(k)$	traffic density that is not induced by freight trucks operated by the transport operator on link $l^{\mathrm{road}}_{i,j}$ for time step k
$\rho^{\mathrm{road,total}}_{i,j}(k)$	total traffic density on link $l^{\mathrm{road}}_{i,j}$ for time step k
$\lambda^{\mathrm{road}}_{i,j}$	number of lanes of freeway link $l^{\mathrm{road}}_{i,j}$
$\boldsymbol{\lambda}_{\mathrm{in},m,n}$	Lagrangian multipliers associated with the interconnecting constraints between operator n and operator m
$\boldsymbol{\lambda}^{s}_{\mathrm{in},m,n}$	Lagrangian multipliers associated with the interconnecting constraints between operator n and operator m at iteration s
ε	iteration stopping threshold
$\lvert\cdot\rvert$	cardinality operation

List of abbreviations

The following abbreviations are used in this thesis:

ADMM	Alternating Direction Method of Multipliers
ALR	Augmented Lagrangian Relaxation
AON	All-Or-Nothing
CMPFC	Coordinated Model Predictive container Flow Control
DMPC	Distributed Model Predictive Control
DMPFC	Distributed Model Predictive container Flow Control
ICT	Information and Communication Technologies
IFTN	Intermodal Freight Transport Network
ILP	Iterative Linear Programming
LCAT	Linear Container Allocation model with Time-restrictions
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MLD	Mixed Logical Dynamic
MPC	Model Predictive Control
MPFC	Model Predictive container Flow Control
NFP	Network Flow Planning
OR	Operation Research
PWA	Piecewise Affine
QP	Quadratic Programming
SND	Service Network Design
SQP	Sequential Quadratic Programming
TEU	Twenty-foot Equivalent Unit

TRAIL Thesis Series

The following list contains the most recent dissertations in the TRAIL Thesis Series. For a complete overview of more than 100 titles see the TRAIL website: www.rsTRAIL.nl.

The TRAIL Thesis Series is a series of the Netherlands TRAIL Research School on transport, infrastructure and logistics.

Li, L., *Coordinated Model Predictive Control of Synchromodal Freight Transport Systems*, T2016/9, June 2016, TRAIL Thesis Series, the Netherlands

Vonk Noordegraaf, D.M., *Road Pricing Policy Implementation*, T2016/8, June 2016, TRAIL Thesis Series, the Netherlands

Liu, S., *Modeling, Robust and Distributed Model Predictive Control for Freeway Networks*, T2016/7, May 2016, TRAIL Thesis Series, the Netherlands

Calvert, S.C., *Stochastic Macroscopic Analysis and Modelling for Traffic Management*, T2016/6, May 2016, TRAIL Thesis Series, the Netherlands

Sparing, D., *Reliable Timetable Design for Railways and Connecting Public Transport Services*, T2016/5, May 2016, TRAIL Thesis Series, the Netherlands

Rasouli, S, *Uncertainty in Modeling Activity-Travel Demand in Complex Urban Systems*, T2016/4, March 2016, TRAIL Thesis Series, the Netherlands

Vries, J. de, *Behavioral Operations in Logistics*, T2016/3, February 2016, TRAIL Thesis Series, the Netherlands

Goñi-Ros, B., *Traffic Flow at Sags: Theory, Modeling and Control*, T2016/2, March 2016, TRAIL Thesis Series, the Netherlands

Khademi, E., *Effects of Pricing Strategies on Dynamic Repertoires of Activity-Travel Behaviour*, T2016/1, February 2016, TRAIL Thesis Series, the Netherlands

Cong, Z., *Efficient Optimization Methods for Freeway Management and Control*, T2015/17, November 2015, TRAIL Thesis Series, the Netherlands

Kersbergen, B., *Modeling and Control of Switching Max-Plus-Linear Systems: Rescheduling of railway traffic and changing gaits in legged locomotion*, T2015/16, October 2015, TRAIL Thesis Series, the Netherlands

Brands, T., *Multi-Objective Optimisation of Multimodal Passenger Transportation Networks*, T2015/15, October 2015, TRAIL Thesis Series, the Netherlands

Ardiç, Özgül, *Road Pricing Policy Process: The interplay between policy actors, the media and*

public, T2015/14, September 2015, TRAIL Thesis Series, the Netherlands

Xin, J., *Control and Coordination for Automated Container Terminals*, T2015/13, September 2015, TRAIL Thesis Series, the Netherlands

Anand, N., *An Agent Based Modelling Approach for Multi-Stakeholder Analysis of City Logistics Solutions*, T2015/12, September 2015, TRAIL Thesis Series, the Netherlands

Hurk, E. van der, *Passengers, Information, and Disruptions*, T2015/11, June 2015, TRAIL Thesis Series, the Netherlands

Davydenko, I., *Logistics Chains in Freight Transport Modelling*, T2015/10, May 2015, TRAIL Thesis Series, the Netherlands

Schakel, W., *Development, Simulation and Evaluation of In-car Advice on Headway, Speed and Lane*, T2015/9, May 2015, TRAIL Thesis Series, the Netherlands

Dorsser, J.C.M. van, *Very Long Term Development of the Dutch Inland Waterway Transport System: Policy analysis, transport projections, shipping scenarios, and a new perspective on economic growth and future discounting*, T2015/8, May 2015, TRAIL Thesis Series, the Netherlands

Hajiahmadi, M., *Optimal and Robust Switching Control Strategies: Theory, and applications in traffic management*, T2015/7, April 2015, TRAIL Thesis Series, the Netherlands

Wang, Y., *On-line Distributed Prediction and Control for a Large-scale Traffic Network*, T2015/6, March 2015, TRAIL Thesis Series, the Netherlands

Vreeswijk, J.D., *The Dynamics of User Perception, Decision Making and Route Choice*, T2015/5, February 2015, TRAIL Thesis Series, the Netherlands

Lu, R., *The Effects of Information and Communication Technologies on Accessibility*, T2015/4, February 2015, TRAIL Thesis Series, the Netherlands

Ramos, G. de, *Dynamic Route Choice Modelling of the Effects of Travel Information using RP Data*, T2015/3, February 2015, TRAIL Thesis Series, the Netherlands

Sierzchula, W.S., *Development and Early Adoption of Electric Vehicles: Understanding the tempest*, T2015/2, January 2015, TRAIL Thesis Series, the Netherlands

Vianen, T. van, *Simulation-integrated Design of Dry Bulk Terminals*, T2015/1, January 2015, TRAIL Thesis Series, the Netherlands

Risto, M., *Cooperative In-Vehicle Advice: A study into drivers' ability and willingness to follow tactical driver advice*, T2014/10, December 2014, TRAIL Thesis Series, the Netherlands

Djukic, T., *Dynamic OD Demand Estimation and Prediction for Dynamic Traffic Management*, T2014/9, November 2014, TRAIL Thesis Series, the Netherlands

Chen, C., *Task Complexity and Time Pressure: Impacts on activity-travel choices*, T2014/8, November 2014, TRAIL Thesis Series, the Netherlands

Summary

Coordinated Model Predictive Control of Synchromodal Freight Transport Systems

In global freight transport, major deep-sea ports act as gateways for import and export cargoes for certain geographical areas, such as the Port of Rotterdam for North and West Europe. These geographical areas are called the hinterlands of the deep-sea ports. Hinterland transport among deep-sea ports and inland terminals has been facing challenges due to increasing cargo volumes, limited capacities of transport infrastructures, traffic congestion on freeways, traffic emission issues, etc. Intermodal freight transport operators strive to organize hinterland transport in an efficient and sustainable way with the integrated use of different modalities (e.g., trucks, trains, barges) over an Intermodal Freight Transport Network (IFTN). Synchromodal freight transport moves one step forward from intermodal freight transport by adopting the mode-free booking concept and allowing flexible selection and timely switching among multiple avaliable modalities at anytime during the freight transport process based on the latest logistics information, e.g., the transport demand, traffic information, available transport capacities in the transport process.

The main focus of this thesis is on control and coordinating of container flows for synchromodal freight transport of intermodal freight transport operators that own or hire transport vehicles, e.g., trucks, trains, and barges, and provide shippers with synchromodal container transport services over an IFTN. We adopt a systems and control approach, for which we first propose two discrete-time IFTN models to represent key characteristics of intermodal freight transport systems among deep-sea terminals and inland terminals at the tactical container flow level. Model predictive control and distributed model predictive control are then investigated for synchromodal freight transport planning of a single transport operator and for coordinated synchromodal freight transport planning among multiple transport operators, respectively. The main topics investigated in this thesis are summarized as follows:

- Models for intermodal freight transport networks
  Key characteristics of intermodal freight transport systems are modality changes at intermodal terminals, physical capacity constraints of terminals and transport connections, time-dependent transport times on freeways, and time schedules for trains and barges. We propose two discrete-time IFTN models. The first linear IFTN model captures the above key characteristics at the tactical container flow level. The second load-dependent IFTN model extends the linear IFTN model to include the impact of freight trucks operated by the transport operator on the freeway transport

times with a multi-class version of the nonlinear and non-convex speed-density relation model. Moreover, a single-region IFTN benchmark system and a multiple-region IFTN benchmark system are presented to illustrate the usage of network modeling approach and to evaluate the proposed container flow control approaches.

- Model predictive control for synchromodal freight transport planning
  We investigate synchromodal freight transport planning among deep-sea terminals and inland terminals for a single intermodal freight transport operator from a systems and control perspective with the use of the proposed IFTN models. The planning objective is to determine container flow control actions (i.e., to select routes and to determine flow assignments) in an IFTN such that a user-supplied objective function given by the transport operator is minimized. To deal with the dynamic transport demand and dynamic traffic conditions in the IFTN, a Model Predictive container Flow Control (MPFC) approach is proposed to control and to reassign container flows in a receding horizon way. For the linear IFTN model, this MPFC approach involves solving linear programming problems and is suited for computationally planning synchromodal freight transport in large-sized networks. For the load-dependent IFTN model, two solution methods, i.e., the multi-start Iterative Linear Programming (ILP) method and the multi-start Sequential Quadratic Programming (SQP) method, are proposed for solving the nonlinear and non-convex MPFC problem. For the MPFC problem with the load-dependent IFTN model in the single-region IFTN benchmark system, the multi-start ILP method achieves a planning performance that is comparable with that of the multi-start SQP method, while it significantly reduces the computation time.

- Distributed model predictive control for coordinated synchromodal freight transport planning
  We also consider coordinated synchromodal freight planning among multiple intermodal freight transport operators in different service areas. The coordination goal is to minimize the total freight delivery cost for serving the transport demand. Three Distributed Model Predictive container Flow Control (DMPFC) approaches are proposed for coordinated synchromodal freight transport planning: the *parallel* augmented Lagrangian relaxation based DMPFC approach, the *serial* augmented Lagrangian relaxation based DMPFC approach, and the Alternating Direction Method of Multipliers (ADMM) based DMPFC approach. When implementing these three DMPFC approaches with the linear IFTN model in the multiple-region IFTN benchmark system, all of them obtain the same total delivery cost as the total delivery cost of a central operator. This central operator is introduced for comparison purposes, and is assumed to be able to obtain all necessary planning information and to plan synchromodal freight transport in the whole network in a centralized way. The simulation results also show that the ADMM based-DMPFC approach takes the smallest actual computation time while the *serial* augmented Lagrangian relaxation based DMPFC approach requires the least iterations and information exchanges in the coordination process.

In short, this thesis investigates synchromodal freight transport planning and coordination problems and shows the potential of the proposed new container flow control

approaches in the realization of synchromodal freight transport planning.

Le Li

Samenvatting

Gecoördineerde Modelgebaseerde Voorspellende Sturing van Synchromodale Goederentransportsystemen

Voor globaal goederentransport werken grote zeehavens als toegangspoorten voor de import en export van goederen voor bepaalde geografische gebieden, zoals de Haven van Rotterdam voor Noord en West Europa. Deze geografische gebieden worden de achterlanden van de zeehavens genoemd. Achterlandtransport tussen zeehavens en binnenhavens wordt geconfronteerd met uitdagingen door toenemende goederenvolumes, beperkte capaciteit van transportinfrastructuur, verkeersopstoppingen op snelwegen, problemen met uitlaatgassen, enzovoort. Intermodale goederentransporteurs streven ernaar om het achterlandtransport te organiseren op een efficiënte en duurzame manier door het geïntegreerde gebruik van verschillende modaliteiten (vrachtwagens, treinen, schepen) over een intermodaal goederentransportnetwerk (een zogenaamd Intermodal Freight Transport Network (IFTN)). Synchromodaal goederentransport gaat een stap verder dan intermodaal goederentransport door het gebruik maken van amodaal reserveren, waardoor het flexibel selecteren en tijdig wisselen tussen de verschillende vervoerswijzen mogelijk wordt, op elk gewenst tijdstip tijdens het goederentransport, gebruikmakend van de nieuwste logistieke informatie, waaronder de transportvraag, verkeersinformatie en beschikbare transportcapaciteit.

Dit proefschrift richt zich op de regeling en coördinatie van containerstromen voor het synchromodale goederentransport van intermodale goederentransporteurs die transportvoertuigen, bijv., vrachtwagens, treinen, en schepen, bezitten of huren, en vervoerders voorzien van synchromodale containertransportservices over IFTNs. We stellen een systeem- en regeltechniek aanpak voor, waarvoor we eerst twee discrete-tijd IFTN modellen ontwikkelen die de belangrijkste karakteristieken van intermodaal goederentransport tussen zeehavens en binnenhavens representeren op het niveau van tactische containerstromen. Modelgebaseerde voorspellende regeltechniek en gedistribueerde modelgebaseerde voorspellende regeltechniek worden onderzocht voor, respectievelijk, de planning van synchromodaal goederentransport voor een enkele transporteur, en voor de gecoördineerde planning van synchromodale goederentransport tussen meerdere transporteurs. De belangrijkste onderwerpen die onderzocht worden zijn:

- Modellen voor intermodale goederentransportnetwerken
  Kernkarakteristieken van intermodale goederentransportsysten zijn het veranderen van vervoerswijze bij intermodale havens, fysieke capaciteitsbeperkingen van havens en transportverbindingen, tijdsafhankelijke transporttijden op snelwegen, en tijdsplanningen van treinen en schepen. We stellen twee discrete-tijd IFTN modellen

voor. Het eerste lineaire IFTN model legt de genoemde karakteristieken vast op het niveau van tactische containerstromen. Het tweede verkeerintensiteitsafhankelijke IFTN model breidt het lineaire IFTN model uit zodat het de impact van vrachtwagens aangestuurd door de transporteur op de transporttijden over de snelwegen meeneemt met behulp van een meerdere categorieën versie van de niet-lineaire en niet-convexe snelheid-dichtheid relatie. Bovendien wordt een evaluatiesysteem voor een IFTN bestaande uit een enkele regio en een evaluatiesysteem voor een IFTN bestaande uit meerdere regio's gepresenteerd om het gebruik van de de netwerkmodeleringsaanpak te illustreren en om de prestaties van de voorgestelde regelmethoden te kunnen beoordelen.

- Modelgebaseerde voorspellende regeltechniek voor synchromodale goederentransportplanning
  We onderzoeken synchromodale goederentransportplanning tussen zeehavens en binnenhavens voor een enkele intermodale goederentransporteur vanuit het oogpunt van systeem- en regeltechniek en maken daarbij gebruik van de voorgestelde IFTN modellen. Het doel van de planning is om acties met betrekking tot de containerstromen in een IFTN zodanig te kiezen dat een door de transporteur geleverde doelfunctie wordt geminimaliseerd. Om in het IFTN om te kunnen gaan met een dynamische vraag voor transport en dynamische verkeerscondities wordt een modelgebaseerde voorspellende containerstroomsturingsbenadering (Model Predictive container Flow Control (MPFC)) voorgesteld. Voor het lineaire IFTN model lost de MPFC aanpak lineaire programmeerproblemen oplossen; deze aanpak is geschikt voor het rekenkundig plannen van synchromodaal goederentransport in grote netwerken. Voor het verkeerintensiteitsafhankelijke IFTN model worden twee oplossingsmethoden voorgesteld om het niet-lineaire en niet-convexe MPFC probleem op te lossen: multi-start iteratief lineair programmeren (Iterative Linear Programming (ILP)) en multi-start sequentieel kwadratische programmeren (Sequential Quadratic Programming (SQP)). Voor het MPFC probleem met het verkeerintensiteitsafhankelijke IFTN model in een enkele regio behaalt de multi-start ILP methode een vergelijkbare planningsprestatie als de multi-start SQP methode, maar met een significant gereduceerde rekentijd.

- Gedistribueerde modelgebaseerde voorspellende regeltechniek voor gecoördineerde synchromodale goederentransportplanning

  We beschouwen ook gecoöördineerde synchromodale goederentransportplanning tussen meerdere intermodale goederentransporteurs in verschillende verzorgingsgebieden. Het gecoördineerde doel is om de totale kosten van het afleveren van de goederen voor het gevraagde transport te minimaliseren. Drie gedistribueerde containerstroomsturingsmethoden (Distributed Model Predictive Container Flow Control (DMPFC)) worden voorgesteld voor de gecoördineerde goederentransportplanning: een *parallele* DMPFC benadering, een *seriële* DMPFC benadering, en een zogenaamde wisselende-richting (Alternating Direction Method of Multipliers (ADMM)) DMPFC benadering. Wanneer we deze drie DMPFC benaderingen implementeren in combinatie met het lineaire IFTN model in het IFTN evaluatiesysteem voor meerdere regio's, dan behaalt elk dezelfde totale afleveringskosten als de totale afleveringskosten van een centrale transporteur. Deze centrale transporteur is geïntroduceerd voor vergelijkingsdoeleinden, waarbij het is aangenomen dat de operator alle benodigde informatie voor de planning kan verkrijgen en dat de operator het synchromodale goederenvervoer voor het hele netwerk kan plannen. De simulatieresultaten laten ook zien dat de ADMM gebaseerde DMPFC de minste rekentijd nodig heeft, terwijl de *seriële* DMPFC benadering de minste iteraties en informatieuitwisseling nodig heeft in het coördinatieproces.

Samengevat onderzoekt dit proefschrift synchromodale goederentransportplannings- en coördinatieproblemen en toont het het potentieel van de voorgestelde nieuwe containerstroomsturingsbenaderingen.

Le Li

Curriculum Vitae

Le Li was born in June 1986, Weinan, Shaanxi Province, China. In 2008, he obtained his B.Sc degree in Automation from the Department of Automatic Control, School of Marine Science and Technology, Northwestern Polytechnical University in Xi'an, China. After this, he was recommended to continue his master education at the same department. He received his M.Sc degree in Control Theory and Control Engineering in 2011.

In December 2011, he was sponsored by the Chinese Scholarship Council to become a Ph.D candidate at Delft Center for Systems and Control, Delft University of Technology. In his Ph.D project, he worked on coordinated model predictive control of synchromodal freight transport systems in port-hinterland freight transport, under the supervision of Prof. dr. ir. Bart De Schutter and Dr. Rudy R. Negenborn. In the mean time he also obtained the certificate of the Dutch Institute of Systems and Control (DISC) graduate school. His research interest include model predictive control, distributed model predictive control, and freight transport systems.