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Title: **Dynamic traffic assignment model for inland waterway freight transport**

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Confidential: No

Initiator (university): Dr. Rudy R. Negenborn

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A. Burgess, Panteia, supervisor
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Specialization:	TEL	Confidential:	No
Creditpoints (EC):	35		

Subject: **Dynamic traffic assignment model for inland waterway freight transport**

Background

Due to the rapid increase in global trade and deepening integration within the EU, freight transport across the EU has had a relatively fast growth. By contrast, constraints of transport infrastructure, interoperability and governance issues slow down the developments of freight transport. Currently, inland waterway freight transport models used by governments for planning are mostly static. The models are based on normal situations, on an annual basis, ignoring the dynamics in freight (e.g. due to congestion, accidents and changes in demand).

From a transportation operations perspective, static models cannot respond to dynamics in the network. Such models can therefore not provide optimal route choices for groups of individual vessels. From a transport engineering perspective, static models cannot provide the real-time transport information that is important for some types of transport analysis and policy-making. Against this background there arises a need for a dynamic traffic assignment (DTA) model.

Research objective

This project aims to develop a DTA model of the Dutch inland waterways system and to apply the model for improving route choice for vessels. The following sub-objectives should be accomplished while doing so:

1) To identify the important factors in freight transport in inland waterways.
2) To implement a DTA based model for inland waterways freight transportation.
3) To analyze and evaluate current and future performance of the waterway network depending on simulations using the model.

Research questions

The following questions are required to be answered in this project:

1) What are the important factors that should be considered for freight transport in the Dutch inland waterways network?
2) How can a DTA model be implemented to realize optimal operational planning in the network?
3) What effects and analysis can be carried out with scenario simulations involving the dynamics in the network?

It is expected that the graduation project is concluded with a written report, including conclusions and recommendations for future research. The report must be written in English and must comply with the guidelines of the section. Details can be found on the website.

The supervisor,
Dr. Rudy R. Negenborn

Executive Summary

Inland water way transport takes 46.6% of whole freight transport in Netherlands [1]. Due to the increase of global trade and the saturation of the road transportation, inland waterway transport will be the new growth area in hinterland transportation. Currently, inland waterways freight transport planning models used by governments are most static. By using static model, a strategic planning is generated to deal with investments, infrastructures development and so on.

However, the evaluation is done under a normal situation or empirical data which ignores the dynamics in freight. When these models are used at the short-term, operational level of planning, they do not fit any more. When these models refer to a steady network state and simulate the network by using static data, the greatest disadvantage, namely the inability to represent the interactions between the components of the network, is apparent. The disadvantages can be found in non-optimized route planning as well as static network representation. Therefore, this master thesis is conducted with the main objective to develop a DTA (Dynamic Traffic Assignment) model that provides individual vehicle assignment as well as time-dependent network information.

The main research question regarding the main objective is: What models can provide more precise network performance and traffic assignment in inland waterways, taking dynamic factors into consideration? Three sub-questions can be made to guide the study towards achieving the main objective. And each sub-question leads to corresponding modelling process and chapter. Detail can be found in Figure 1.

To achieve the main objective, the first step is to define key factors that are related to DTA model in inland waterway network. There are no standard criteria to define important factors in inland waterway models. Some key factors are defined based on literature reviews. Literature

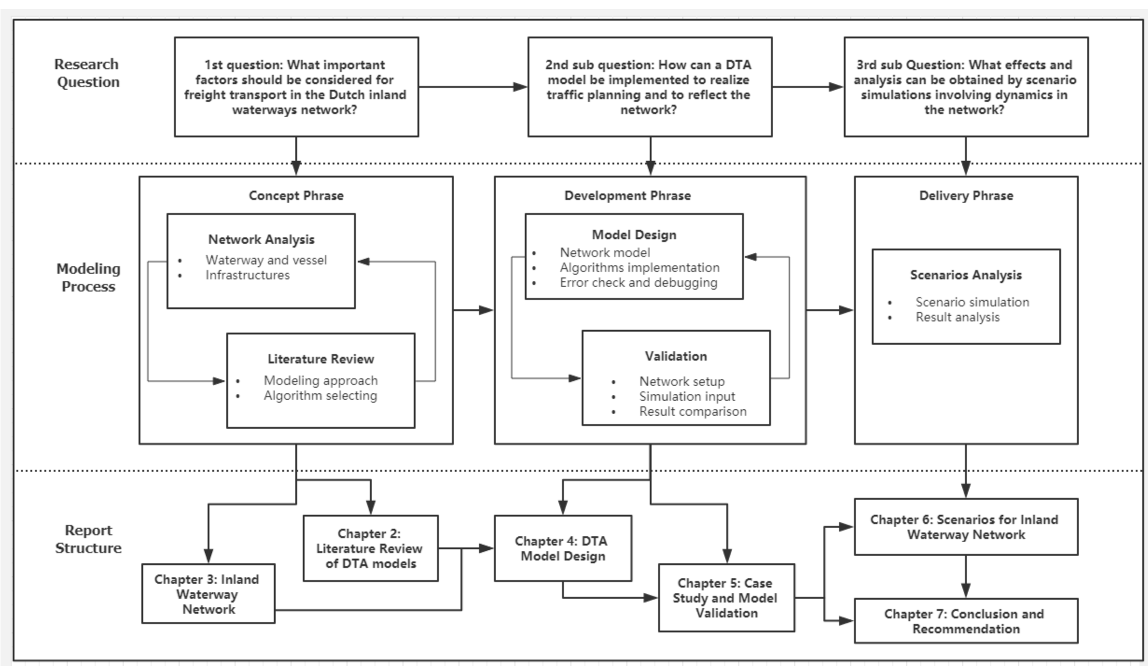

Figure 1 Research Approach

reviews are more likely to provide a set of mathematical factors as well as the type of DTA model based on study scope and previous studies. Other important factors are defined by analyzing the Dutch inland waterways. These factors comprise the distinctive attributes of inland waterway network such as particular infrastructures and fairways.

Literature review of DTA models enables us to select the factors that can determine the design of a DTA model for an inland waterways network. The literature review also helps us find feasible algorithms. The important factors based on literature review in second chapter are:

- **Modelling considerations:** DTA model can be applied to different size and resolutions to different contexts and time frames. The model in this research is mesoscopic, which provides more detailed information and dynamics as well as less computing time comparing to microscopic model.
- **Experienced travel time:** ETT is a time that needs to be evaluated after the fact, by which point the traffic condition along the entire journey is revealed and experienced.
- **DTA modelling approach:** for reasons like user optimal path and stable OD demand matrix, the equilibrium-based modelling approach is chosen in this research. The main components in DTA algorithmic procedure is in Figure 2.
- **Network loading:** Network loading is one of the main procedures in model simulation. It estimates network performance successively on simulation intervals by using the results of path adjustment.
- **Time-dependent shortest path:** an improved Dijkstra's shortest path algorithm is used to determine the traveller path.
- **Path adjustment:** The traffic flow moves from the paths that have longer travel time to paths that have shorter travel time. The method of successive average (MSA) is used in this research.
- **Criteria for DTA model:** According to *The Primer for Dynamic Traffic Assignment* [7] and specificity of inland water way network, a brief summary on the DTA models is shown in Table 1.

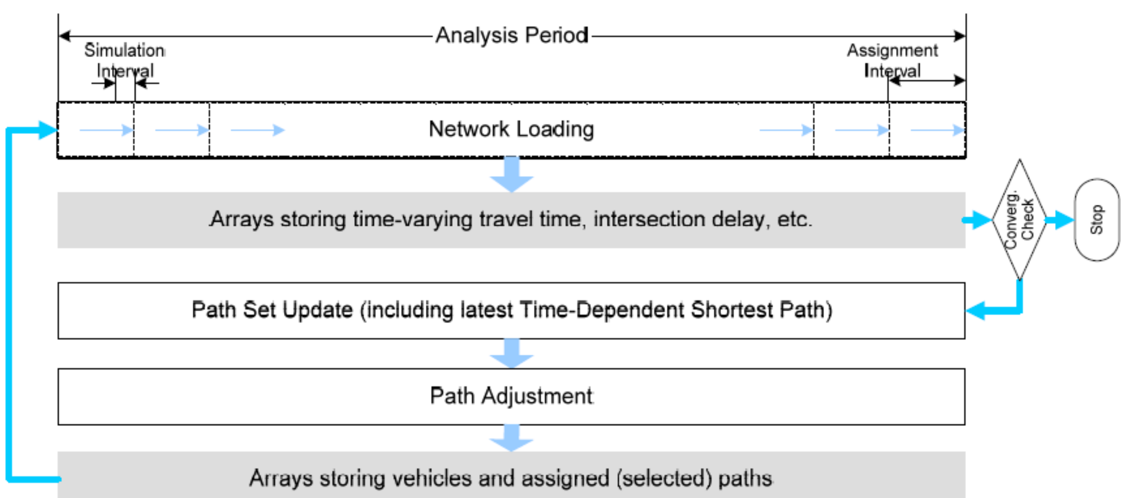

Figure 2 DTA algorithmic procedure

<table>
<tr><th>Criteria</th><th colspan="12">DTA methods</th></tr>
<tr><td rowspan="2">Geographic Scope:
Country and region</td><td colspan="4">Microscopic simulation</td><td colspan="4">Mesoscopic simulation</td><td colspan="4">Macroscopic simulation</td></tr>
<tr><td colspan="4">☒</td><td colspan="4">☑</td><td colspan="4">☑</td></tr>
<tr><td rowspan="2">Facility Type:
Inland waterways</td><td colspan="3">Dijkstra's</td><td colspan="3">SSSP</td><td colspan="3">Preprocessing phase</td><td colspan="3">A*</td></tr>
<tr><td colspan="3">☑</td><td colspan="3">☑</td><td colspan="3">☒</td><td colspan="3">☒</td></tr>
<tr><td rowspan="2">Travel Mode:
Commercial vessel</td><td colspan="6">MSA</td><td colspan="6">Bush-based</td></tr>
<tr><td colspan="6">☑</td><td colspan="6">☒</td></tr>
<tr><td rowspan="2">Management Strategy:
Operational planning</td><td colspan="6">Instantaneous travel time</td><td colspan="6">Experienced travel time</td></tr>
<tr><td colspan="6">☒</td><td colspan="6">☑</td></tr>
<tr><td rowspan="2">Traveler Response:
Route diversion Pre-Trip</td><td colspan="6">Equilibrium-based DTA approach</td><td colspan="6">Non-equilibrium DTA approach</td></tr>
<tr><td colspan="6">☑</td><td colspan="6">☒</td></tr>
<tr><td rowspan="3">Performance Measures:
Volume
Travel distance
Travel time
Queue Length
User optimization</td><td colspan="6">DTA model</td><td colspan="6">STA model</td></tr>
<tr><td colspan="3">Simulation-based approach</td><td colspan="3">Overall formulation</td><td colspan="6" rowspan="2">☒</td></tr>
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Table 1 Criteia of DTA model

Chapter 3 describes an overview of Dutch inland waterways network. The important factors related to the specificity of inland water ways are:

- **CEMT classification:** CEMT classification is an international classification system which divided waterways into classes.
- **Water profile:** there are four types of waterway: trunk routes, key waterways, other main waterways and other waterways. There are three types of profile: normal profile for two-lane traffic, narrow profile for two-lane traffic and single-lane profile.
- **Reference vessels:** reference vessel is the largest vessel that can smoothly and safely navigate the waterway. It is used with CEMT classification to indicate the appropriate fairway for vessels.
- **Vessel behaviour:** The vessels in two directions in same waterway will not affect each other. Overtaking between ships is allowed and almost no influence on ship speed.
- **Infrastructures:** The main infrastructures on inland waterways determine the traffic characteristics of the network. They are: junction, port, lock and bridge. Each type of infrastructures has character and is used in DTA model design.

The next step of the research is to define an implementation for the DTA model to realize the research objective. The network model is composed of nodes and links. Nodes can be infrastructures or junctions of fairways while links represent two-way waterways. Infrastructures have special dynamic design characteristics that get from previous chapters. The network loading process simulates network performance every time interval. There are two sub-processes, one traces all the vehicles that are on links and the other manages the queue. After the network loading, the network performance on each time interval is simulated and stored. And the travel time of each vessel is calculated. The search for shortest path basically follows from Dijkstra. It calculates travel times from one point to all the other points in network. By using the network performance of different time interval, the result is time-dependent. The travel time simulated by shortest path may be different from that simulated by network loading. Then the path adjustment process moves the traffic flow into the new path. The network loading process, time-dependent shortest path process and path adjustment process work together as a loop until there is a relative gap below the quit criteria. When relative gap becomes quite small, it means the network loading process results fit the time-dependent shortest path. Then all vessels travel on their optimal path. The model is programed in C# and a database is used to store all data.

The DTA model is validated by a case study. The case study simulates OD pairs in the waterways between Rotterdam to Antwerp. The network can be found in Figure 3. The main data input come from BIVAS and IVS databases. IVS databases provide the lock information while BIVAS database provide the OD demand and vessel data such as speed and CEMT classification. 01/07/2014 is chosen as the simulation period.

The simulation result is shown in Figure 4. The border the line is, the greater the number of trips alone the particular fairway. And all details of traffic flow, such as waiting time, mooring place and experienced travel time, are calculated by simulation. In order to validate the DTA model, we compare the output with that of static model and with real data. Three indicators are used as KPI: travel time of vessels, waiting time of vessels and traffic flow on locks. In BIVAS, travel time of one vessel is fixed due to the static model limitations. While in DTA model, travel time of a vessel is relate to the departure time and network performance. In BIVAS, the waiting time on lock is a fixed time period, and it is the same for all trips. By comparing DTA model results and BIVAS results with real data, the DTA model results are far more close to real situation. For the lock information, DTA model provides more detailed and more precise results comparing to BIVAS. The lock enter time of vessel calculate by DTA is more closed to real data.

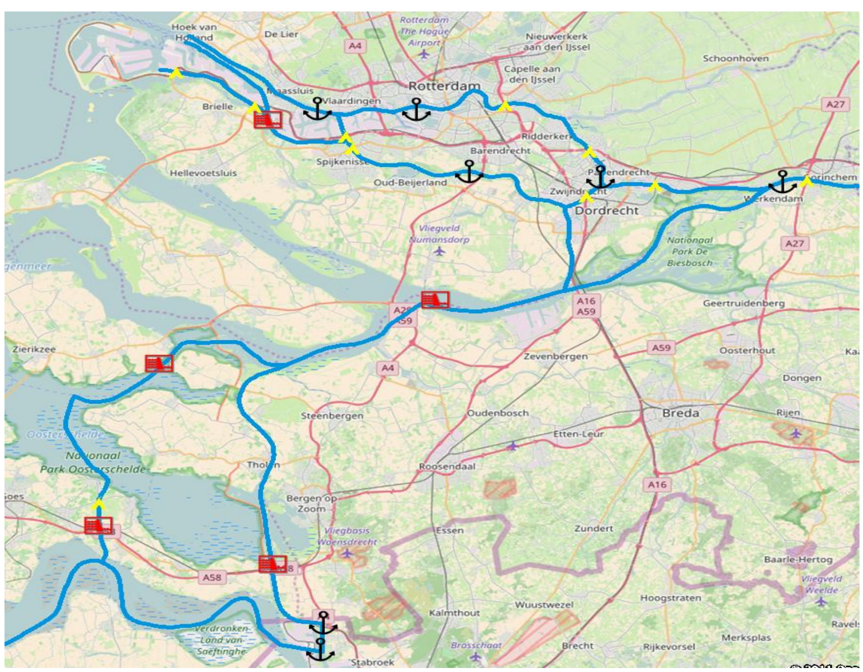
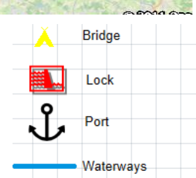


Figure 3 Network of Rotterdam-Antwerp



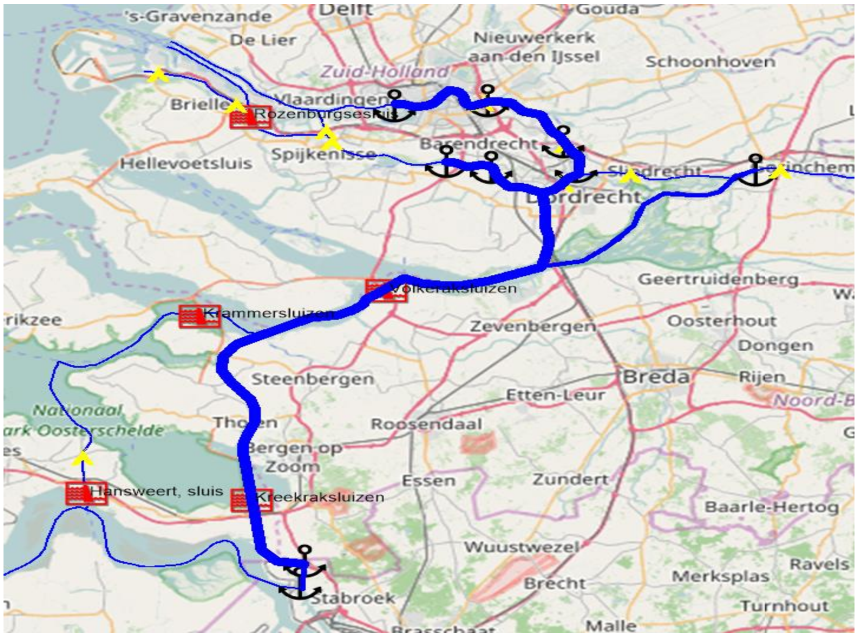


Figure 4 Trips route of simulation

In Chapter 6, two scenarios are illustrated to give practical examples of the kind of analysis the DTA model can be used for. We choose the Trunk routes and main waterways as the baseline waterway network, is shown in Figure 5.

Figure 5 Baseline inland waterway network for scenarios

As data input, there are 16 OD pairs, from Rotterdam and Amsterdam to the other ports. The original network performance comes from real situation on 1st July, 2014. There are altogether 997 ship-times traversing on the network. These ships will represent the normal, baseline performance of the network. Then the baseline is used to study how scenario assumption affects network performance.

The first scenario discusses the impact of increased OD demand in network. The impact of OD pairs is shown in Figure 6. The increased traffic flow last from 00:00 to 4:00, so the shipments departing in the morning are affected. And a rapid rise in the number of ships in one OD pair will affect trips in another OD pair, if they share the same lock. The workload add to locks are different, due to their different original loading share, see in Figure 7. Furthermore, the DTA model will balance the locks' workloads and average the travel times by assigning ships to routes are longer, but which minimize delays.

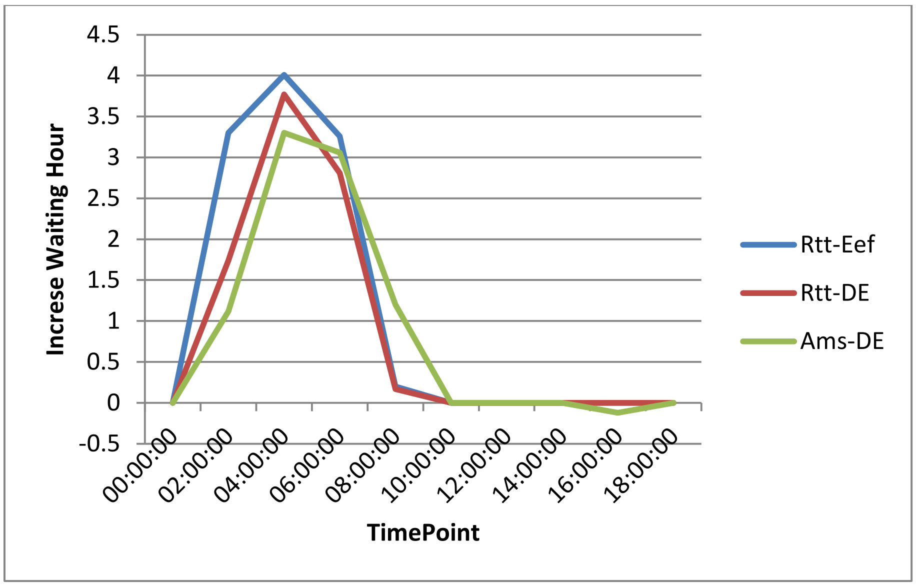


Figure 6 Impact on OD pairs

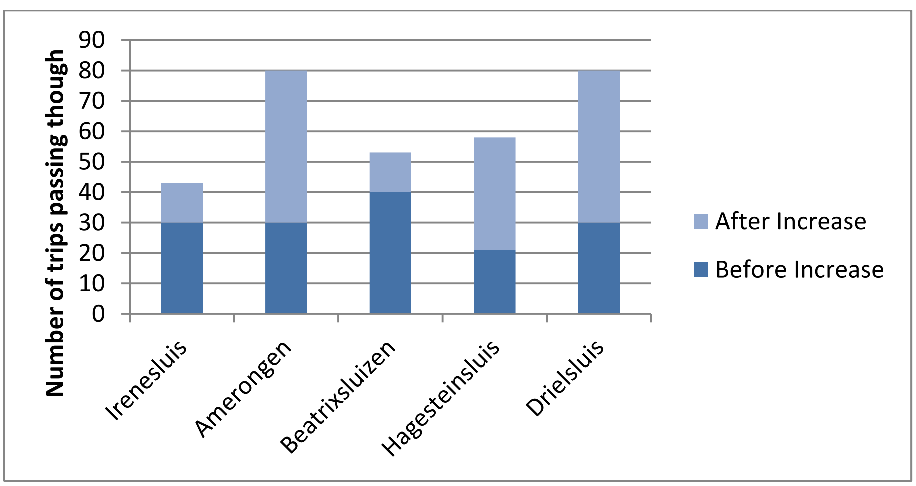


Figure 7 Lock workload increase

The second scenario discusses the impact on network if one fairway disabled. When there is a break down in a fairway, it affects all the ships that were planned to pass through it, and the waiting time for these ships increases significantly. But the trips that not pass the blocked waterway are also got influenced, see in Figure 8. The fairways besides it or on alternative route are going to be crowd, see in Figure 9.

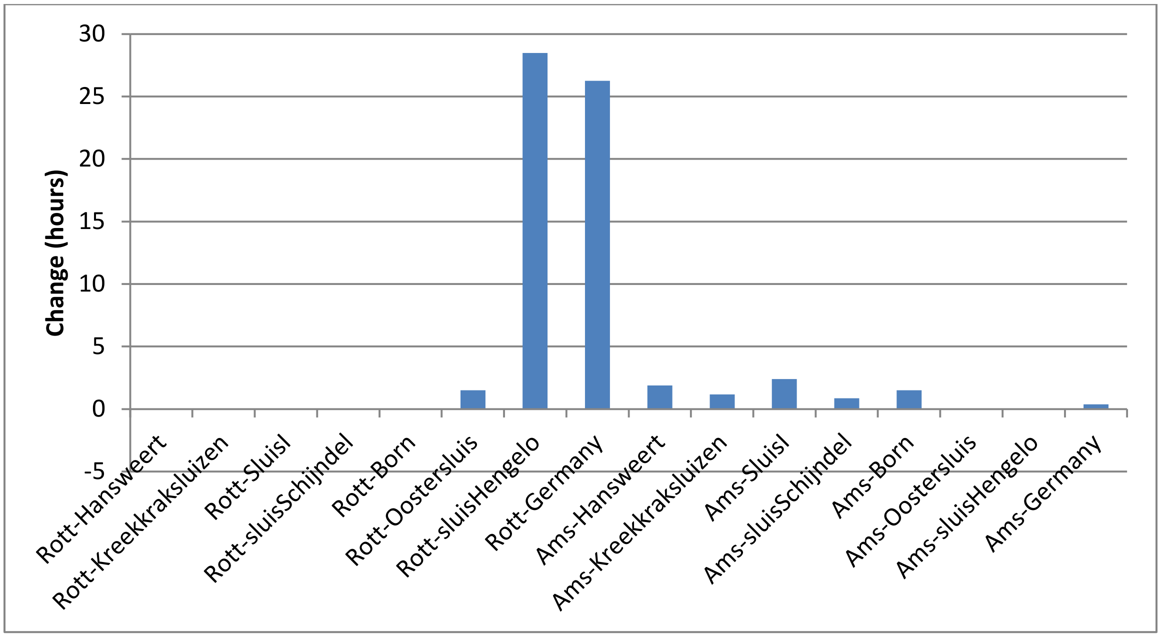


Figure 8 Travel time increase for each OD

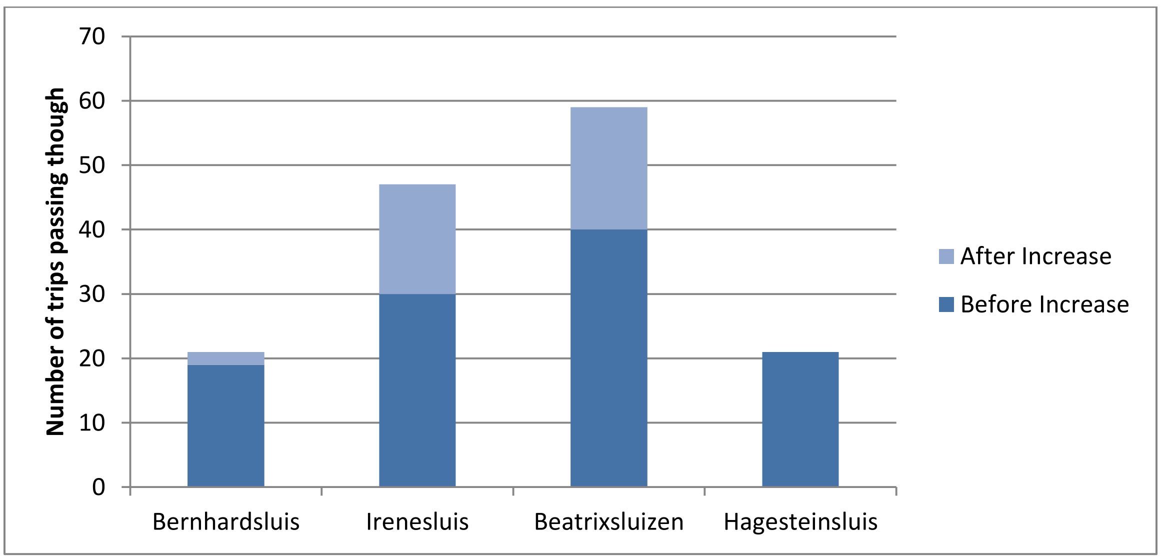


Figure 9 Locks workload increase

As a conclusion, DTA model works at a lower level, involving shorter time durations. But it represents the dynamic interaction between the components of the network and provides more detailed information comparing to static model. The information is useful to individual skipper (e.g. skippers can get more precise travelling information) as well as to network performance analysis (e.g. traffic analyst can get network performance which is closer to real). Chapter 2 and 3 illustrate the important factors of DTA model for inland waterway network. In Chapter 4, the DTA model for inland waterways is formulated. The model takes in all the important factors that have been identified in previous chapters. Chapter 5 uses a case study to validate the DTA model and compares DTA results with static model and real data. In Chapter 6, two scenarios are discussed to give practical examples of the kind of analysis the DTA model can be used for.

However, there are further researches in the area of dynamic traffic assignment in inland waterways can be made in the future. In this study, the most important simplifications were with regard to real-time vessel traffic, Multiple Traveller Classes and flexible vessel departure times. It is recommended that future research could deal with these challenges.

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Abstract

Due to the rapid increase of global trade and deepening integration within the European Union (EU), freight transport across the EU has had relatively fast growth. However, constraints of transport infrastructure, interoperability and governance issues do slow down the developments of freight transport. There is a need for transport planning models to support the growth of freight transport, especially in inland waterways.

Currently, the inland waterways freight transport planning models used by EU governments like Germany, Belgium, France and The Netherlands are mostly static. In static models, evaluations are done under normal, static conditions, on an annual basis, ignoring the dynamics in freight.

This research presents a dynamic model for Dutch freight transport via inland waterways. The Dutch inland waterways are interpreted as a network. Freight shipments are assigned to the network in a dynamic way, with the goal of minimizing the travel time. To achieve this, the research comprises a network model and the corresponding mathematical model.

The network model includes the main infrastructures of the waterways, such as bridges, locks and ports. Whereas the mathematical model includes a time-dependent shortest path algorithm, a network loading process and a path adjustment algorithm. The model is validated by simulating historical data and by comparing the results with those from a static model. Several scenarios are given to illustrate uses of the DTA model.

Keywords: Netherlands, dynamic traffic assignment, inland waterways, route planning, network performance, freight transport, simulation, network shortest path, algorithm

1. Introduction

1.1. Background

Due to the rapid increase of global trade and deepening integration within the European Union (EU), freight transport across the EU has had relatively fast growth. This growth occurred in spite of constraints, such as transport infrastructure, interoperability and governance issues, which slowed down the developments of freight transport.

In 2013, the total inland freight traffic in the 28 member states of the EU (the EU-28) was over 2200 billion tonne-kilometres. 7% of this was along inland waterways [3]. Freight transport via water accounts for 46.6% of inland freight transport in The Netherlands, which is far more than that in any other EU-28 country [1].

Freight transportation by water costs much less than by road. Another advantage of inland waterways over roads is that vessels have more load capacity than road vehicles. This implies that more freight tonnage is transported by water than by road, for the same level of traffic.

In the past 4 years, inland waterways freight transport growth rates remained stable at 2% in The Netherlands [4]. According to Rijkswaterstaat [5], the road network is getting saturated and, in the next 10 years, inland waterways will become the new growth area in hinterland transportation. Therefore, any measures to reduce costs and increase efficiency in freight transportation by inland waterways will only lead to greater economic benefits. One of the tools used to reduce cost and improve efficiency is a transport planning model.

Freight transport planning models aim at evaluating the impact of different policies on the performances of transport systems. The freight transport planning models that most governments currently use are static. For example, the Dutch government uses the static model BIVAS [6].

In such static models, the evaluation is done annually, under normal conditions, ignoring the dynamics in freight. In contrast, models based on dynamic network analysis provide more comprehensive ways to represent the interaction between traffic flow, route choice and cost in a time-varying network.

The so-called Dynamic Traffic Assignment (DTA) analysis is the subject of this thesis. The thesis provides a simulation method for evaluating traffic performance in inland waterways. The results are key performance indicators that can be used to improve the efficiency of individual vessels and systemwide network measures that can be used for regional planning purposes.

1.2. Research problems

Current problems in current network

The main problems in transport planning modelling are encountered when static models are used. Nevertheless, current static transport planning models, like BIVAS, serve a strategic purpose [7]. Strategic or long term planning involves the highest levels of management and deals with major capital investments and physical network development. Since strategic planning is long term and on a large scale, static models can provide reliable analysis in an acceptable time frame.

However, when these models are used at the short-term, operational level of transport planning [7], the disadvantages are apparent at once. Static models are unable to deal with short term decisions on transport activities, such as scheduling of services, maintenance, allocation of crews and routing of vehicles. Dynamic models are needed here, as they are good at the operational level of transport planning.

The freight transport planning models currently used by governments and companies are mostly static. They work by simulating route choice based on static data (e.g. average cruising speed in a canal) or on empirical data (e.g. steady-state travel time on a congested road). That is, they ignore most of the dynamics in freight transport. What is more, their representation of a transport network is structural rather than behavioral. This arises from the fact that static models represent a network in a steady state instead of at runtime. Hence their greatest disadvantage: their inability to represent the dynamic interaction between the components of the network.

The planning of static model refers to a steady network state. The travel time is an instantaneous travel time which ignores the other components behavior. In case of congestion or rapid flow growth, behaviors of other component will affect the travel time. To illustrate with an example, when several vehicles having the same OD pair depart at same time, we may, in general, wish to assign the traffic flow to different paths to achieve the least travel time for each of the vehicles. However, in a static model, the vehicles in such a situation share the same route. In the network, these vehicles may cause congestion along their path, resulting in a large difference in the actual traveling times.

Why Dynamic traffic assignment is needed?

Dynamic models work at a lower level, involving shorter time durations and the runtime of the system. Interaction of system components like congestion, rush hour and network disruption can be considered in dynamic models [2]. This makes the network performance estimated by dynamic model closer to reality than that estimated by a static model.

The real-life power of a dynamic model also means it can be used by other analysis tools. For example, in inland waterways, congestions occur more often at locks than at bridges, due to their longer operation time compared to that of bridges. Dynamic models are more suitable than static models at representing the resulting queues. These queues in turn serve as input for the analysis tools used at locks and bridges. We cannot achieve such an analysis with static models, as they are weak in queue presentation.

Inland waterway freight transport involves large investment and long cumulative travel times. Consequently, a knowledge of the optimal path and travel time is important to drivers and shippers. That knowledge can be provided by dynamic models. For example, if congestion occurs at a lock, the ship owner will need to find a mooring location for his vessel. The time table and queue length provided by a dynamic model can help him find the nearest location.

Who will use Dynamic traffic assignment models?

Transport planning models not only evaluate the impact of different changes in transportation facilities on the performance of a region's transportation system. They also provide individual vehicles with a comparatively optimal path and time planning.

From a transportation planning perspective

Cost and time are two key components in transport planning models. They are also the two main factors that concern individual travelers. The cost and time of a change in travel plans depend on a lot of time-varying factors in the network. For example, in inland waterways freight transport, the travel time of a specific barge is affected by time-windows at ship locks and bridges, and even by the choice made by other barges.

The travel time and cost evaluated in static network analysis use variables that are time-invariant. That is obviously not sufficient for an individual traveler. Especially when an emergency occurs, static models will not adjust route choice accordingly. Furthermore, route choices made by static models for multiple travelers with same Origin-Destination (OD) pair, at same time, are all the same. This will easily create congestion during peak times. As dynamic network analysis models can provide more detailed representation of the interactions and time-varying factors, they have become more important in freight transport planning.

From a traffic engineering perspective

Transport planning models are also used to analyze or evaluate the current or future performance of transportation facilities in the network. There are a variety of traffic models available that support different aspects of traffic analyses. Static models provide route choices that depend on instantaneous travel time, whereby the minimum travel time is calculated before departure. So the planning cannot take into account any situations that happen after departure.

In practice, most travelers will choose a route with a minimal experienced travel time (ETT) instead of a minimal instantaneous travel time (ITT) [8]. The ETT needs to be evaluated at the end of the journey. So the route followed by the traveler may change due to dynamic factors in network. This is the reason that existing static models are limited, being incapable of analyzing effects such as queue spillback, oversaturation and peak spreading.

1.3. Research objectives

Considering the above research problems, the main objective, and contribution, of this research is to develop a DTA model that provides individual vehicle assignment as well as time-dependent network information.

Firstly, an individual user who wants to plan his route will get an optimal path. The optimization result is according to the user's objectives (e.g. minimizes travel cost or minimizes integration of both travel time and travel cost). The user cannot get a better route by unilaterally changing to a different route. Then, the model can represent the time-dependent traffic information. The simulated result is a sort of user optimization instead of system optimization. It is more consistent with the real situation, because every user travels along their optimal path. The model provides more precise network performance to traffic engineers and can be used in other transportation analyses.

In the meantime, some sub-objectives to support the main objectives are:

- To identify the important factors in freight transport in inland waterways.
- To implement a DTA based model for inland waterways freight transportation.
- To analyze and evaluate current or future performances of a network, depending on simulations of the model.

As for the first sub-objective, the important factors are related to the actual situation, such as at bridges and at ship locks. There will also be a literature review of the factors.

The factors will be used to determine data input, variables, assumptions, and limitations of the model. As for the second sub-objective, the transport assignment model provides route choices, and the time table of individual vehicles, with minimum travel cost and time. During the trip, the vehicle keeps contact with an assignment tool to update the navigation data. The analysis and evaluation of the network and infrastructure performance are obtained by simulation of the model. The simulations will consist of some scenarios which take into account peak-hour traffic as well as accidents.

1.4. Research questions

The main research question regarding the main objective is: "What models can provide more precise network performance and traffic assignment in inland waterways, taking dynamic factors into consideration?" The above question will be followed by research sub-questions which guide this study towards achieving the research objectives.

1st sub question: What important factors should be considered for freight transport in the Dutch inland waterways network? The important factors are determined based on both literature reviews and analysis of Dutch inland waterways network. They are used to identify useful information for the model to be implemented, such as data input, assumptions, parameters and limitations.

2nd sub question: How can a DTA model be implemented to realize traffic planning and to reflect the network? The second sub question needs to achieve two goals: each traveler should get his optimized path and, at the same time, a network profile and network performance based on his optimal path.

3rd sub Question: What effects and analysis can be obtained by scenario simulations involving dynamics in the network? The third sub question relates to scenario simulations to demonstrate some applications of the model. As the model involves dynamics, the simulation results will be closer to real-life situations, hence will be useful to other researchers.

1.5. Scope of study

The research time of this graduate project is expected to be 6 to 7 months. The project focuses on developing a DTA model that provides both transport planning and real-time traffic information for freight transport in Dutch inland waterways.

The container transport to and from the main ports of Rotterdam via inland waterways is expected to grow significantly in the next 20 years [9]. Most of the growth will be in international container transport via trunk routes and key waterways. In a dynamic network, the route choices change according to time-varying factors. So a modest network size needs to be defined to ensure the efficiency and effectiveness of the calculations. Therefore, the network in this study will only cover the main network routes (that is, trunk routes and key waterways).

Other inland transportation modalities (road and railway) may affect the inland waterways freight. But integrating road and railway transportation into the model would make this research very complex. Since DTA models offer dynamic network modeling capability that distinguish them from the static traffic assignment, DTA models are primarily applied in operational planning and real-time operational control of vehicular traffic systems [2]. In this research, the assignment model focuses on operational planning. That is, it aims to make planning decisions for major operations, and to undertake demand-management actions that will induce a temporal or spatial pattern shift of traffic in the network.

1.6. Research approach

There are no standard criteria to define important factors in inland waterway models. So in order to answer the first research question, some key factors are defined by literature reviews. Literature reviews are more likely to provide a set of general factors such as travel time and queue time. Literature reviews also determine the type of DTA model based on the research objectives and previous studies. Different from road network, the inland waterway network has some particular characteristics. The analysis of the Dutch inland waterway helps to define some special factors which need to be considered in inland waterway network models in general. For example, a movable bridge is one of the infrastructures which distinguishes an inland waterway network from a road network. Movable bridges have operation time and small width comparing to ship length. These factors will affect bridge model in the DTA model.

Important factors from literature reviews and Dutch inland waterway analysis are the main considerations in model design. Firstly, main infrastructures such as waterways and bridges are modelled in a network modelling process. These infrastructures are modelled based on the analysis of Dutch inland waterway network. Then the DTA model is developed to realize traffic planning and to reflect the network.

The DTA model consists of three sub-processes: network loading, time-dependent shortest path and path adjustment. Each sub-process is introduced by formulation and flow chart. The validation process compares the model outputs to the observed traffic conditions (e.g. traffic counts and speeds) to evaluate the quality of model outputs [2] [8]. The model is implemented by programming in Visual Studio 2015. MapInfo is used to provide a visualization of the results.

After the model validation, it is necessary to say what we use DTA model for. We will show why DTA models are widespread in traffic analysis. That is their performance on time-varying network and demand interactions.

There will be three practical scenarios that show how the DTA model responds to dynamics in the network: a scenario based on geometric factors such as accident or maintenance work in the network; a scenario based on control factors such as time-windows at ship locks and bridges; a scenario based on demand factors such as a doubling of the OD demand. The network performances that result from these scenarios can be material for other research, such as on lock capacity and on traffic optimization at movable bridges.

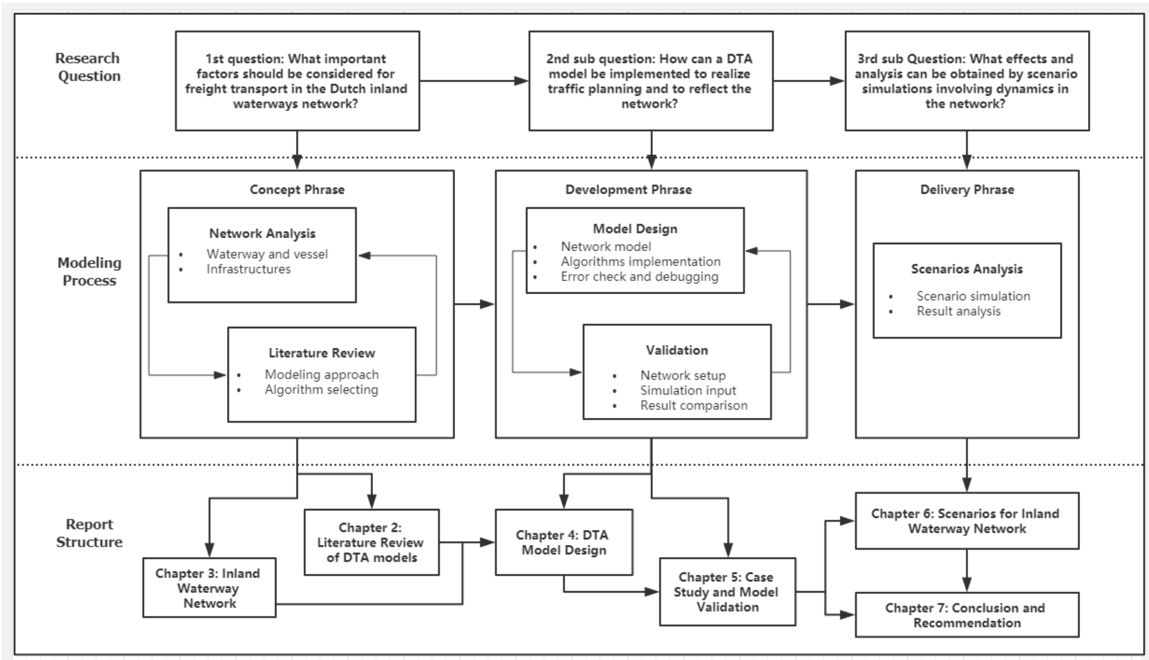

Figure 10 Research Approach

1.7. Report structure

The modeling process can be divided into 3 phases: concept phase, development phase and delivery phase [10]. Each phase corresponds to a sub research question. The relation of research question, modelling process, and report structure can be seen in Figure 10.

The first chapter introduces research problems, research objectives and research questions. The scope of the study is identified based on both research objectives and the workload of the thesis.

The second chapter reviews the literature on dynamic traffic model design in general and of some models and algorithms used in this study. In conclusion, some main factors and modeling methods that will be used in designing the model are identified.

The third chapter analyzes the current inland waterway network in Netherlands. It firstly introduces the characters of waterways include CEMT class and lanes. Then some infrastructures in the network are introduced such as bridges, locks and cross-sections. Ship types and OD demand are also introduced to help identify the leading characters of the network. The main environmental factors that will be used in the model are then identified.

The first research question is related to the concept phase. It will be discussed in Chapter 2-3. The second research question is related to the development phase corresponding to Chapter 4-5. In order to answer the third research question, scenario analysis will be done as delivery phase corresponding to Chapter 6. In the end, all research questions will be answered as a part of the conclusion in Chapter 7.

2. Literature Review of DTA Models

In this chapter, a literature review of DTA models is discussed. It enables us to select the factors that are important in designing a DTA model for an inland waterways network. These factors are important because they determine the design of the model. The literature review also helps us find feasible algorithms.

2.1. DTA modeling considerations and model objectives

DTA aims to capture the dynamic relationships between paths, start times and network characteristics [8]. Since the 1970s, DTA models were used to analyze both long-term and short-term planning. DTA research consisted of wide ranges of model sizes using different model types (e.g. micro and macro scope). DTA is a modeling method that can be applied to models of different sizes and resolutions and to different contexts and time frames. These three considerations are shown along different axes in Figure 11.

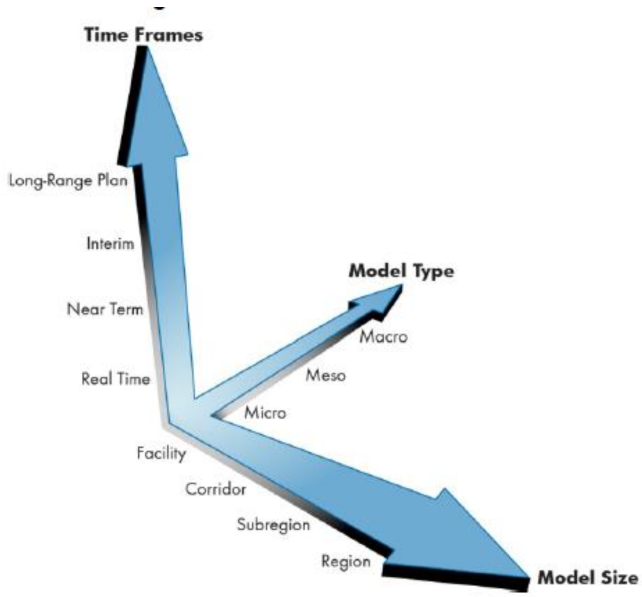

Figure 11 DTA Modeling Considerations (Source: Cambridge Systematics)

The size of model networks can vary greatly when DTA is applied. But the model network size should at least be big enough to include alternative routes to allow path selection. Improving software and computing capabilities are making it possible to apply DTA at different scales. Figure 12 is an illustration of how different scales of DTA could be applied.

DTA can be applied for various time periods and time intervals. DTA also can be applied to near-term and future long-range plans, to fine-tune travel demand estimates, and to conduct operational analysis on design improvements [8]. The three considerations are related to calculation complexity. Time frames and model size determine calculation quantity while model type determines simulation accuracy. A DTA model needs to balance these considerations with simulation time, according to the model objectives [8].

The model objectives can be divided into system-optimal and user-optimal [11]. System-optimal requires that the average journey time of travelers in the network be minimized. This implies that all travelers select the routes cooperatively to ensure the most efficient of the whole system. User-optimal ensures each traveler has a minimized transportation cost and no one may lower his own cost through unilateral action. This means the total costs of the system may not be minimized. The system-optimal and user-optimal also can be explained by Wardrop's principle published in 1952. Wardrop's principles will be discussed later.

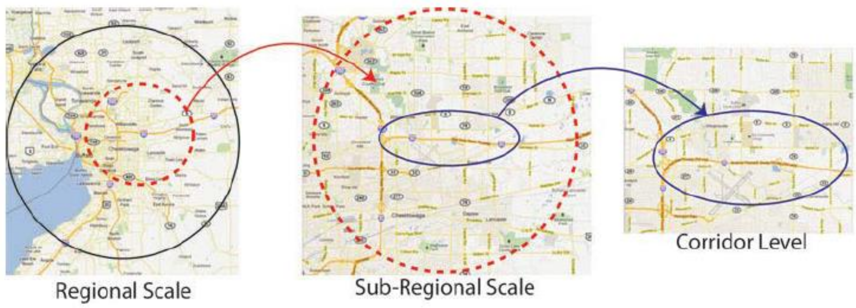

Figure 12 Model scales (Source: Cambridge Systematics)

Abdelghany, Mahmassani et al developed an equilibrium-based DTA model to design high-occupancy toll lanes [12]. They evaluated the impact to highway capacity caused by a long-term work-zone condition. As daily travelers of the highway are motivated to try different routes, over time, they eventually (after repeated learning) settle down to a set of optimal routes that best satisfy their travel objectives. As for some short-term or emergency evacuation, non-equilibrium-based DTA modeling approach would be more appropriate than the equilibrium-based approach. Henk, Ballardet al developed a non-equilibrium-based DTA model for disaster preparedness in Texas [13]. Similar research was done by Sbayti and Mahmassani who used the system-optimal DTA model [14]. In this case, the research objective is to understand the best network performance with all travelers' coordination. In summary, the modeling considerations and modeling approach should be determined by the research problems and research objectives.

2.2. Instantaneous and experienced travel times

Travel time is the main factor in all traffic models. This section introduces concepts of both Instantaneous and experienced travel time. These concepts are frequently mentioned in following chapters. They will be used to demonstrate one of the main differences between dynamic and static models, which is the travel time is used in model.

Instantaneous travel time (ITT) is a snapshot travel time measured at a specific point in time. It has no physical meaning but represents traffic flow conditions at a given instant [2] [15]. Experienced travel time (ETT) is a time that needs to be evaluated after the fact, by which point the traffic condition along the entire journey is revealed and experienced [2] [15]. In reality, the majority of travelers will choose a path with minimum ETT instead of ITT. Consequently, a traffic model which uses ETT to evaluate travelers behavior can represent the traffic conditions better.

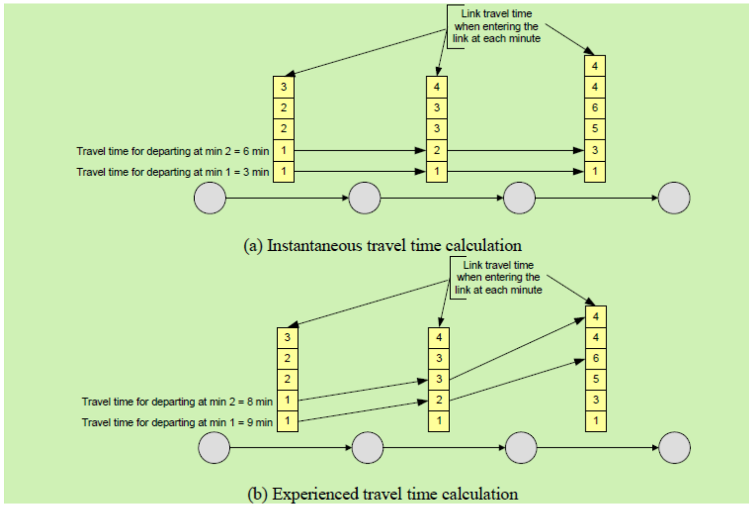

Figure 13 Instantaneous and experienced travel time determination (Source: DTA prime [7])

Figure 13 illustrates the calculation of instantaneous and experienced travel time. There are 4 nodes and 3 connections among them. The number in stack represent the travel time of links by entering the link at a different time. ITT of the path is calculated by summing up the travel time of each link corresponding to the same departure time. Relatively, the ETT calculation accounts for the travel time of one link and the downstream travel time based on the exit time. For example, the ITTs for departing at min 1 and min 2 are 3 mins and 6 mins, respectively, while the ETTs for departing at min 1 and min 2 are 9 mins and 8 mins instead.

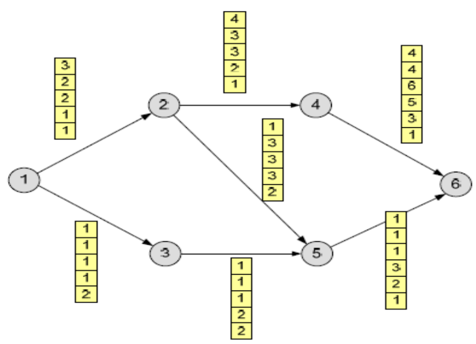

Figure 14 Example network with time-varying link travel times (Source: DTA prime [7])

Different calculations of travel time also affect route finding. Figure 14 illustrates a network with time-varying link travel times. There are 3 routes connecting the nodes 1 and 6. They are Route 1-2-4-6, Route 1-2-5-6 and Route 1-3-5-6. Figure 15 illustrates the shortest routes calculated by ITT and ETT approaches with a departure at time 1. The pictures with green background are the shortest path obtained by different algorithms. Consequently, the Route 1-2-4-6 has the shortest ITT while Route 1-3-5-6 has the shortest ETT. This is a simple example of ITT and ETT calculation. In a real-world traffic network, shortest route algorithms according to the two approaches will have significant difference.

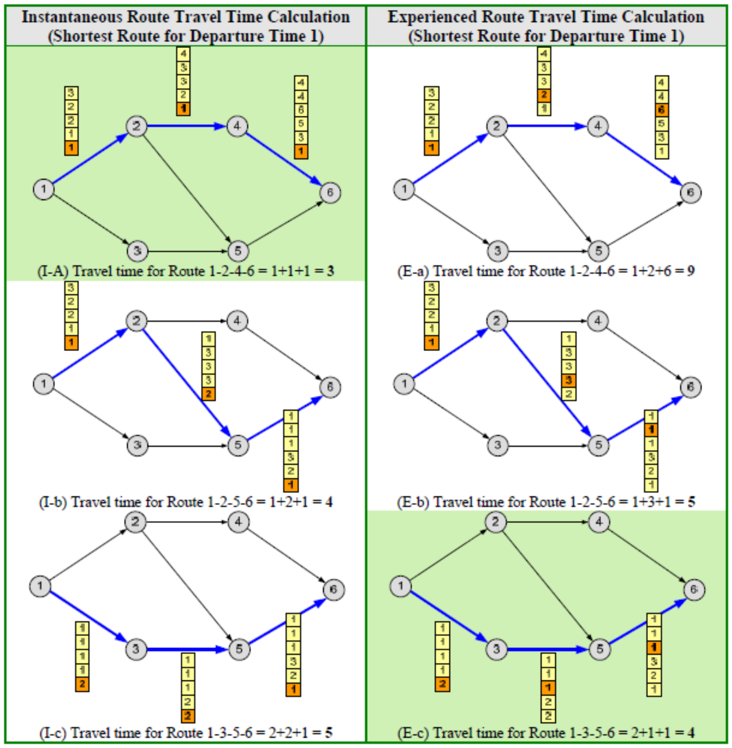

Figure 15 Different shortest routes obtained by ITT and ETT approach (Source: DTA prime [7])

2.3. DTA modeling approaches

Both *The Primer for Dynamic Traffic Assignment* [2] and *Dynamic Traffic Assignment in Modeling* [8] classify DTA modeling approaches into equilibrium- based and non-equilibrium-based approach. The equilibrium is based on Wardrop's principle published in 1952 [16]. These two DTA modeling approaches are discussed next.

2.3.1. Equilibrium-based DTA approach

Wardrop's User-Equilibrium (UE) principle [8] defines the equilibrium condition that equilibrium-based DTA models and algorithms must satisfy.

Wardrop's First principle: In a model network with many possible routes for each O-D pair, all used routes have equal and lowest travel time (generalized cost). No user may lower their travel time (generalized cost) by unilaterally changing to a different route.

Many models and algorithms were developed based on Wardrop's first principle. Peeta and Ziliaskopoulos provided a review of DTA's past and future foundations.They cite the following condition as a common agreement between dynamic user equilibrium (DUE) and the related original user equilibrium (UE) [7].

D-UE condition: In a network with many O-D zones and in a specific time period, for each O-D pair and departure time increment, all used routes have equal and lowest experienced travel time (generalized cost) and no user may lower their experienced travel time (generalized cost) through unilateral action.

Consequently, in DTA, the DUE condition not only considers the travel time of each O-D pair of different departure times. The DUE is also relevant to those who travel at the same time, sharing the same route and O-D pair. As such, ETT must be considered as an important factor in DTA models. In a DUE solution, which is a set of time-varying route choices, volumes and travel times that satisfy the DUE condition for a given network and demand pattern, the traveler's best route choice is not isolated. It depends on the route choices and progress of other travelers in the network who depart earlier or later. These two reasons ensure that solutions need an iterative process that starts with an initial set of route choices, and continues improving it.

However, finding an exact DUE is hard and time-consuming. Many current DTA models find an approximate equilibrium instead. The approximate equilibrium converges to exact equilibrium to obtain both feasibility and efficiency.

The equilibrium-based DTA model's algorithmic procedures include an evaluation of shortest paths, assignment of trips to paths and evaluation of the resultant traffic conditions [8].These are also the main components in DTA algorithmic procedure, See Figure 16.

In network loading, it is assumed that the set of paths between O-D pairs at any instant and the corresponding path flow values have been determined from the previous iteration. Then a mesoscopic simulation approach will be used to represent changes in traffic flow. The next step is path set update. Based on the congestion pattern and travel times identified in the network loading step, the routes with the lowest experienced travel time between every O-D pair, for each departure time period (also called an assignment interval), are found by a Time-Dependent Shortest Path (TDSP) algorithm. The newly found TDSP for a specific O-D pair and departure time period would be combined with all TDSPs found in previous iterations for the same O-D pair and departure time to form an updated path set.

In path assignment adjustment, only some travelers' route choices should be adjusted, in order to avoid overcorrecting. Generally this step involves finding which routes in the set need to be increased with assignment flow–vehicles and which to be decreased, and by how much. Normally, the newly found TDSP along with several other good routes (with close to minimal travel time) are among those to be increased with flows. Underperforming routes (long travel time) are decreased with flow. The adjustment made is only what is necessary in order to achieve equal travel among all routes in the current set. The three steps work in a sequential manner: the output of network loading provides the input for path set update; the output of path set update provides the input for path assignment adjustment; and the output of path assignment adjustment provides the input for network loading. These three steps are repeated until a stopping criterion is met. The algorithmic structure is illustrated in Figure 16. The stopping criterion is typically computed at the end of the network loading step. Recent algorithms employ the notion of relative gap as the stopping criterion.

2.3.2. Non-equilibrium DTA approach

In the non-equilibrium DTA modeling approach, each vehicle is assigned an initial route when starting the trip. Different types of routes (e.g. habitual routes, instantaneous shortest paths, and analyst-defined routes) may be assigned to vehicles and each type corresponds to distinct behavior and information assumptions. The habitual routes can be supplied from a previously completed DUE model run. Doing so would assume that vehicles select a route based on prior knowledge of and experience in the network. Instantaneous shortest paths are typically

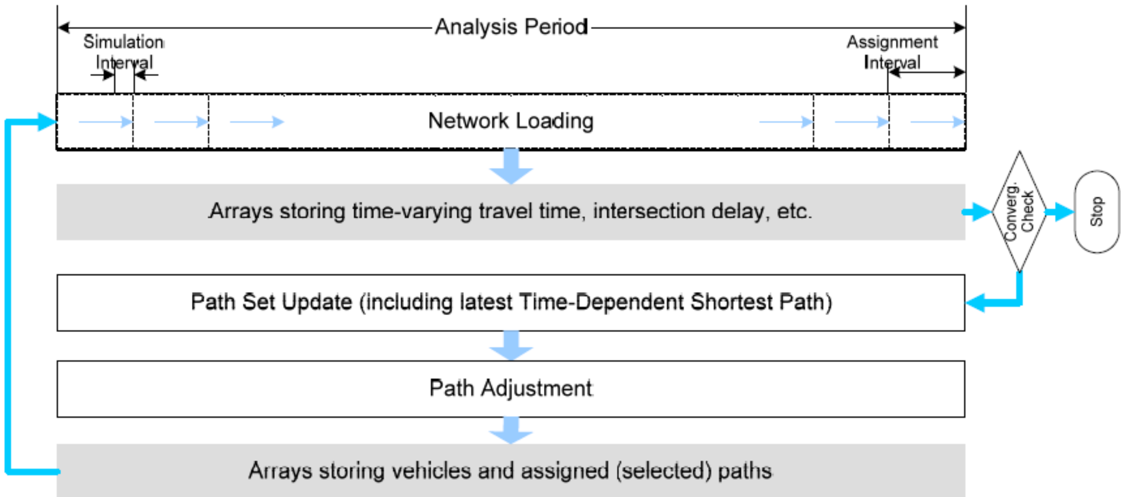

Figure 16 General DTA algorithmic procedure [2]

calculated regularly during simulation by using snapshots of the network's traffic state. Such sets of routes are made available for all newly generated vehicles until the next time instance at which a new set of shortest path times is calculated. This type of routing can be regarded as the outcome of pre-trip traveler information, where vehicles departing at different times access the best routes known at the departure time. The last type of routing is manually specified by the analyst based on certain objectives and needs. Each vehicle reevaluates the current route at each decision node (or way-points), based on current (instantaneous) link travel times. A decision node is one at which there is at least one feasible route to the destination on each of two or more of the outgoing links of the node. This approach allows the traveler to abandon the current route for a better one for the remaining trip, as a result of changes in link travel times since the last route choice was made (at an earlier decision node, or at the origin node). This method is sometimes referred to as one-shot dynamic assignment with feedback, see Figure 17.

Compared to the Equilibrium-based DTA approach, it would be more precise to call this network loading with incremental route updating. That is because it does not attempt to achieve user equilibrium and does not reach consistency between the travel time used in route generation and the experienced route travel time. However, the traveler's choices are based on some myopic decision rather than anticipating the traffic condition along the route so as to minimize the actual experienced travel time. In the simulated world, if all vehicles were to select myopic routes, network congestion would likely be overestimated. As long as experienced travel time plays a significant role in the route choice criteria, which it does in most real-life situations, the iterative equilibrium solution provides the desired consistency between the route choices and the simulation results.

With regard to model design, which approach should be used depends on specific research questions and research objectives. For this research, the equilibrium-based DTA model should be chosen. There are at least 3 reasons:

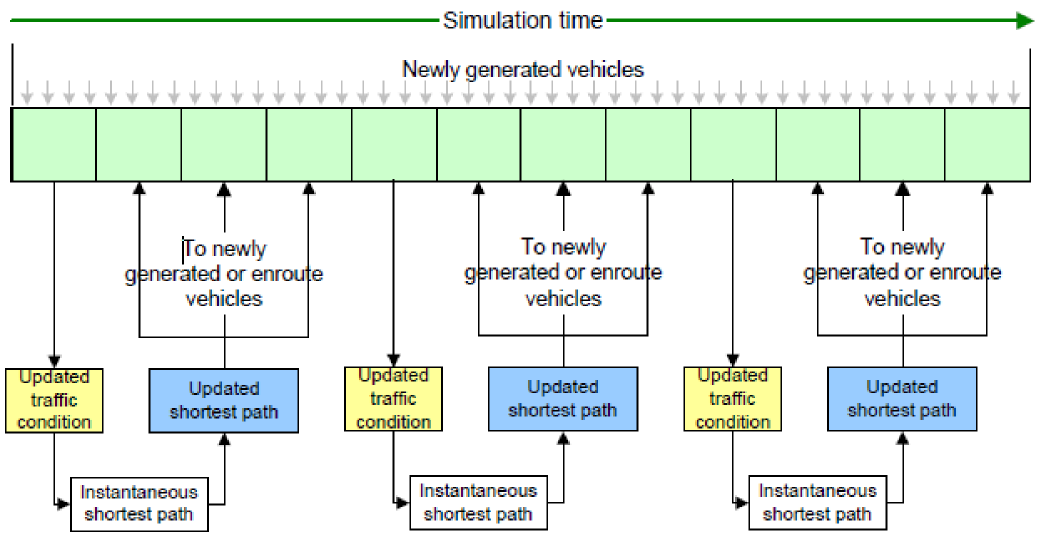

Figure 17 Dynamic assignment with feedback in a one-shot simulation [7]

- **Optimal path for each individual traveler**

Non-equilibrium DTA approach is a dynamic model but use instantaneous travel time. The shortest path that is calculated on decision node depends on a snapshot of the network. The dynamics of non-equilibrium DTA approach is reacting to things that had happened rather than an anticipation of the whole trip. In other words, it is a greedy algorithm which is, in many cases, not optimal for users. Besides, the myopic decision of each user ignores other user's decision. This will cause congestion in a free link, sometimes because a lot of users choose it at the same time.

- **Relatively stable OD demand matrix and network**

Non-equilibrium DTA approach has better performance with some emergencies. For example, if one link becomes unavailable, the user on the network can respond to this at once. But the equilibrium-based DTA approach cannot respond to this kind of emergency as all the paths have been decided. In this case, another simulation is needed to get new routes. In short, the equilibrium-based approach has bad performance, given some unpredictable events. In our project, freight transportation is not a stochastic event, and each trip is scheduled days even weeks before. As for the network, traffic accidents on waterways rarely happen and any maintenance will be published a long time before. Consequently, the equilibrium-based approach is applicable to this project.

- **Consistency between simulated results and reality**

As the non-equilibrium approach uses instantaneous travel time and myopic decision, it has limited ability to represent scheduled user behavior in a relatively stable network. The network performance consists of all trips that pass through the network. Consequently, the network performance evaluated by non-equilibrium is not precise in our project.

Multiple traveler class (MTC) DTA model is an integrated model of equilibrium-based and non-equilibrium DTA model [8]. In the MTC framework, some travelers may choose to follow the DUE route choice principle while some may choose to follow en route navigation. But this kind of model is out of our scope.

2.4. Equilibrium-Based DTA algorithmic procedures

2.4.1. Network Loading

In DTA, a mesoscopic simulation can be used to load the network [17] [18] [19]. The set of paths in time-dependent O-D pairs and path flow have been determined from the path adjustment section. The period of analysis is divided into intervals. The vehicles in a specific time-dependent OD pair are loaded onto the network incrementally. In a particular time interval, the location of the vehicle of the next time interval can be easily calculated. If the vehicle stays in the same link, the location information will be updated. If the vehicle moves from an upstream link to a downstream link, there will be two situations. When the downstream link is blocked (i.e. the amount of vehicles in next link equals the link capacity), the vehicle will join the queue at the end of current link. Otherwise, the vehicle will enter the downstream link. The loading procedure is repeated until all time intervals have been dealt with. Besides, there will be a queue server in each link to decide the sequence of different vehicles. After the network loading, the resulting route travel time can be obtained which can be used in the relative gap [2]. In the loading process, a lot of network information will be calculated, such as queue length, flow rate, congestion. These data will be updated within each iteration and used by the TDSP algorithm in next iteration.

2.4.2. Time-dependent shortest path (TDSP)

The most famous shortest path algorithm was developed by Dijkstra [16]. For each origin, Dijkstra's algorithm picks the origin as start, calculates the distance through it to each unvisited neighbor nodes. If the distance is smaller than the previous one, updates the neighbor's distance and previous-node data. Then pick another node until all nodes have been calculated. After the calculation, each reachable node gets a shortest distance and a previous-node. The shortest path can be found by tracing previous-node from destination. A single-source shortest-paths (SSSP) algorithm by Kumar and Schwabe [20] uses I/O-efficient tournament trees to improve Dijkstra's algorithm. Kumar's algorithm eliminates a graph traversal problem of Dijkstra's algorithm which is keeping track of settled nodes. Meyer and Zeh [21] resolve another problem of Dijkstra's algorithm that is unstructured accesses to the adjacency lists. They use a preprocessing phase where the adjacency lists are re-arranged. However, the preprocessing phase takes time. Only if the number of feasible paths is large enough, is this algorithm proved to be efficient. A* [22] is a goal-directed graph traversal strategy that finds the least-cost path from a given source node to a target node. A* algorithm uses a heuristic function that provides A* a search direction. So the A* traverses a part of the graph while Dijkstra's algorithm will traverse all the nodes. However, the performance of A* depends on the quality of the heuristic function and the function needs to satisfy several conditions [23].

Choosing which algorithms to use depends on the network scope. The A* algorithm eliminates the unidirectional adjacency lists, but this advantage is only obvious when the network is big enough. In other words, the efficiency advantage depends on the number of joint nodes in the networks [23]. Unlike road networks, for key inland waterway network, the number of joint nodes is around 35. However, the heuristic function of the A* algorithm should be monotonic to ensure the algorithm does not have to re-evaluate nodes [22]. Indeed, A* does not guarantee an optimal path when we introduce time-dependence into the model, especially when congestion occurs in the network [24]. The heuristic function will miss the optimal path, although this happens rarely. A preprocessing algorithm is not used because of the dynamics of networks. Since the cost of the route is varying with time, the preprocessing algorithm is meaningless. In the end, Dijkstra's algorithm is not available for time-dependent networks. An improved TDSP algorithm will be illustrated in following chapter.

2.4.3. Path adjustment

In DTA, the purpose of path adjustment is to determine, for a given amount of vehicles in a time-dependent O-D pair, the assignment of trips to respective routes such that the resulting travel times for each trip are equal [8]. Since it is hard to make the travel times equal, this process is used to reduce the relevant gap. Some modern methods (e.g. method of successive averages (MSA) [25], gradient projection [17], origin-based or bush-based algorithms [26] [27]) can be used in this process. The earlier DTA models used MSA while most of the modern methods tended to apply gradient projection-based methods [8].

Method of successive average (MSA)

MSA is also used in static traffic assignment (STA). The difference is, in STA, the path flows are time independent, the averaging on path flows is equivalent to that on link flows; in DTA, the path flows in previous iterations need be assigned onto the network again in the current iteration. For example, in DTA, when some of the trips in one time-dependent O-D pair are taken away from a previous path, the remaining vehicles on that path will be affected (perhaps faster) as well as other vehicles on other paths (perhaps slower or congested). In MSA, a path flow vector represents the path adjustment and it depends on the set of shortest paths found before, on the newly generated shortest path and on the iterations. The iteration is repeated until certain convergence criteria are satisfied. The duality gap [25] can be one of the convergence criteria in MSA. The MSA algorithm stops when the duality gap is below an acceptable error or when the iterations have increased to the maximum number.

Bush-based and origin-based algorithm

Bush-based algorithm can be dubbed Algorithm B. Algorithm B decomposes a user equilibrium (UE) problem into a sequence of origin-restricted UE problems in an acyclic subnetwork. It loads and shifts flow from expensive paths to the cheapest paths with efficiency. It stops when all the used paths costs are equal or in a tolerable range. Algorithm B removes the need for both computer time and storage costs for path enumeration [27]. In algorithm B, "A bush is a subset of arcs of the original problem's network and comprises an acyclic sub-network rooted at a given origin, together with the arc flows that carry all and only trips from that origin to their specific destinations [27]." The B procedure is as below:

1. Initialization: Create initial bush and feasible arc flows for each origin
2. General step: Transform its current feasible bush into an equilibrated bush. Firstly, find the cheapest path and the costliest used path. Secondly, shift trips from costliest used path to the cheapest path. Thirdly, if the bush is not optimal, update the bush with

feasible arc flows but containing cheaper paths. Fourthly, if bush changes, back to first step with a new bush, otherwise repeat first step for next origin's bush.

3. Termination: Quit when every origin's bush is optimal.

The origin-based assignment algorithm [26] is similar to the bush-based algorithm. But Bar-Gera's model adds the transport modality assignment into the model which makes it more feasible for passenger behavior in public transportation.

By comparing different algorithms that are mentioned above, the origin-based algorithms got efficiency in large-scale networks with quantities of trips. For example, Dial's model works on the Chicago regional network, which consists of more than 41200 arcs, 1700 zones and 12900 nodes. The number of trips is more than one million. In the test, origin-based algorithm was much faster than the prevailing alternatives at that time [26]. In our case, origin-based algorithm cannot be transplanted directly for several reasons: The origin-based algorithms use instantaneous travel time for the assignment adjustment. Travel time is calculated by an arc cost-flow function instead of a simulated approach. Besides, as it works for large-scale networks, a lot of details are missed in the process (e.g. waiting queues and congestion of links). Inland waterway transport has a much smaller network with fewer trips, so the simulated approach is available. A modified MSA approach will be illustrated in following chapter.

2.4.4. Quit criterion

Relative gap is a stopping criterion used in DTA models. The relative gap is the gap between total travel time of assigned traffic flows divided by total experience travel time of all vehicles. When the relative gap is close to zero, it means all used routes have travel time very close to the shortest route travel time. The solution is assumed to have converged to an equilibrium solution when the relative gap is less than a pre specified tolerance level.

2.5. Summary of important factors in DTA model

From the literature reviews, main components in DTA models and modeling approach that are needed to be considered in this research are determined. A brief summary on the DTA models is shown in Table 2. The criteria are determined according to *The Primer for Dynamic Traffic Assignment* [2].

Based on the comparison in Table 2 and the objectives of the research, the DTA method for inland waterway networks in this report is selected. The characteristics of the method are described as follows:

1. Modeling considerations

As discussed previously, the model in this research works on a regional scale with a near term or interim period. The model is mesoscopic, which provides more detailed information and dynamics in the network than the macroscopic model. But, compared to the microscopic model, it provides less information and is not a real-time simulation.

2. Model objective

As introduced in Chapter 1, the model should provide route choice which means each traveler will need an optimal path. Then the model objective will be user-optimal. In a relatively stable network, the result is a representation of the network performance because travelers will settle down to optimal routes according to their user-optimal state (lowest cost).

<table>
<tr><th>Criteria</th><th colspan="6">DTA methods</th></tr>
<tr><td rowspan="2">Geographic Scope:
Country and region</td><td colspan="2">Microscopic simulation</td><td colspan="2">Mesoscopic simulation</td><td colspan="2">Macroscopic simulation</td></tr>
<tr><td colspan="2">☒</td><td colspan="2">☑</td><td colspan="2">☑</td></tr>
<tr><td rowspan="2">Facility Type:
Inland waterways</td><td>Dijkstra's</td><td colspan="2">SSSP</td><td colspan="2">Preprocessing phase</td><td>A*</td></tr>
<tr><td>☑</td><td colspan="2">☑</td><td colspan="2">☒</td><td>☒</td></tr>
<tr><td rowspan="2">Travel Mode:
Commercial vessel</td><td colspan="3">MSA</td><td colspan="3">Bush-based</td></tr>
<tr><td colspan="3">☑</td><td colspan="3">☒</td></tr>
<tr><td rowspan="2">Management Strategy:
Operational planning</td><td colspan="3">Instantaneous travel time</td><td colspan="3">Experienced travel time</td></tr>
<tr><td colspan="3">☒</td><td colspan="3">☑</td></tr>
<tr><td rowspan="2">Traveler Response:
Route diversion Pre-Trip</td><td colspan="3">Equilibrium-based DTA approach</td><td colspan="3">Non-equilibrium DTA approach</td></tr>
<tr><td colspan="3">☑</td><td colspan="3">☒</td></tr>
<tr><td rowspan="3">Performance Measures:
Volume
Travel distance
Travel time
Queue Length
User optimization</td><td colspan="3">DTA model</td><td colspan="3">STA model</td></tr>
<tr><td>Simulation-based approach</td><td colspan="2">Overall formulation</td><td colspan="3" rowspan="2">☒</td></tr>
<tr><td>☑</td><td colspan="2">☒</td></tr>
</table>

Table 2 Criteria for selecting DTA method

3. Experienced travel time

As introduced in section 2.2, each traveler's behavior will affect others So instantaneous travel time is not accurate especially when congestion occurs. The experienced travel time becomes an important factor in this research. Even the experienced travel time is actually estimated before trip, but it is closer to real travel time compared to instantaneous travel time.

4. DTA modeling approach

The modeling approach is a main factor in DTA modeling design. For reasons such as optimal path of each individual traveler and relatively stable OD demand matrix and network, the equilibrium-based modeling approach is chosen in this research.

5. Network Loading

Network loading is a simulation procedure, introduced previously. Network loading is realized by a mesoscopic simulation. The model estimates network performance successively on simulation intervals and traffic flows are assigned onto network at each assignment interval. The result of network loading is used as input in the path adjustment procedure.

6. Time-dependent shortest path

The DTA model provides optimal route for each traveler. So the shortest path is an important factor in DTA model design. In this research, an improved TDSP algorithm (based on Dijkstra's algorithm) is used to determine the traveler path.

7. Path adjustment

In a user-equilibrium DTA model, different users with same OD pair and departure time should arrive at destination at the same time. The traffic flow moves from the paths that have longer travel time to paths that have shorter travel time. So the path adjustment is an important factor of model design. In this research, a MSA is used to realize path adjustment.

3. Inland Waterways Network

This chapter describes an overview of the Dutch inland waterways network. It is a summary of the important factors considered in this research. They are the factors used in designing the model, and include waterway navigation, infrastructure elements, reference vessels and the OD demand of the network.

3.1. Waterways

3.1.1. CEMT classification

There are many parameters of the waterway that limit vessel navigation, such as width, depth, and cross-section. The Conference Europeenne des Ministres des Transports (CEMT)classification is used to align the dimensions of waterways in Europe.

	Type de voies navigables Type of inland waterway	Classe de voies navigables Class of navigable waterway	Automoteurs et chalands Motor vessels and barges					Convois poussés Pushed convoys					Hauteur minimale sous les ponts
			Type de bateaux: caractéristiques générales Type of vessel: générales characteristics					Type de convoi- Caractéristiques générales Type of convoy- Générales characteristics					Minimum height under bridges
			Dénomination Designation	Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage		Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage	
				m	m	m	t		m	m	m	t	m
D'INTERET REGIONAL	OF REGIONAL IMPORTANCE	I	Péniche Barge	38,50	5,05	1,80-2,20	250-400						4,00
		II	Kast-Caminois Campine-Barge	50-55	6,60	2,50	4,00-650						4,00-5,00
		III	Gustav Koenings	67-80	8,20	2,50	650-1000						4,00-5,00
D'INTERET INTERNATIONAL	OF INTERNATIONAL IMPORTANCE	IV	Johan Welker	80-85	9,50	2,50	1000-1500		85	9,50	2,50-2,80	1250-1450	5,25/or 7,00
		Va	Grand bateaux Rhenands/Large Rhine Vessels	95-110	11.40	2.50-2.80	1500-3000		95-110	11.40	2.50-4.50	1600-3000	5,25/or 7,00/or 9,10
		Vb							172-185	11.40	2.50-4.50	3200-6000	
		VIa							95-110	22.80	2.50-4.50	3200-6000	7,10/or 9,10
		VIb		140	15.00	3.90			185-195	22,80	2,50-4,50	6400-12000	7,10/or 9,10
		VIc							270-280 193-200	22,80 33,00-34,20	2,50-4,50 2,50-4,50	9600-18000	9,10
		VII							285 195	33.00 34,20	2.50-4.50	14500-27000	9.10

Figure 18 CEMT 1992 classification of waterways [28]

CEMT's history can be traced back to 1954. It is an international classification system which divided waterways into classes, according to their horizontal dimensions [28]. The CEMT classification is based on the dimensions of standard vessel types. The class of a waterway depends on the largest standard vessel that can pass through. The CEMT classification is also used in guidelines for canals, bridges and locks. For example, a class VI waterway can accommodate vessels which have equal or lower CEMT classification. The bridges and locks on the waterway are designed according to class VI. In our model, we use CEMT classification as a property of the waterway. Then it becomes a criterion, deciding whether the vessel can pass through a fairway.

3.1.2. Waterway profile

According to the Policy Document on Mobility, there are four types of waterways: trunk routes, key waterways, other main waterways and other waterways [29]. The trunk routes connect the important transport hubs of Rotterdam and Amsterdam with external waterways, mainly Germany and Belgium. The key waterways connect important economic areas in the Netherlands with the trunk routes. See Figure 19 [28].

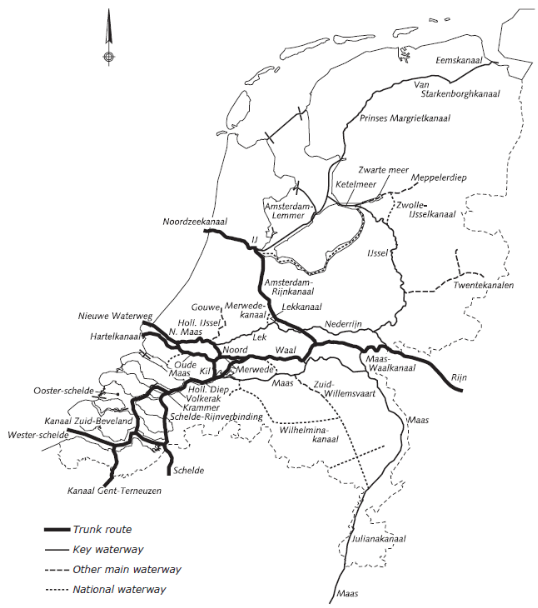

Figure 19 Trunk routes and main waterways

Besides, there are bridges and locks in the network. Some movable bridges need operation time when vessels pass through. Locks need much more time to lift vessels between different water levels, and they are the places where congestions mostly happen.

vessels/year commercial	description	choice of waterway profile
> 50.000	very busy	further investigation required
30.000 – 50.000	busy	further investigation required
15.000 - 30.000	normal	normalprofilefor two-lane traffic
5.000 - 15.000	quiet	normalprofile, narrow profile on short sections
< 5.000	very quiet	narrowprofilefor two-lane traffic, single-lane profile in exceptional cases

Table 3 Appropriate waterway profile and traffic volume of commercial vessels per year [28]

Normally, there are three types of profile for commercial navigation: normal profile for two-lane traffic, narrow profile for two-lane traffic and single-lane profile [28]. Two-lane traffic allows two ships travelling in opposite directions and normally applies to waterways that are up to class V. But if the volume of traffic is more than 30000 commercial vessel movements a year, some further investigation will be made to satisfy the flow. In the Dutch inland waterway network, the trunk route and key waterway is at least class Va and the minimum traffic volume is around 15000 vessels/year [6].

3.2. Vessels

3.2.1. Reference vessels

There are three types of cargo-carrying commercial vessels: motor cargo vessels, pushed convoys and coupled units. Once the waterway class has been selected, the reference motor cargo vessel, pushed convoy and coupled unit must be defined. The reference vessel is the largest vessel that can smoothly and safely navigate the waterway [28]. The Rijkswaterstaat (RWS) 2010 classification is a further specification of the CEMT classification. It distinguishes ship types and contains the current largest motor cargo vessels and coupled units added. Generally, in Netherlands, the RWS classification is used to represent the ship types. In our model, RWS classification is a property of vessel. Details can be found in Appendix 1, 2 and 3.

Ship speed is related to ship type and load type. Loaded ships get lower speed compared to empty ones. According to the BIVAS database [6], the ship speed of all types and loading conditions is shown in Appendix 7. Ship cost consists of labor cost, maintenance cost, insurance cost, interest cost, harbor fees, and so on. All costs are based on the travel time. The maintenance cost is related to travel distance.

3.2.2. Vessel behavior

Figure 20 illustrates the shipping lanes theory which is used to determine the width of a waterway. There are two bank lanes, the safe distance between navigation lane and canal bank. There is at least one safety lane between two navigation lanes. The safety lane is also used for vessel passing or overtaking.

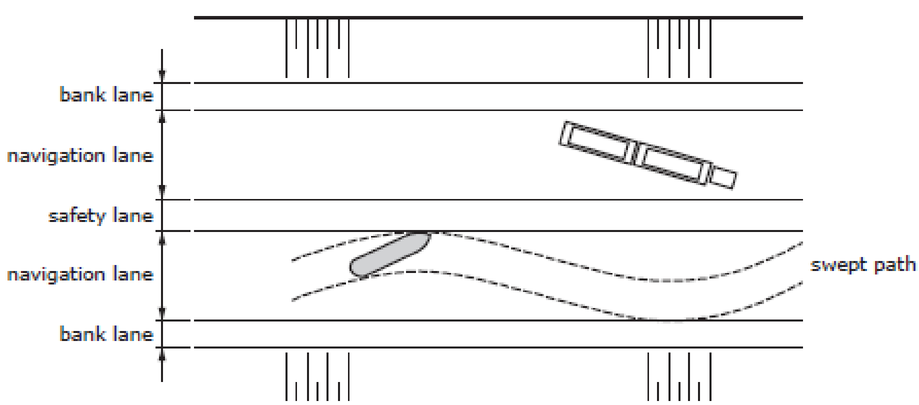

Figure 20 Shipping lanes [28]

On waterways with a maximum traffic volume of 15,000 to 30,000 commercial vessels a year (i.e. normal profile for commercial navigation), the following level of traffic handling should be possible [28]:

- Two laden reference vessels travelling in opposite directions should be able to pass each other with little or no need to reduce speed.

- One laden reference vessel should be able to carefully overtake another (in other words, with a slight reduction in speed)
- A laden reference vessel should be able to pass an unladen reference vessel travelling in the opposite direction in a strong side wind

If the volume of traffic is larger than 30000 commercial vessel movements per year, then further investigation will be needed. Consequently, we may assume that the trunk routes and key waterways have a normal profile for commercial navigation. In other words, vessel movements in opposite directions will not affect each other, and overtaking in same lane is possible with slight speed reduction.

3.3. Infrastructures

There are lots of infrastructures on inland waterways which determine the traffic characteristics of the waterway.

3.3.1. Junctions

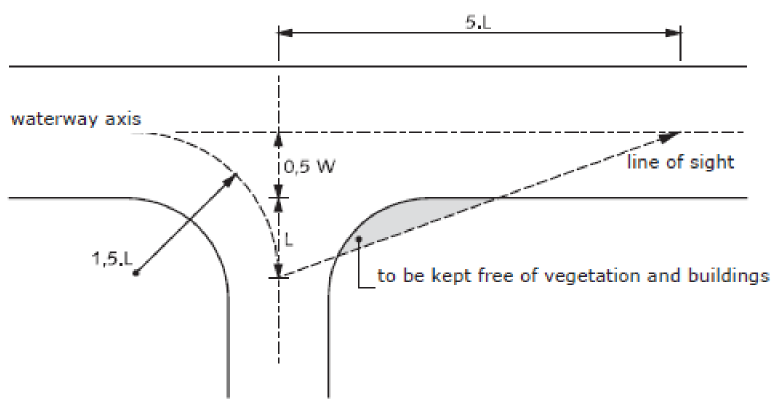

Figure 21 Schematic diagram of junction [28]

Junction of a waterway is a location where waterways cross. Vessels change routes at junctions. Figure 21 illustrates a junction's structure. There will be unimpeded sight for the skipper and enough room for navigating the bend (no need for bend widening to provide extra path width). Consequently, vessels will not sacrifice too much speed on bending while navigating. Unlike road traffic, there are no traffic lights at cross-sections because there is much less traffic load in waterways. If two vessels meet at a junction at the same time, the pass priority is normally decided through consultation.

3.3.2. Ports

Inland ports are an important infrastructure in inland networks. They are mostly multimodal transport hubs. The transport modal can be distinguished as: Dry bulk, wet bulk, container and general cargo (or called remaining cargo, e.g. dangerous cargo and perishable goods). Inland ports connect ocean-going shipping, road and rail with intersections in the area close to the coast and the hinterland. Inland ports have a complete logistic system include loading, unloading and stack. An example can be found in Figure 22. A big inland port has several stacks and can handle all types of cargo. It has a complete and complex supply chain and can handle interaction between different transport modalities. This research will not consider logistic processes in port. We will only consider an inland port as origin or destination in the network. Generally, an inland port has more than one loading/unloading spot which means more than one vessel can depart/arrive at same time.

Figure 22 Inland Port of Antwerp [30]

3.3.3. Locks

Locks in large waterways are customized according to the surroundings and cannot be represented in a general way. Figure 23 illustrates a typical structure of a lock. Generally, the main dimensions of a lock are determined by chamber length, holding basin, reference low water level and the headroom under gates or bridges over the lock. For commercial navigation, a lock handles one vessel at a time, and the sequence is according to first-in-first-out (FIFO). Recreational vessels can be handled together with commercial vessels or, in some cases, at an additional chamber.

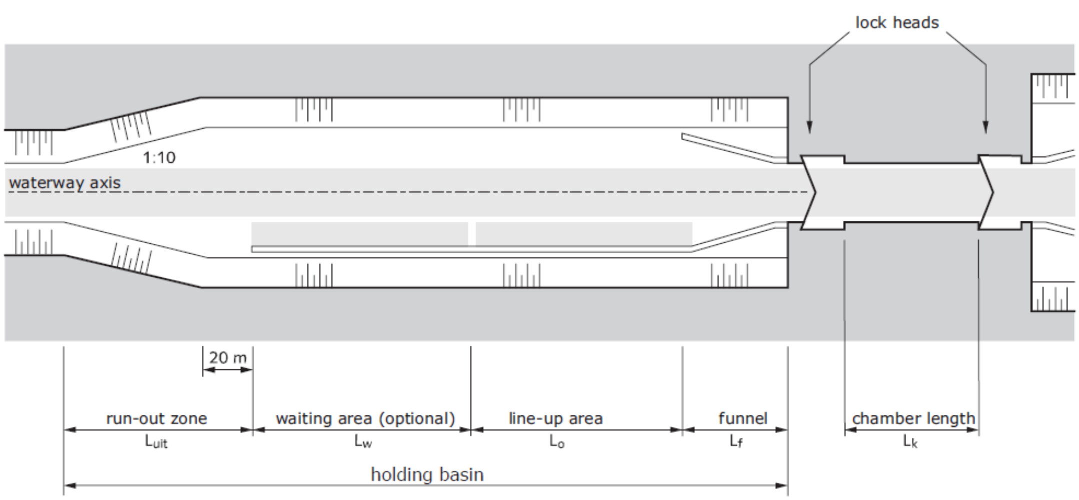

Figure 23 Schematic representation of a typical lock [28]

The congestion of handling of shipping traffic at a lock is represented as a standard waiting time, or as an I/C factor (the ratio of traffic volume to lock capacity). See Figure 24. The standard waiting time for locks on main waterways is an average total waiting time of 30 minutes for commercial vessels in the reference period, usually the busiest months in the spring and autumn [31]. The standard waiting time for each lock is available in the BIVAS database [6]. Normally, most standard waiting times are around 30mins, in some special cases, higher.

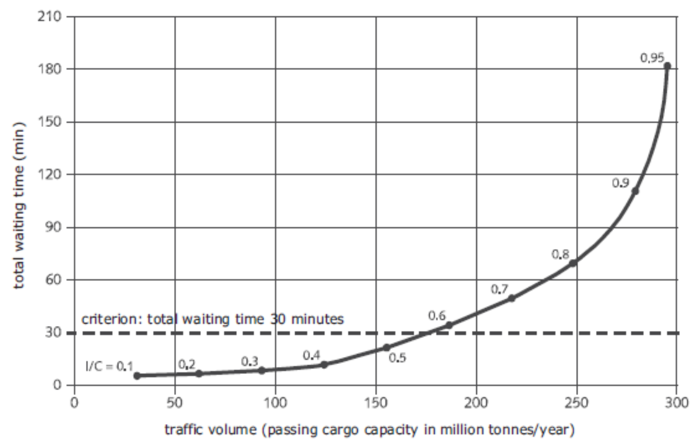

Figure 24 Waiting time at locks as a function of traffic volume

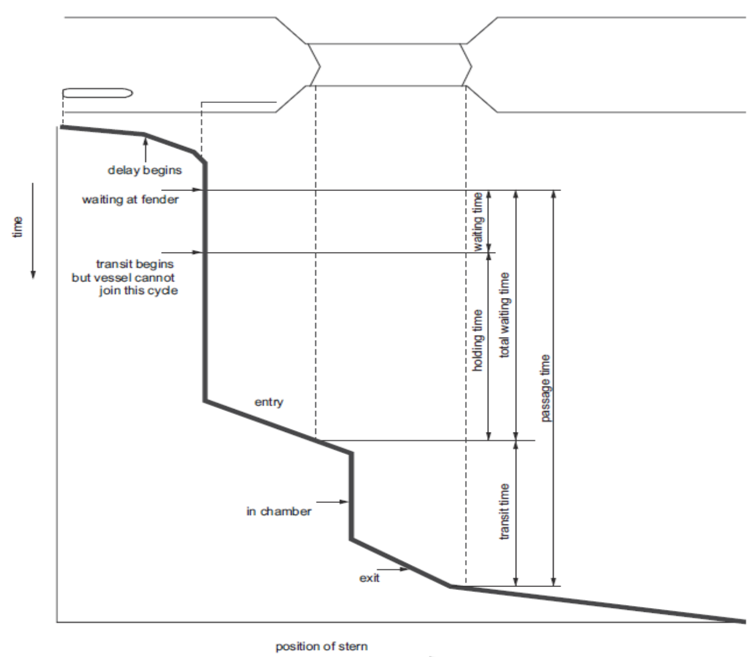

Figure 25 Time-distance diagram of a lock [28]

Figure 25 illustrates the time-distance diagram of a vessel passing through a lock. The passage time is the total time a vessel requires to pass through a lock. Waiting time starts when the vessels arrive at the lock and lasts till the transit time or holding time starts. The holding time starts when the entrance gates close (transit process of previous vessel) and ends when the transit time for the vessel in question begins. The time of entering the chamber is part of the holding time. The transit time ends when the stern of the vessel passes the exit gate. In our model, we separate the passage time into total waiting time and transit time, which are the properties of certain locks. In inland waterway freight transport, the locks are the places where congestion mostly happens. As locks are denoted by nodes in the model, the queues along the corresponding arcs represent the holding basin of the locks.

3.3.4. Bridges

Bridges in the system can be separated into movable and fixed bridges. Fixed fridges have no operation time or transit time. Generally, fixed bridges will not affect vessel travel time. Only movable bridges need be considered in this research.

Figure 26 gives an example of moveable bridges. When a vessel arrives at a bridge, it will wait till the bridge open. In reality, inland water transport gets higher priority than road transport and pedestrian traffic. This means commercial vessels will not be blocked by road transport when it arrives at movable bridges. So the waiting time at movable bridges are fixed based on the bridges operation time.

Figure 26 Schroebrug movable bridge

3.4. Summary

In this chapter, Dutch inland waterways network are analyzed to identify the factors that related to traffic assignment. A summary of the important factors is illustrated as follows:

1. **Waterways**

There are a lot of inland waterway parameters such as depth, width and water level. CEMT classification identifies the navigable waterways and unifies all these parameters into one. In route planning, this limits the vessel's available fairways.

2. **Vessels**

1) Reference vessels

Commercial vessels traveling in inland waterways consist of three types: motor vessels, barges and convoys. RWS class is the classification for vessels and each RWS class corresponds to a CEMT class. Ship speed is related to ship RWS class and loading conditions, while ship cost is related to travel time and travel distance.

2) Overtaking

Section 3.1.2 introduced waterway profile in The Netherlands. The CEMT classification of trunk routes and key waterways are higher than Va and use normal profile for two-lane traffic. Section 3.1.3 introduces the shipping lanes theory for commercial navigation. The shipping lanes theory for normal waterway profile regulates vessels in two directions in same waterway. They will not affect each other or overtake one another.

3. Infrastructures

1) Junction:
Junction in inland waterway will guarantee a clear field of vision for the shipper and allow the smooth passing of vessel. There are no traffic lights on junction. Consequently, when vessels arrive at junctions, there is no waiting time or speed reduction. For route planning, junctions are decision points for different routes but with no passing time.
2) Ports:
The cargo handling in inland ports can be distinguished into 4 types: dry bulk, wet bulk, container and remaining cargo. Several vessels can depart/arrive from/to a port at the same time. This means two vessels having same OD pair and departure at the same time need to be considered. The logistic processes in ports are complicated. So the loading/unloading processes and interaction between inland waterway transport with other transport modalities will not be considered in this model.
3) Locks:
Locks are the main places where congestion happens. Locks consist of chamber length and holding basin. The waiting time at locks consists of lockage time (time for handling traffic) and waiting time. The waiting time can be expressed as standard waiting time or I/OC factor. A lock operates on one commercial vessel for each operation cycle.It handles recreational as well as commercial vessels. In most cases, recreational navigationdoes not affect commercial navigation.
4) Bridges:
Bridges can be classified into fixed and movable. Fixed bridges will not affect inland waterway transport. Movable bridges have operation time for commercial navigation and the operation time is based on the bridge design. in The Netherlands, waterway transport has priority over road traffic, so vessels will not wait for road traffic and the transit time equals the bridge operation time.

Subsequently, these factors are used to design a DTA model for inland waterway networks.

4. DTA Model Design

In this chapter, the DTA model for inland waterways is formulated. The model takes in all the important factors that have been identified in previous chapters. The DTA model consists of two sub-models: network and mathematical.

In the network model, the main purpose is to build up a model for the inland waterways network. The other sections formulate the mathematical model for the inland waterways freight DTA model.

4.1. Network structure

The traffic network is represented by a map consisting of nodes and links. The nodes can denote geographic points (e.g. network boundaries and intersections) or infrastructures (e.g. bridges, locks and ports). Nodes like boundaries and intersections do not have transit time while nodes like bridges or locks have specific transit times. The links represent the waterway between two nodes with unidirectionality. This separates one normal waterway into two links, one for each direction. And each node has at least two connected links, one is incoming, the other is outgoing. Since this model is mesoscopic, the lanes of waterways are not represented separately, and traffic details like overtaking will not be shown in the model.

4.1.1. Link model

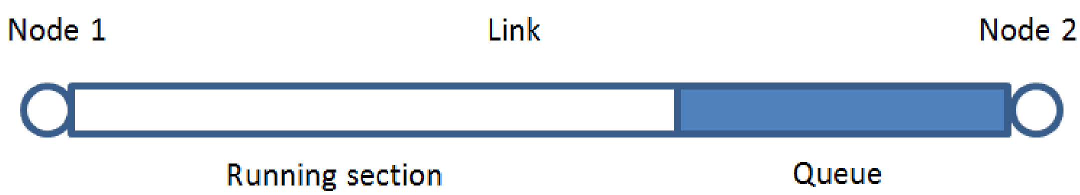

Figure 27 Representation of a link

As can be seen in Figure 27, the link is divided into two parts, the running part and the queue part. The queue part starts at the downstream node and grows towards the upstream node, when the incoming flow exceeds the outgoing flow on the link. For instance, when a traffic light at the downstream node goes to red, the queue part will grow. The running part is the part of the link that contains vehicles that are on their way to the downstream node, but are not (yet) delayed by the downstream capacity limit (e.g. the traffic light). This means that the boundary between the running part and queue part is dynamic, and usually varies over time, depending on the variations in the inflow and outflow. In the case of an empty link, there is no queue, and the running part occupies the whole link. Conversely, if the whole link is full, the queue occupies the whole link, and there is no running part.

4.1.2. Node model

Each node has the two coordinates, X and Y, which determine the node position in two-dimensional space. Nodes can be classified into two types: boundary points and junction points.

Boundary is a geographic point connecting Dutch key waterways with foreign waterways or with smaller level waterways. A boundary can be an origin or destination of a trip. Boundary nodes have no transit time. When a vessel needs to move to some location out of the system (e.g. to a location in Germany), the vessel is considered to move out of our scope. We then regard the boundary node as the ultimate destination. When vessels come in from a foreign country, we set boundary nodes as the origins.

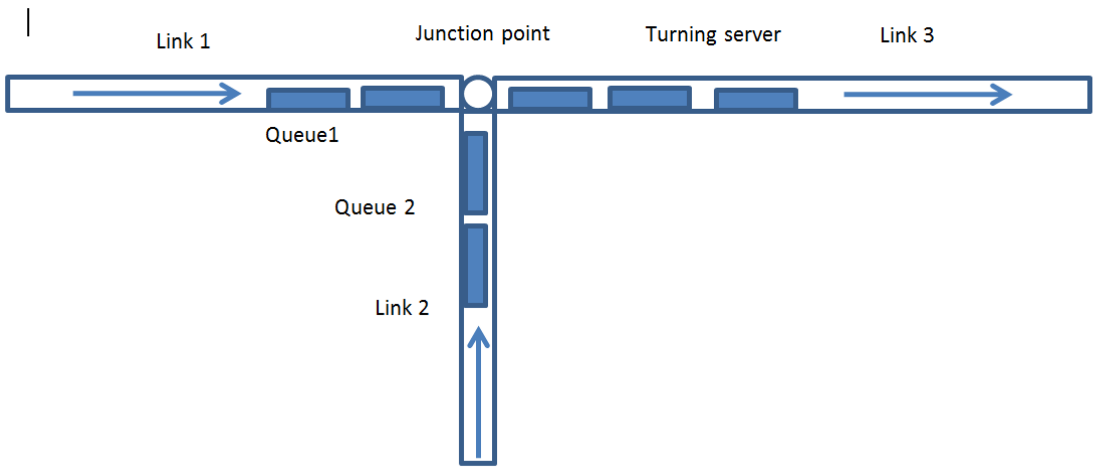

Figure 28 Junction points connecting two incoming links to one outgoing link

Junction point or intersection is a geographic point where multiple waterways join or diverge. There are no traffic lights at intersections. It means there will not be traffic waiting at junction points. Also, junction points have no transit time; here we ignore the velocity loss of vessels at intersections. Generally, if a downstream link is not totally congested, there will be no congestion in the upstream link. But, in the unlikely event that a downstream link is totally congested, a turning server is needed.

As shown in Figure 28, link3 is the downstream link of link1 and link2. Link3 is totally blocked, causing congestion in both link1 and link2. The function of the turning server is to decide the entering sequence of vehicles that are in the queues of link1 and link2.

4.2. User equilibrium

We consider a network with multiple origins and destinations. The traffic network is represented by a directed graph with nodes and directed links. The period of analysis is denoted by $[0,T]$. A time-dependent OD demand is assumed to be known and given as $d_{rs}(t)$ which denotes the traffic demand to the destination node s departing from the origin node r at time t. Let $P_{rs}(t)$ be the set of paths between OD pair r-s for those travelers leaving their origin node r at time t. Assuming that the traffic flow leaving origin r at time t via path p between OD pair r-s is $f_{rsp}(t)$, the flow conservation equations can be written as

$$d_{rs}(t) = \sum_{p \in P_{rs}(t)} f_{rsp}(t) \;\; \forall r, s, t \qquad (1)$$

Denote $A_a(t)$ as the cumulative arrival curve recording the number of vehicles entering link a by time t and $D_a(t)$ as the cumulative departure curve recording the number of vehicles departing from link a by time t. Assuming that the network is empty at time $t = 0$, then we have $A_a(t) \geq D_a(t)$. The number of vehicles traversing link a at time t can be calculated as

$$x_a(t) = A_a(t) - D_a(t) \ \forall a, t \tag{2}$$

Let $L_{rsp}(t) = (a_1, a_2, \dots, a_m) \in P_{rs}(t)$ be a sequence of m consecutive links on the path p between OD pair r-s for vehicles embarking at time t, and $T_{rspa}, \forall a \in L_{rsp}(t)$ be the time a vehicle leaves the link a while on the way to destination node s. We have

$$T_{rspa_i} = T_{rspa_{i-1}} + \tau_{rspa_i}, i = 1, 2, \dots, m \tag{3}$$

Where τ_{rspa_i} is the time that the vehicle spends on link a. With $T_{rspa_0} = t$, The actual travel time on the path becomes

$$\mu_{rsp}(t) = T_{rspa_m} - t, \tag{4}$$

where T_{rspa_m} is the arrival time at the destination node s, when a vehicle embarks onto the network at time t and travels on path p between OD pair r-s.

The predictive dynamic user equilibrium conditions are satisfied when

$$d_{rs}(t) \cdot \left| \mu_{rsp_m}(t) - \mu_{rsp_n}(t) \right| = 0 \ \forall r, s, t, p \tag{5}$$

Eq.(5) means all vehicles departing at time t in OD pair r-s have the same travel time with different routes. Then the predictive dynamic user equilibrium conditions are equivalent to the following minimization problem:

$$minimize \ Z = \sum_{\forall r,s,p} \int_0^T f_{rsp}(t)dt \tag{6}$$

Subject to

$$d_{rs}(t) = \sum_{p \in P_{rs}(t)} f_{rsp}(t) \ \forall r, s, t \tag{7}$$

$$f_{rsp}(t) \ \geq 0 \ \forall r, s, t, p \in P_{rs}(t) \tag{8}$$

4.3. Network loading

In this section, it is assumed that the set of paths between OD pairs at any instant and the corresponding path flow values have been determined from the previous iterations. These traffic flows are then loaded onto the network, using a traffic simulation model, thereby forming a building block to solve the predictive dynamic user-optimal assignment problem. As usual, the period of analysis *[0, T]* is divided into m_τ number of intervals, each of length τ, where the number of vehicles travelling between OD pair *r-s* departing from the origin during the t_{th} time interval is given by

$$d_{rst} = \int_{(t-1)\tau}^{t\tau} d_{rs}(t)dt, \ \ t = 1,2, \dots, m_T \tag{9}$$

Similarly, the number of vehicles travelling on path $p \in P_{rst}$ between OD pair r-s departing from the origin during the t_{th} time interval is given by

$$f_{rspt} = \int_{(t-1)\tau}^{t\tau} f_{rsp}(t)dt, \ \ t = 1,2, \dots, m_T \tag{10}$$

where P_{rst} is the set of paths used by vehicles between OD pair r-s during the t_{th} time interval. We assume that this set of paths is used throughout the t_{th} interval. We assume further that the vehicles f_{rspt} are loaded onto the network incrementally in time.

There are then two sub-processes in network loading. The first sub-process traces all the vehicles in a time interval t in all links and the second sub-process manages the queue. In a particular time interval t, the location of a vehicle on a link can be easily traced out using the speed as follows:

$$\gamma_{at} = \gamma_{at-1} + \tau v_{at} \tag{12}$$

Where γ_{at} is the distance of the location of vehicles measured from the starting nodes of link a at the end of the t_{th} time interval, and v_{at} is the vehicle velocity in link a at time interval t.

When a vehicle arrives at the end node of a link, it will join the queue with an entry time. If a vehicle remains in the same link a after traversing a complete time interval t, the location of the vehicle γ_{at} is updated according to Eq.(12). However, if a vehicle moves from an upstream link a to a downstream link b within the t_{th} time interval, it will enter the queue of link a, and its entry time t_a is recorded.

After tracing all vehicles in the t_{th} time interval, the queues of all links are updated. Some situations, such as transit time of nodes and jams in downstream link, may block a vehicle in the current link.

However, the queue mechanism solves the shifting of vehicles between links. In the t_{th} time interval, if the downstream link is not blocked, the queue of the upstream link will let vehicle enter the downstream link. The vehicle's initial position at the downstream link for the next time interval will be determined based on the vehicle velocity and remaining time after which it arrived at the end node of the upstream link.

Let x_{at} be the number of vehicles on link a at time interval t and δ_a be the transit time of end node of link a. In such cases, the density of links is updated by

$$x_{a,t+1} = x_{a,t+1} - 1 \tag{13}$$

and

$$x_{b,t+1} = x_{b,t-1} + 1 \tag{14}$$

The vehicle position is updated by

$$\gamma_{b,t+1} = v_{b,t+1}(\tau t - t_a - \delta_a)\ , when\ (\tau t - t_a - \delta_a)\ \geq 0 \tag{15}$$

When $(\tau t - t_a - \delta_a)\ < 0$, this means the remaining time is less than the transit time of the end node. So the vehicle will stay in the queue and wait for the next time interval. When the downstream link is blocked, the vehicle will keep in queue and wait until the density of the downstream link falls below the jam density at a later time. In time interval t, if the queue become empty, the time point will be recorded as $\varepsilon_{a,t}$ which denote empty time of link a at t_{th} time interval.

The network loading procedure is repeated until all time intervals have been dealt with. The result can then be used in TDSP algorithm. Figure 29 illustrates the network process with a flow chart.

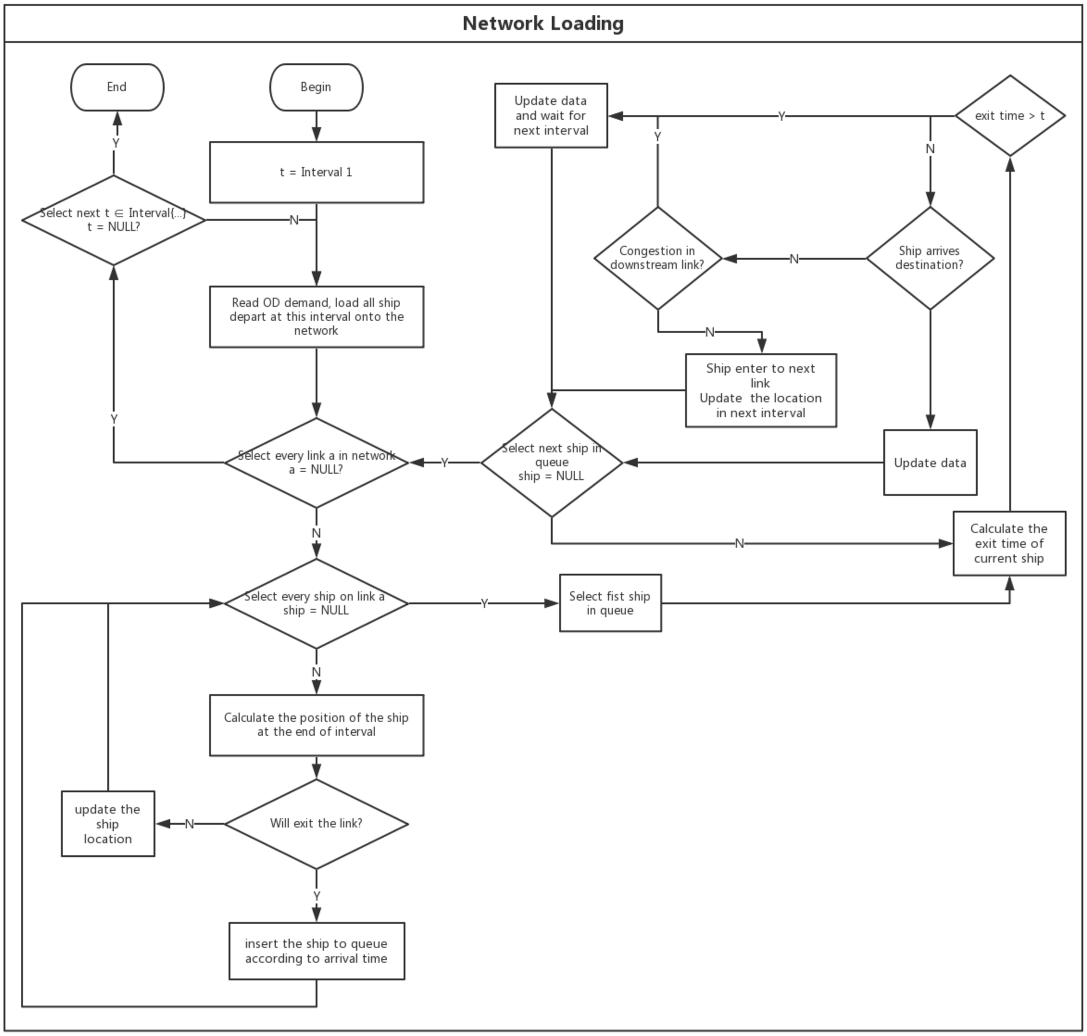

Figure 29 Flow chart of network loading process

4.4. Time-dependent shortest path

The search for time-dependent shortest path basically follows from Dijkstra. For a particular vehicle leaving its origin r at time t, let λ_{rtA} be the time this vehicle just leaves node A and ψ_{rtA} be the predecessor or back node of A so that the link (ψ_{rtA}, A) forms part of the shortest path from the origin r embarked at time t to the node A. A loose-end table $\mathbb{L}$ is defined such as to contain nodes already reached by the shortest path algorithm but not fully explored as predecessors for further nodes.

The time-dependent shortest paths from node r to all destinations s in the network are determined by the following procedure:

Step 1: Set all $\lambda_{rtA} = \infty$ except $\lambda_{rtA} = t$, and $\mathbb{L} = \emptyset$;

Step 2: Start with the origin node r as a current node A;

Step 3: Examine each link $a = (A, B)$ from the current node A in turn, and if $\lambda'_{rtB} < \lambda_{rtB}$ (λ'_{rtB} *is the time that travel along link* a) then set $\lambda_{rtB} = \lambda'_{rtB}, \psi_{rtB} = A$, and add B to $\mathbb{L}$ when B is not a destination node. λ'_{rtB} is calculated by the following network loading procedure:

$$\lambda'_{rtB} = \max\left\{\lambda_{rtA} + \frac{L_a}{v_{a,i}}, \varepsilon_{a,i}\right\}, where\ i \geq \frac{\lambda_{rtA}}{\tau} \tag{16}$$

Step 4: Remove A from $\mathbb{L}$, and if the loose-end table is empty then stop;

Step 5: Select a node L_i from the loose-end table such that λ_{rtL_i} is the minimum among all the nodes in the table, and then return to Step 3 with L_i being set as the current node.

From the above, the sequence of consecutive links on the path p, $L_{rsp}(t) = (a_1, a_2, \ldots, a_m)$, can be traced as follows: $a_m = (\psi_{rts}, s), a_{m-1} = (\psi_{rt\psi_{rts}} - \psi_{rts})$ etc.. The actual travel time on the minimum path becomes $\lambda_{rtA} - t$.

With these time-dependent shortest paths, the predictive dynamic user-optimal assignment problem can be solved by the path adjustment algorithm. Figure 30 shows a flow chart of shortest path algorithm.

4.5. Path adjustment

The Method of Successive Averages (MSA) is a simple but effective method in static assignment. It is based on a pre-determined series of step sizes for overcoming the problem of allocating traffic to congested links. By proper choice of the node size in each iteration, MSA in static assignment converges to the Wardrop equilibrium solution. In dynamic assignment, the MSA needs a slight modification.

Let $\mathbb{F}^{(n)} = \left\{f^{(n)}_{rspt}\ \forall r, s, t, p \in P^{(n)}_{rst}\right\}$ be the path flow vector at the n_{th} iteration, , n = 0,1, 2, … , where $P^{(n)}_{rst}$ is the set of all paths obtained from previous iterations so far, and $f^{(n)}_{rspt}$ is the corresponding path flow value. These path flows are then loaded onto the network as shown in network loading procedure in Figure 31. The set of TDSP for all OD pairs at all time intervals, $\mathbb{Y} = \{y_{rst}\ \forall r, s, t\}$, is determined from the TDSP algorithm, where y_{rst} is the shortest path for a vehicle travelling to the destination node s from the origin node r, departing at time t.

If the shortest path is newly generated ($P^{(n)}_{rst} \cap y_{rst} = \emptyset$), the updated path flow vector is determined by

$$f^{(n+1)}_{rspt} = \begin{cases} \dfrac{n}{n+1} f^{(n)}_{rspt} & if\ p \in P^{(n)}_{rst} \\ \dfrac{1}{n+1} d_{rst} & if\ p = y_{rst} \end{cases} \quad \forall r, s, t \tag{17}$$

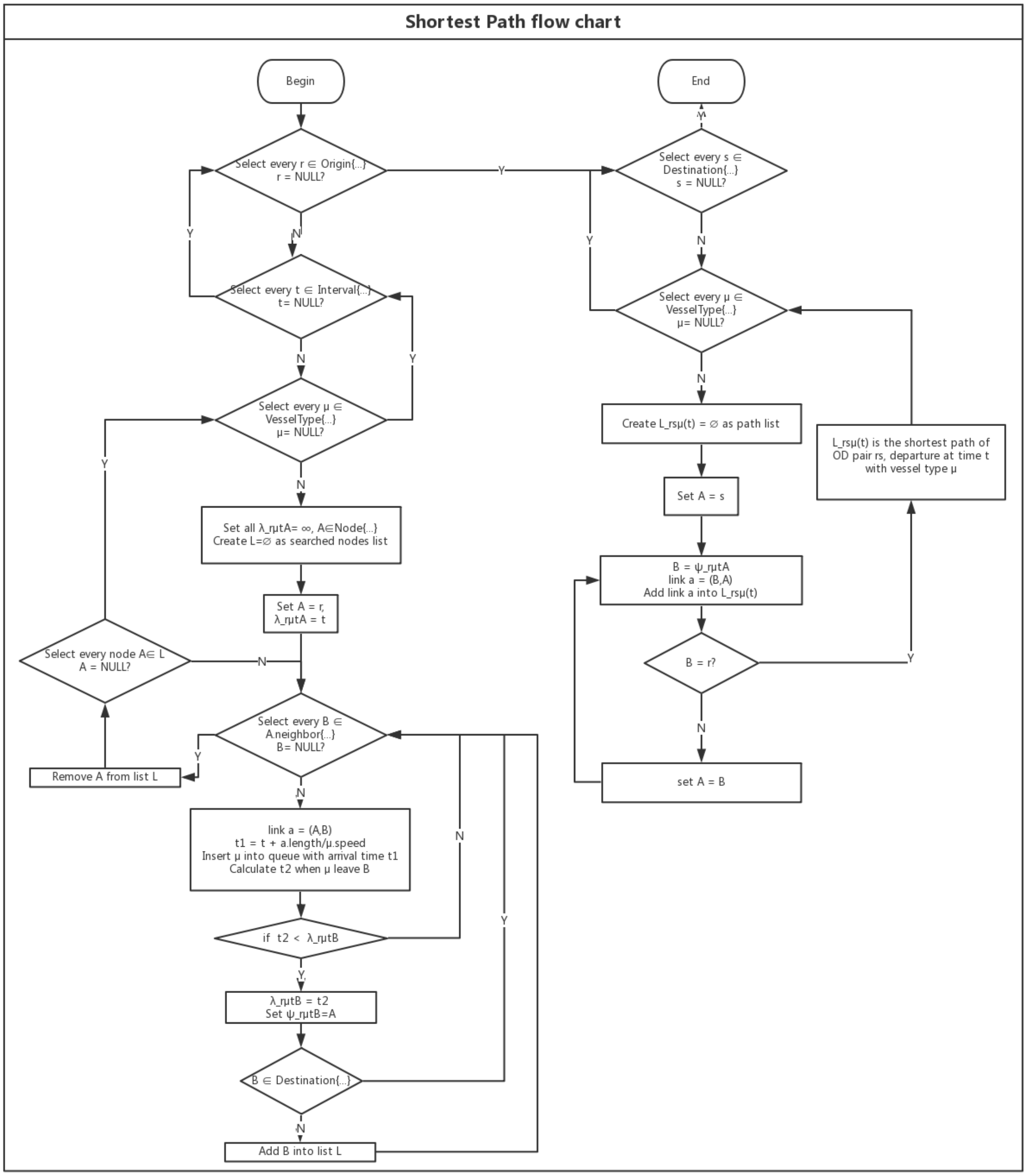

Figure 30 Flow chart of time-dependent shortest path

The set of used paths at the *(n+1)th* iteration is updated as $P_{rst}^{(n+!)} = P_{rst}^{(n)} \cup y_{rst}$. However, if the shortest path is an old path ($y_{rst} \in P_{rst}^{(n)}$), the updated path flow vector becomes

$$f_{rspt}^{(n+1)} = \begin{cases} \frac{n}{n+1} f_{rspt}^{(n)} & if\ p \neq y_{rst} \\ \frac{n}{n+1} f_{rspt}^{(n)} + \frac{1}{n+1} d_{rst} & if\ p = y_{rst} \end{cases} \quad \forall r, s, t \tag{18}$$

And the set of used paths remains ($P_{rst}^{(n+!)} = P_{rst}^{(n)}$). The above-mentioned procedure is repeated until certain convergence criteria are satisfied.

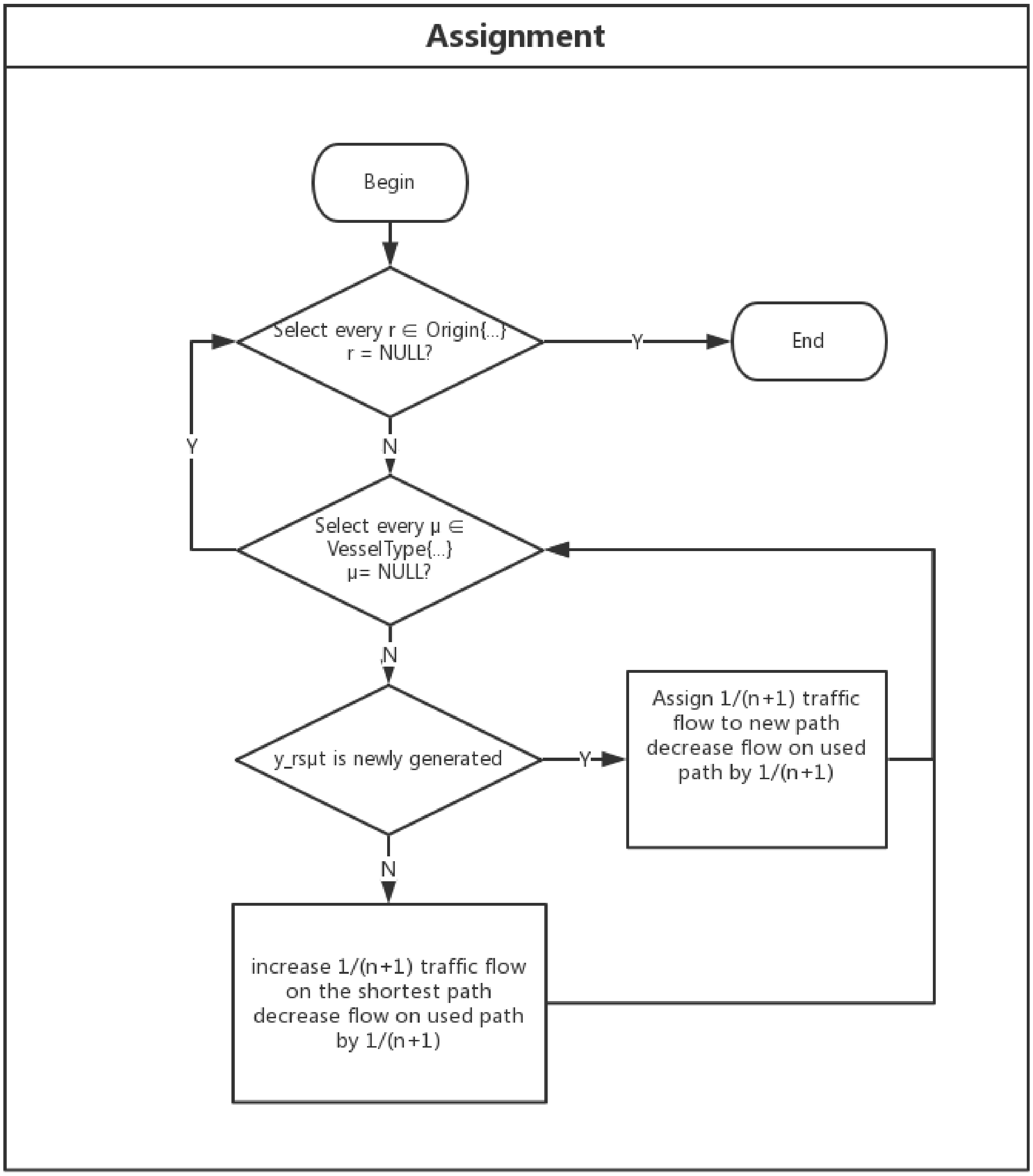

Figure 31 Flow chart of path adjustment

4.6. Relative Gap

The relative gap is a rather common stopping criterion also used by static traffic assignment models. The typical definition of the total relative gap is

$$rel_{gap} = \frac{\sum_t \sum_{i\in I}\left(\sum_{k\in K_i} f_k^t \tau_k^t\right) - \sum_t \sum_{i\in I} d_i^t u_i^t}{\sum_t \sum_{i\in I}\left(\sum_{k\in K_i} f_k^t \tau_k^t\right)}$$

Where

T = set of all departure time intervals

t = departure time interval, $t \in T$

I = set of all origin-destination trip pairs

i = origin-destination trip pair, $i \in I$

K_i = set of all used routes for origin-destination pair i

k = used route for origin-destination pair i, $k \in Ki$

f_k^t = flow from used route k at departure time interval t

τ_k^t = experienced travel time on used route k at departure time interval t

d_i^t = total flow from origin-destination pair i at departure time interval t

u_i^t = shortest route travel time from origin-destination pair i at departure time interval t

The numerator is the total gap, which measures how far the current the assignment solution is from the ideal shortest route time. Taking the total gap divided by the total shortest path times describes the ratio of the total gap to the total shortest path times.

Intuitively, the relative gap tells us that, if all used routes have travel time very close to the shortest route travel time, then the numerator will be close to zero, and the relative gap value will be small. Since the travel time on all used routes will always be greater than or equal to the shortest route, the value of relative gap will never be negative. In most DTA applications, the solution is assumed to converge to an equilibrium solution when the relative gap is less than a pre-specified tolerance level.

4.7. Summary

In this chapter, a DTA model for inland waterway network is designed. The network model is composed of nodes and links. Nodes can be infrastructures or junctions of links, while links represent waterways. Infrastructures have special dynamic design characteristics, such as the service time of a bridge and the queues of vessels at a lock. The network loading process, time-dependent shortest path process and path adjustment process work together as a loop until there is a relative gap below the quit criteria. The following chapter will discuss the validation and application of the model.

5. Case Study and Model Validation

In this chapter, a case study is used to validate the DTA model. The case study simulates OD pairs in the waterways between Rotterdam to Antwerp. The results of the model are then compared with the results from a static model and with real data.

5.1. Network Setup

Here we choose one OD pair, namely from Rotterdam to Antwerp. It happens to be one of the busiest freight fairways in the Dutch inland waterways. We choose 1st of July as the simulation period. The network graph can be found in Figure 32.

The infrastructure elements are

Port: Rotterdam port has 5 loading/unloading points and Antwerp port has 2 loading/unloading points. Ports are Origin or Destination in the model. The position of ports can be found in Figure 32. In the model, each port is represented as a node. The OD pair for ships is recorded as from origin node to destination node. However, the operation of ports is not taken into account in the model. So a port has no operation time.

Bridges: In our model, we only consider moveable bridges, as they are the ones that have service time. However, as mentioned in section 3.2.3, we must bear in mind two qualifications with regard to bridges: firstly, inland waterway traffic gets priority over road traffic; secondly, the operation time of bridges is short. Besides, one bridge may allow several ships to pass simultaneously and a ship may pass a bridge by following the ship in front instead of waiting for another bridge operation. For these reasons, there is rarely congestion at bridges. Therefore, in our model, the passing time at bridges is fixed, in most cases, 5 minutes.

Locks: There are 5 locks in this network: Rozenburgsesluis, Hansweert sluis, Volkeraksluizen, Krammersluizen and Kreekraksluizen. As mentioned in 3.2.3, a lock is the place where the most congestion occurs. In static models, a fixed waiting time is used to estimate the lock passage time.Such models assume that this time depends on the average waiting time from the previous year.

In contrast, in our model, locks are represented as nodes each having a lock server. During the simulation's network loading process, when a ship enters a lock, the lock server calculates the waiting time and passage time, taking into account the other ships waiting at the lock.

Figure 32 Inland waterway network of Rotterdam- Antwerp

5.2. Model simulation input

OD demand

On 1st July 2014, there are 19 trips departing from Rotterdam to Antwerp. The details can be found below in Table 4 [32].

Other trips

According to the BIVAS and IVS databases, there are a total of 408 ship passage times across these locks and waterways. The arrival time of each trip is available. So all trips passing through the network on 1st July 2014 are known to us.

Ship speed

Ship speed depends on the load type and ship type. The ship speed of each trip comes from the BIVAS database.

Date	Origin	Desti-nation	Load Type	Total Weight	Depth	Load Capacity	Length meters	Width meters
01/07/2014 09:35	Rotterdam	Antwerp	Empty	Null	1.3	1629	86	8.62
01/07/2014 06:01	Rotterdam	Antwerp	Loaded	1050	2.4	1495	86	9.5
01/07/2014 01:10	Rotterdam	Antwerp	Loaded	Null	1.9	3306	110	11.4
01/07/2014 04:25	Rotterdam	Antwerp	Loaded	1022	2.4	1637	110	10.46
01/07/2014 22:09	Rotterdam	Antwerp	Loaded	500	2.2	896	70	10.3
01/07/2014 11:51	Rotterdam	Antwerp	Loaded	5900	4.3	6350	135	15
01/07/2014 07:40	Rotterdam	Antwerp	Loaded	4860	3.7	5977	135	15
01/07/2014 01:20	Rotterdam	Antwerp	Loaded	1880	2.6	2705	110	11.4
01/07/2014 22:09	Rotterdam	Antwerp	Loaded	3398	3.63	4200	110	13.5
01/07/2014 16:29	Rotterdam	Antwerp	Loaded	1998	2.75	3135	110	11.45
01/07/2014 06:47	Rotterdam	Antwerp	Loaded	430.62	1.39	6396	135	17.1
01/07/2014 12:00	Rotterdam	Antwerp	Empty	Null	1.2	1697	80	8.5
01/07/2014 03:05	Rotterdam	Antwerp	Loaded	500	2.17	896	70	10.3
01/07/2014 20:02	Rotterdam	Antwerp	Loaded	3500	3.5	4043	125	11.45
01/07/2014 08:41	Rotterdam	Antwerp	Empty	Null	1.6	3495	110	13.5
01/07/2014 08:03	Rotterdam	Antwerp	Empty	Null	1.5	1850	85	10.5
01/07/2014 12:06	Rotterdam	Antwerp	Empty	Null	2.5	1702	86	9.6
01/07/2014 23:09	Rotterdam	Antwerp	Loaded	925	2.77	1635	86	9.6
01/07/2014 15:23	Rotterdam	Antwerp	Empty	Null	1.35	2494	110	11.4

Table 4 OD demand

5.3. Simulation results

5.3.1. DTA output (table)

Trips

All trips and simulation results are shown in Table 5 below.

Trip ID	Lock Name	Enter Time	Exit Time	Waiting Time_hr	Mooring distance_km	Total Travel Distance_km	TotalWating Time_hr	Experienced Travel Time_hr
62212	Volkerak sluizen	01/07/2014 04:03	01/07/2014 04:11	0.13	2	96.574	0.65	6.79
62212	Kreekrak sluizen	01/07/2014 06:15	01/07/2014 06:47	0.52	3.4	96.574	0.65	6.79
187558	Volkerak sluizen	01/07/2014 09:34	01/07/2014 11:22	1.79	7.6	96.574	2.36	8.66
187558	Kreekrak sluizen	01/07/2014 13:29	01/07/2014 14:04	0.57	7.4	96.574	2.36	8.66
223036	Volkerak sluizen	01/07/2014 05:02	01/07/2014 05:10	0.13	1.8	96.574	0.31	7.2
223036	Kreekrak sluizen	01/07/2014 07:30	01/07/2014 07:41	0.18	3.6	96.574	0.31	7.2
241231	Volkerak sluizen	01/07/2014 08:32	01/07/2014 09:14	0.69	4.6	96.574	0.87	8.19
241231	Kreekrak sluizen	01/07/2014 11:42	01/07/2014 11:53	0.18	5.8	96.574	0.87	8.19
304418	Volkerak sluizen	01/07/2014 16:16	01/07/2014 17:22	1.09	14.8	88.623	2.79	10.11
304418	Kreekrak sluizen	01/07/2014 19:50	01/07/2014 21:33	1.7	12.2	88.623	2.79	10.11
314738	Volkerak sluizen	01/07/2014 15:58	01/07/2014 17:06	1.12	15	92.377	2.54	9.86
314738	Kreekrak sluizen	01/07/2014 19:34	01/07/2014 21:00	1.42	12.2	92.377	2.54	9.86
316328	Volkerak sluizen	01/07/2014 11:13	01/07/2014 12:58	1.74	9.8	96.574	2.19	8.49
316328	Kreekrak sluizen	01/07/2014 15:05	01/07/2014 15:33	0.45	8.8	96.574	2.19	8.49
322352	Volkerak sluizen	01/07/2014 05:27	01/07/2014 06:10	0.71	2.8	96.574	0.89	8.21
322352	Kreekrak sluizen	01/07/2014 08:38	01/07/2014 08:49	0.18	4.4	96.574	0.89	8.21
325811	Volkerak sluizen	01/07/2014 16:16	01/07/2014 17:14	0.96	14.8	88.623	2.61	9.93
325811	Kreekrak sluizen	01/07/2014 19:42	01/07/2014 21:22	1.65	12.2	88.623	2.61	9.93
338368	Volkerak sluizen	01/07/2014 20:02	01/07/2014 23:30	3.46	23.2	96.574	3.64	9.94
338368	Kreekrak sluizen	02/07/2014 01:37	02/07/2014 01:48	0.18	15	96.574	3.64	9.94
340031	Volkerak sluizen	01/07/2014 11:53	01/07/2014 13:38	1.74	10.6	96.574	1.92	11.02
340031	Kreekrak sluizen	01/07/2014 16:44	01/07/2014 16:55	0.18	9	96.574	1.92	11.02
357393	Volkerak sluizen	01/07/2014 16:07	01/07/2014 17:14	1.11	15	92.377	2.58	9.89
357393	Kreekrak sluizen	01/07/2014 19:42	01/07/2014 21:11	1.47	12.2	92.377	2.58	9.89
363655	Volkerak sluizen	01/07/2014 08:11	01/07/2014 08:58	0.78	4.4	92.377	1.68	10.77
363655	Kreekrak sluizen	01/07/2014 12:04	01/07/2014 12:58	0.9	6.4	92.377	1.68	10.77
367383	Volkerak sluizen	01/07/2014 15:08	01/07/2014 16:10	1.03	13.8	96.574	2.58	11.67
367383	Kreekrak sluizen	01/07/2014 19:16	01/07/2014 20:49	1.55	12.2	96.574	2.58	11.67
373687	Volkerak sluizen	01/07/2014 13:47	01/07/2014 14:42	0.91	11.8	96.574	1.34	10.44
373687	Kreekrak sluizen	01/07/2014 17:48	01/07/2014 18:14	0.43	10.2	96.574	1.34	10.44
381311	Volkerak sluizen	01/07/2014 12:18	01/07/2014 13:46	1.46	10.6	96.574	1.64	9.2
381311	Kreekrak sluizen	01/07/2014 16:20	01/07/2014 16:31	0.18	9.2	96.574	1.64	9.2

393 284	Volkerak sluizen	01/07/201 4 16:21	01/07/201 4 17:30	1.14	14.8	96.574	2.8	10.36
393 284	Kreekrak sluizen	01/07/201 4 20:04	01/07/201 4 21:44	1.66	12.2	96.574	2.8	10.36
404 853	Volkerak sluizen	01/07/201 4 17:16	01/07/201 4 19:22	2.09	17.4	92.377	2.89	10.21
404 853	Kreekrak sluizen	01/07/201 4 21:50	01/07/201 4 22:39	0.8	13	92.377	2.89	10.21
241 762	Volkerak sluizen	01/07/201 4 19:30	01/07/201 4 21:54	2.39	21	96.574	2.86	10.18
241 762	Kreekrak sluizen	02/07/201 4 00:22	02/07/201 4 00:51	0.47	15.2	96.574	2.86	10.18

Table 5 DTA trip statistics

The total waiting time is for a trip during which there is a wait at the locks. A trip's total waiting time depends on the time the vessel arrives at the lock. Our simulation calculates the experienced travel time of the trip upon arrival at the destination Antwerp. This contrasts with static models, which may calculate total waiting times before departure from the origin Rotterdam. The experienced travel time simulates the reality of a trip, as it considers all possible interactions within a trip and between trips. In our model, there are moorings for each trip. The distance between ships is assumed to be 100 m, and waiting time is assumed to be proportional to mooring distance.The 19 trips all go through the Volkeraksluizen and Kreekraksluizen locks. Their route is shown in Figure 33. The bolder the line is, the greater the number of trips along the particular fairway. There are two reasons for the route choice. Firstly, the route passing through Hansweert sluis and Krammersluizen is longer than the route passing through Kreekraksluizen (about 40km longer). Secondly, there are 2 more moveable bridges on this route. The work load of Kreekraksluizen during simulation time horizon is 110 ship-times, whereas the work loads of Hansweert sluis and Krammersluizen are 56 and 60 ship-times, respectively. Our simulation shows that, even though the waiting queue at Kreekraksluizen is longer than that at Hansweert sluis and Krammersluizen, the level of congestion is insufficient to make this route lose its competitiveness.

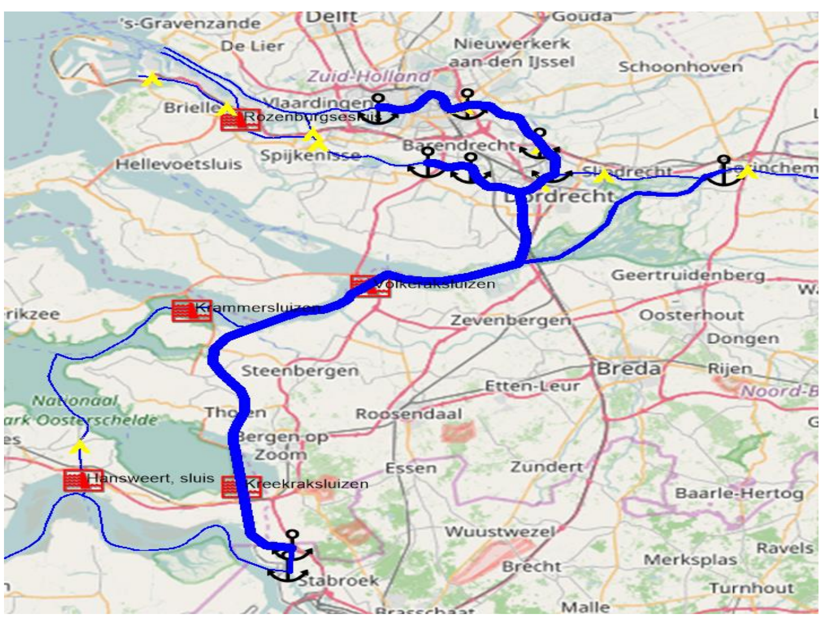

Figure 33 Trips route in model simulation test results

Lock

The lock simulation results show the arrival time of a trip. In inland waterway network, locks can be counting points, where you can record vessel traffic. In this regard, the enter time of trips is useful in lock capacity analysis.

NodeID	DateTime	tripID	actionType
Volkeraksluizen	01/07/2014 04:03	62212	InLock
Volkeraksluizen	01/07/2014 05:02	223036	InLock
Volkeraksluizen	01/07/2014 05:27	322352	InLock
Volkeraksluizen	01/07/2014 08:11	363655	InLock
Volkeraksluizen	01/07/2014 08:32	241231	InLock
Volkeraksluizen	01/07/2014 09:34	187558	InLock
Volkeraksluizen	01/07/2014 11:13	316328	InLock
Volkeraksluizen	01/07/2014 11:53	340031	InLock
Volkeraksluizen	01/07/2014 12:18	381311	InLock
Volkeraksluizen	01/07/2014 13:47	373687	InLock
Volkeraksluizen	01/07/2014 15:08	367383	InLock
Volkeraksluizen	01/07/2014 15:58	314738	InLock
Volkeraksluizen	01/07/2014 16:07	357393	InLock
Volkeraksluizen	01/07/2014 16:16	325811	InLock
Volkeraksluizen	01/07/2014 16:16	304418	InLock
Volkeraksluizen	01/07/2014 16:21	393284	InLock
Volkeraksluizen	01/07/2014 17:16	404853	InLock
Volkeraksluizen	01/07/2014 19:30	241762	InLock
Volkeraksluizen	01/07/2014 20:02	338368	InLock
Kreekraksluizen	01/07/2014 06:15	62212	InLock
Kreekraksluizen	01/07/2014 07:30	223036	InLock
Kreekraksluizen	01/07/2014 08:38	322352	InLock
Kreekraksluizen	01/07/2014 11:42	241231	InLock
Kreekraksluizen	01/07/2014 12:04	363655	InLock
Kreekraksluizen	01/07/2014 13:29	187558	InLock
Kreekraksluizen	01/07/2014 15:05	316328	InLock
Kreekraksluizen	01/07/2014 16:20	381311	InLock
Kreekraksluizen	01/07/2014 16:44	340031	InLock
Kreekraksluizen	01/07/2014 17:48	373687	InLock
Kreekraksluizen	01/07/2014 19:16	367383	InLock
Kreekraksluizen	01/07/2014 19:34	314738	InLock
Kreekraksluizen	01/07/2014 19:42	357393	InLock
Kreekraksluizen	01/07/2014 19:42	325811	InLock
Kreekraksluizen	01/07/2014 19:50	304418	InLock
Kreekraksluizen	01/07/2014 20:04	393284	InLock
Kreekraksluizen	01/07/2014 21:50	404853	InLock
Kreekraksluizen	02/07/2014 00:22	241762	InLock
Kreekraksluizen	02/07/2014 01:37	338368	InLock

Table 6 Lock statistic

5.3.2. Model Validation

In order to validate the DTA model, we compare the output with that of the static model and with real data. We use the extensive data from BIVAS's simulation as the static output and IVS data as real data. Furthermore, IVS provides the time stamp that we use here to indicate when a trip enters a lock.

Key Performance Indicator (KPI)

The greatest difference that this study found between dynamic and static models is in the way each considers the interactions between trips. In static model, interactions at locks are represented by a fixed waiting time based on empirical data. Whereas, in a dynamic model such as ours, the interactions are calculated dynamically by simulating every trip in the network. The difference in the results manifests itself eventually as a difference in trip travel time and waiting time. We may therefore consider as a KPI the closeness of a simulation's travel time and waiting time to real values.

It is hard to obtain trip information from ports since these data are usually considered business secrets. The real data we use come from the IVS database, which provides detailed data on locks. The 3 KPIs we finally chose to measure the performance of the DTA model are travel time, waiting time and lock enter time.

Travel time as KPI

The results of travel time as KPI can be seen in Figure 34. The results from BIVAS get smaller deviations due only to the influence of ship speed on travel time. Even there is a congestion on locks, the increased waiting time is not revealed by BIVAS. The DTA results have larger deviations between ships because the travel time depends on the queue length when the ship enters a lock.

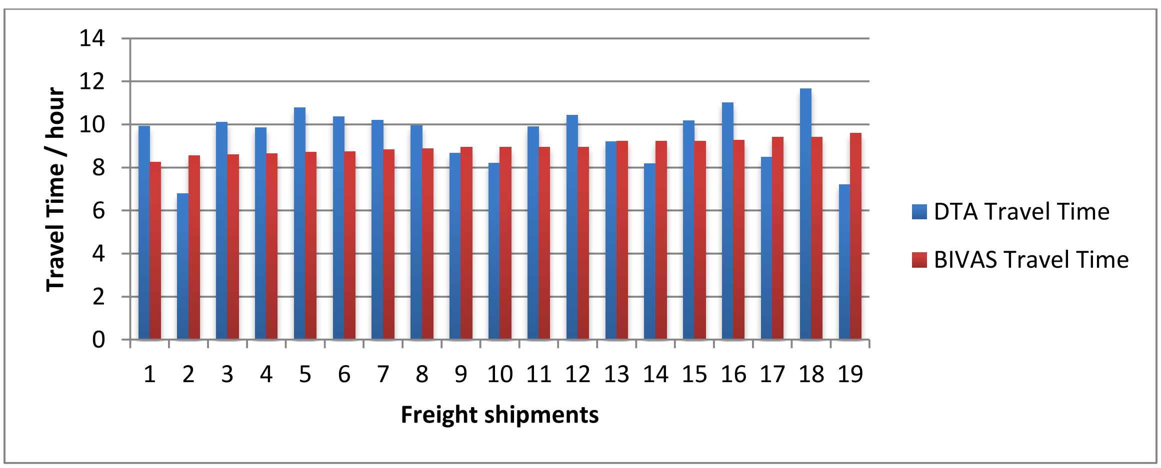

Figure 34 Travel Time of Each Freight Shipment

Waiting time as KPI

The waiting time of each ship is shown in Figure 35. In BIVAS, the waiting time is a fixed time period, so all trips' waiting times are the same. But, when we compare the DTA waiting time with the real waiting time, we find that they are very close. The deviation between the various simulation results and real data is shown visually in Figure 36. The DTA estimates are clearly closer to reality.

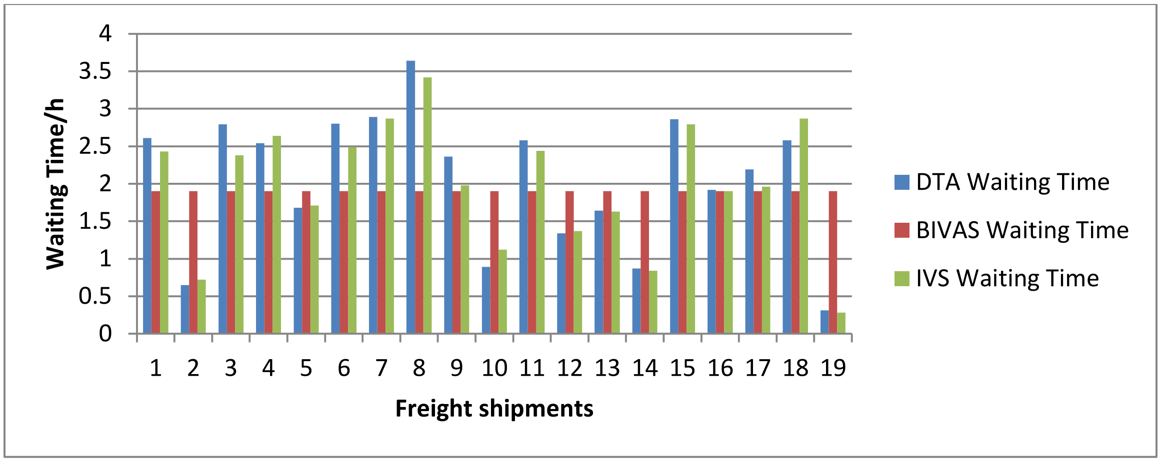

Figure 35 Waiting Time of Each Freight Shipment

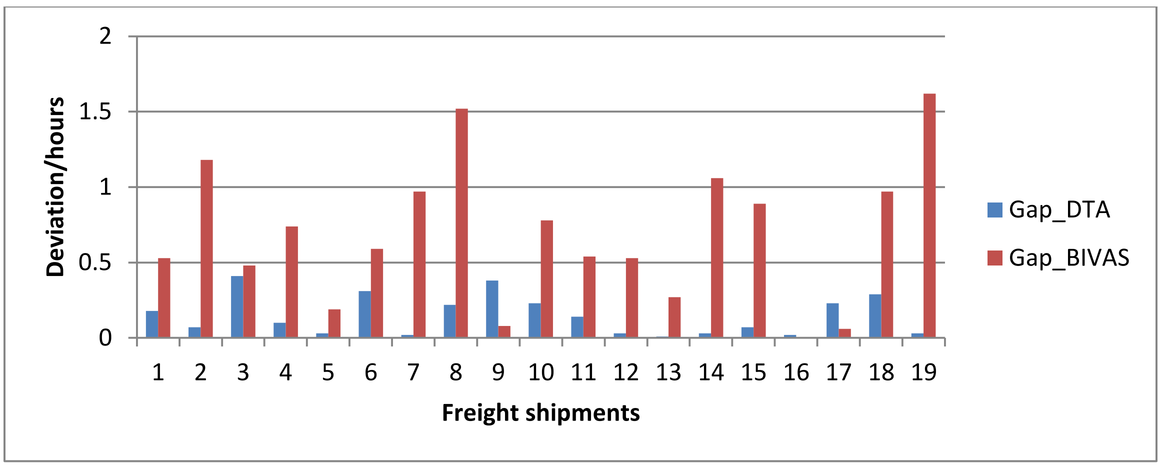

Figure 36 Deviations between simulation results and real data for Freight Shipments

Lock enter time as KPI

Figure 37 illustrates the enter time of each ship to the lock. In both the DTA model and the BIVAS model, each of the 19 trips chooses the route that passes through the Kreekraksluizen lock. So, in this respect, there is no difference between the routes assigned by the two models. The ship information (e.g. speed and CEMT classification) is the some in both models. This implies that the respective timestamps at the Volkeraksluizen lock are the same in both models. But the exception here is the enter time. The values of enter time at the Kreekraksluizen lock for our DTA model are different from those of the static models. This is obviously due to the difference in operation time at the Volkeraksluizen lock. We can clearly see that the results of DTA model are closer to real data.

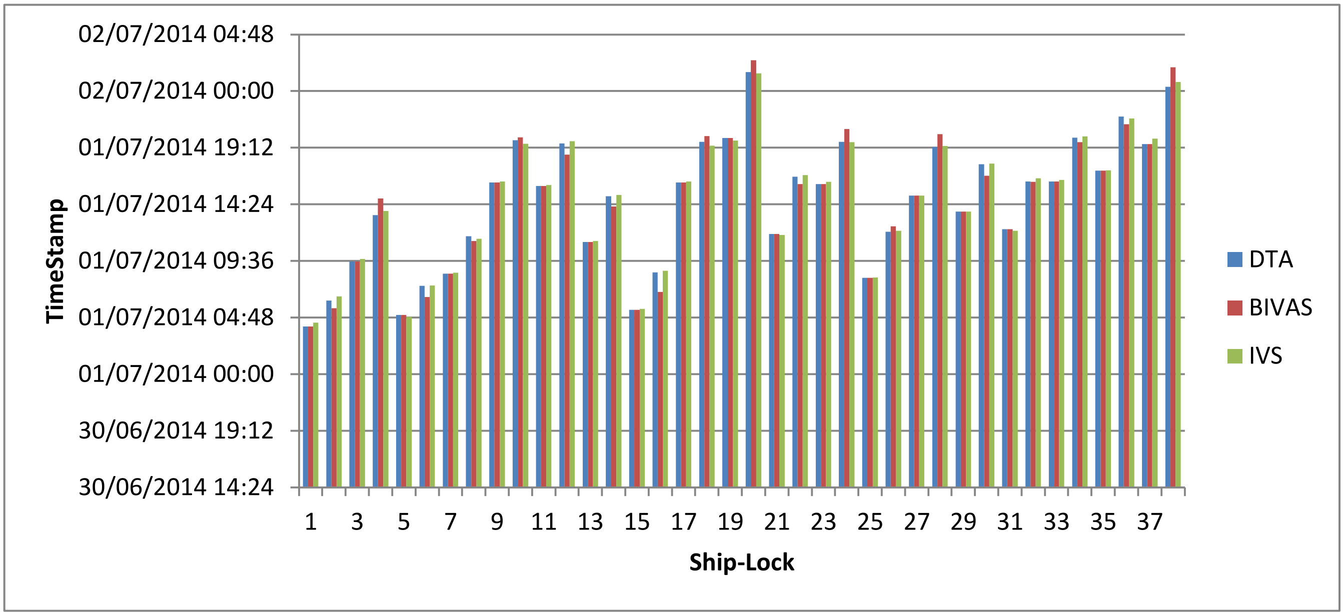

Figure 37 Enter Time of each ship to each lock

5.4. Summary

In this chapter, a simulation of the vessel traffic between Rotterdam to Antwerp is carried out. It demonstrates that the DTA model is capable of providing detailed trip information such as waiting time at locks, mooring before locks and experienced travel time. By comparing the DTA results with those of BIVAS and with real data, we show that DTA achieves better performance than static models, especially with regard to travel time, waiting time and enter time at locks. Travel time in static models is mainly related to ship speed. However, in dynamic model such as DTA, travel time is related to the time-varying network environment and to other ships. We show that the DTA, by considering interactions between ships at locks, calculates lock waiting times and enter times that are more precise than static values. Besides, the DTA model provides further useful details such as queue length at locks and time-varying travel times.

6. Scenarios for inland waterway network

This chapter discusses two scenarios and the resulting simulation results. The objective of the scenarios is to give practical examples of the kind of analysis the DTA model can be used for. As our DTA model is tried and tested using the Dutch inland waterways network, we shall use this network as the baseline for evaluating scenarios.

6.1. Network introduction and data input

The Network

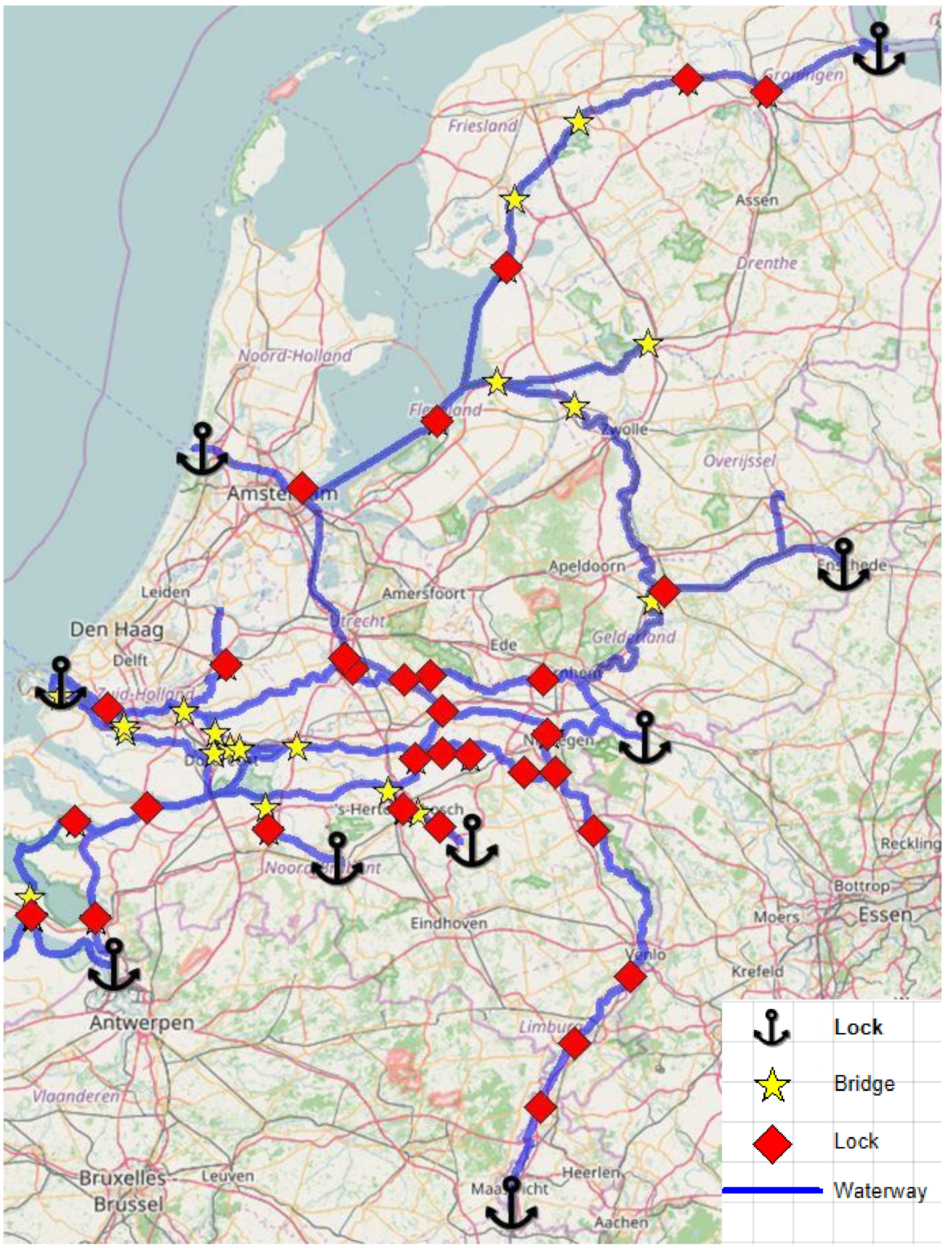

Figure 38 Baseline Inland Waterway Network for Scenarios

The baseline waterway network we shall compare the scenarios against is depicted in Figure 29. We choose several OD pairs, namely from Amsterdam and Rotterdam to the national borders of The Netherlands. Choosing the whole of the Dutch inland waterway network gives us a complex network we are already familiar with, together with familiar routes and route changes. We recall the infrastructures in the network, namely:

Port: There are 9 ports in the network. They are Rotterdam, Amsterdam and 7 other points on borders. See Figure 38.

Bridges: There are 19 moveable bridges in the network. Not all moveable bridges are included. That is valid to a first approximation because here bridges have negligible influence on a ship's travel time, and there is no precise operation time for each bridge.

Locks: There are 22 locks in this network. Locks are the places where the most congestion occurs. They are also main infrastructures for which dynamic models work better than static models.

We choose 1st of July as the simulation period. All real ships are assumed to be inputs at locks. The simulation trips are generated on each OD pair; all factors being considered average or having default value. We are then in a position to research how simulation trips will affect the network and how they will affect each other.

Data input

There are 16 OD pairs, from Rotterdam and Amsterdam to the other ports. Every OD pair has 10 trips, which means every two hours there will be a trip in one OD pair. According to IVS data, there are altogether 997 ship-times traversing 22 locks. These ships will represent the normal, baseline performance of the network. We shall then use this baseline to study how our scenario assumption affects network performance.

6.2. Scenario I: Impact of increased OD demand in inland waterway

In this scenario, we will increase the traffic flow on one OD pair, namely from Rotterdam to Germany, to find the change in network performance and in the voyage of other simulation ships. We add another 100 shipments to the network. Every 5 mins there is a ship departure from Rotterdam to Germany. This OD pair runs from west to east, involving most of the locks and including many fairways. The subnetwork is shown in Figure 39.

Figure 39 Subnetwork for Scenario I

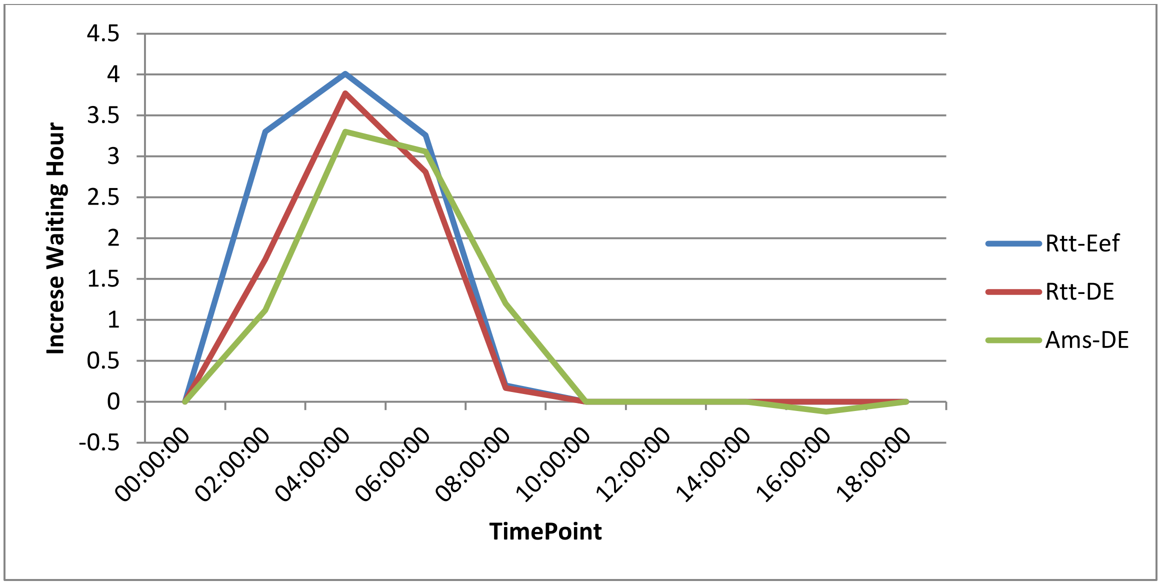

Figure 40 Impact on other OD pairs

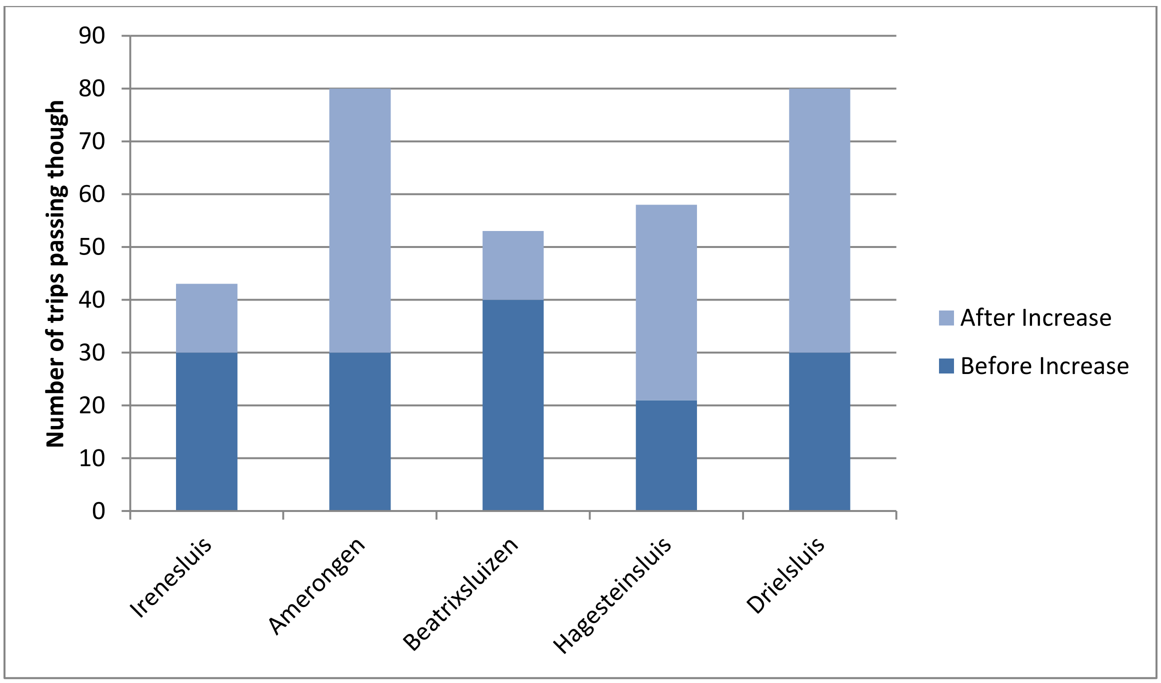

Figure 41 Effect of Workload Increase

Our simulation results show that there are 3 OD pairs that have the most impact. They are: Rotterdam-Eefde, Rotterdam-Germany and Amsterdam-Germany. The increase in the number of ships last from 00:00 to 4:00, so only the ships departing in the morning are affected.

The impact is shown in Figure 40. Not all OD pairs are affected. For example, for the OD pair Amsterdam-Henriettesluis, the trips only get a delay of 0.1 hour, and the OD ships all go through Irenesluis.

Figure 42 Lock Position

There are two reasons for this: Firstly, the lock Irenesluis gets less loading share (see in Figure 41), and most of the increase in ships goes through Hagestinsluis. Secondly, in daily situations, though ships may wait longer at Irenesluis, they get less waiting time than normal later at Andries sluis.

The normal workloads of Irenesluis and Beatrixsluizen (more than 70) are much higher than those at Amerongen and Hagesteinsluis (around 20). The DTA model will balance the workload between several locks when the congestion occurs.

For example, ships of Ams-DE all go through the Prinses Irenesluis lock When the volume of ships increases, some ships go through Prinse Beatrixsluizen then turn around to Irenesluis. This is a longer route, but it saves time. See in Figure 42.

To summarize, this scenario demonstrates that a rapid rise in te number of ships in one OD pair will affect trips in another OD pair, if they share the same lock. Furthermore, the DTA model will balance the locks' workloads and average the travel times by assigning ships to routes that are longer, but which minimize delays.

6.3. Scenario II: Impact on whole network if one fairway disabled

In this scenario, we simulate breaking down one lock, namely Hagestin sluis. All ships going through this lock will switch to other routes. The subnetwork can be found in Figure 42.

There are 3 OD pairs that get the most impact, namely Rotterdam-Oostersluis, Rotterdam-Eefde and Rotterdam-Germany. Ships choose the alternative path (Beatrixsluizen -> Irenesluis -> Amerongen) instead.

Figure 34 shows the workload change at the locks. The workload spreads to locks near Hagestin sluis.

The travel time change for each trip can be found in Figure 44. Trips from 60 to 80 are along routes in the 3 OD pairs Rotterdam-Oostersluis, Rotterdam-Eefde and Rotterdam-Germany. The delay there can be up to 5 hours.

The trips along OD pairs Ams-Hansweert, Ams-kreekraksluis, Ams-sluisI and Ams-Henrietteslui have only a slight influence on other ships.

In the real data, the Hagestin sluis had up to 22 ships pass during 1st June 2014. These trips will switch paths, making the other 3 locks busier.

In conclusion, when there is a break down in a fairway, it affects all the ships that were planned to pass through it, and the waiting time for these ships increases significantly. The fairways besides it or on alternative route are going to be crowd.

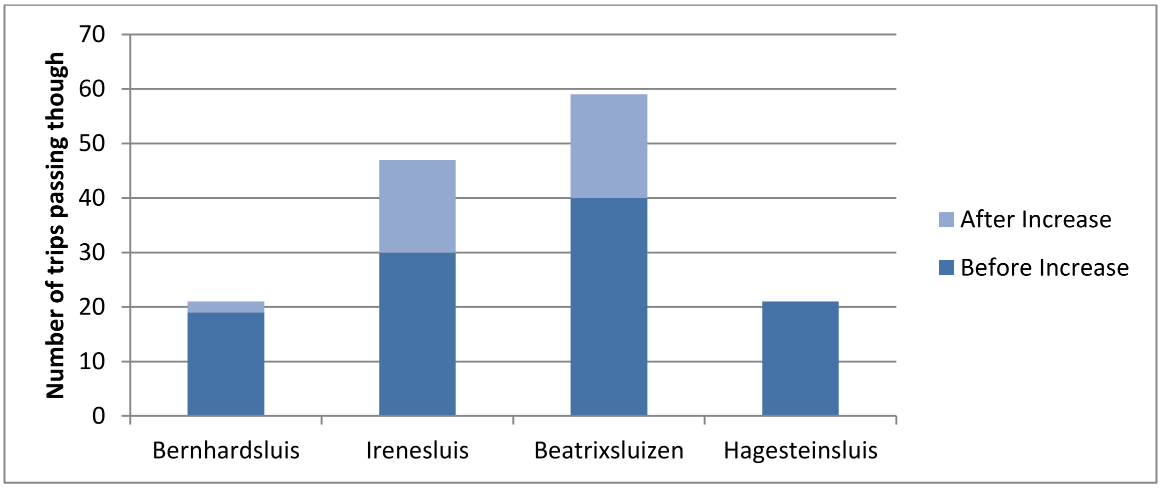

Figure 43 Lock Workload Change

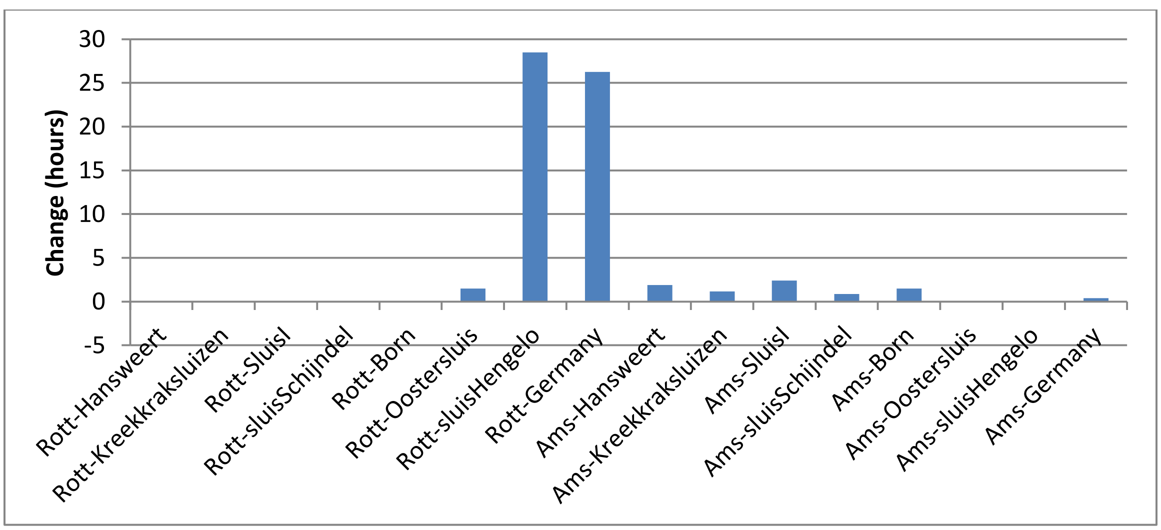

Figure 44 Travel Time change for each OD

6.4. Summary

In this chapter, our DTA simulation is used to evaluate two scenarios, using real data and the whole of the Dutch inland waterway network as baseline network. Scenario I demonstrates that when one OD demand in the network rises rapidly, it affects the wait times of other ships that share the same routes. The impact is significant when demand rises, and fades away when the demand returns to normal. Scenario II demonstrates that when one fairway or infrastructure goes down, all ships along that path will opt for an alternative path. This certainly affects the network around the broken infrastructure.

7. Conclusion and Recommendation

In this chapter, a conclusion is drawn from the research carried out in the preceding chapters. The conclusion is structured such as to answer the 3 basic research questions we started off with.

Certainly, further research can still be done to improve the model. So recommendations for further studies in this area are discussed subsequently.

7.1. Conclusion

The conclusion is structured in a question-and-answer form. It consists of an answer to 3 fundamental research questions we started with, namely:

1. Which important engineering factors should be taken into consideration for optimizing freight transport in the Dutch inland waterways network?

2. How can a DTA model be implemented to realize traffic planning and to reflect the dynamics of the network?

3. What analyses, results and uses can be obtained from scenario simulations involving the dynamics in the network?

1st question: What important engineering factors should be taken into consideration for optimizing freight transport in the Dutch inland waterways network?

The research has discovered that the important engineering factors that should be taken into consideration are: dynamics, calculation performance, experienced travel time, user runtime state, route choice, shortest path and infrastructure elements.

The result of the research is a mesoscopic simulation model. As such it can provide both the dynamics and calculation performance for an inland waterways network. Route planning is based on the experienced travel time and the user-optimal state. We have found that a shortest path algorithm needs to be time-varying and that we need to consider interactions between ships. We have also found that the optimal routes based on the user-equilibrium approach will allow two ships which have same OD pair and departure time to travel through different routes but with the same travel time. CEMT classification is used to classify waterways and freight vessels. Infrastructures like bridges and locks are important to the model design. They are the nodes in the network, at which travel-time events occur, hence are of central importance to the optimization.

2nd question: How can a DTA model be implemented to realize traffic planning and to reflect the dynamics of the network?

The network model is composed of nodes and links. Nodes can be infrastructures or junctions of links, while links represent waterways. Infrastructures have special dynamic design characteristics, such as the service time of a bridge and the queues of vessels at a lock. These embody, between them, the events that determine traffic planning. We have found that, to optimize the planning, the network loading process, time-dependent shortest path process and path adjustment process have to work together as a loop until there is a relative gap below the quit criteria. We also found, by comparing simulation results, that the DTA model yields more precise results than the static model, and provides further useful details such as queue length at locks and time-varying travel times.

3rd question: What analyses, results and uses can be obtained from scenario simulations involving the dynamics in the network?

The DTA model's scenario simulations confirm that the model can be used in other research, such as in the analysis of lock performance and in the investigation into emergency services in the network. We also found confirmation from the scenario simulations that the DTA model can provide detailed and precise results. This enables freight ships to obtain optimal and precise alternative routes when the network environment changes.

7.2. Recommendations

In this section recommendations are made for further research in the area of dynamic traffic assignment in inland waterways. In the present study, the limited research scope meant that some processes had to be simplified and some choices had to be made. The most important simplifications were with regard to real-time ship data, Multiple Traveller Classes and vessel departure times. The following paragraphs sketch how future research could deal with these challenges.

7.2.1. Real-time vessel traffic

Dynamic models take ship interactions into account. The input data is then expected to comprise the travel details of all ships that go through the network during the simulation time horizon. The current assumption is that ship information is available and that the information comes from historical data. However, the experience from this study is that your dynamic model will rarely find all the ship data it requires. It is recommended that, when the DTA model is used in future short-term and real-time analyses, a link be made between model and real-time data. For example, the European AIS Database can be used as a provider of real-time data. In addition, future simulations could use the real-time data to reduce the deviation between their simulation results and real-life situations.

7.2.2. Multiple traveler classes (MTC)

The Multiple Traveler Class implementation allows stratification of the traveler mix to follow different route choices. A certain percent of ships may choose to follow the DTA route choice, while others may use empirical route or en-route information. With the development of IT technology, there may come a time when a large number of ships follow the routes recommended by navigation systems. The recommendation is then to use MTC capability. It has the advantage of granularity and flexibility, and models reality better.

7.2.3. Departure time optimization

In this research, the departure time of a ship is used as input in the simulation. It would be interesting if we could also determine the ship departure time based on the given OD demand. The recommendation to future research is to implement this by integrating the departure time into the algorithm. For example, if a ship avoids the peak hour, the travel time and waiting time will decrease significantly. However, this will increase the simulation time exponentially. Because shortest path, network loading and path adjustment processes are all related to the departure time, the more ships there are, the more decision variables to be added to the simulation. This will offer many possibilities for optimization and for further research.

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Appendices

CEMT Class	RWS Class	Motor vessels					
		Characteristics of reference vessel				Classification	
		Designation	Beam(m)	Length(m)	Draught (m)	Cargo capacity (t)	Beam and length (m)
0	M0	Other				1-250	B<=5.00 L<=38.00
I	M1	Peniche	5.05	38.5	2.5	251-400	B= 5.01-5.10 L>=38.01
II	M2	Kempenaar	6.6	50-55	2.6	400-650	B=5.11-6.70 L>=38.01
III	M3	Hagenaar	7.2	55-70	2.6	651-800	B=6.71-7.30 L>=38.01
	M4	Dortmund Eems	8.2	67-73	2.7	801-1050	B=7.31-8.30 L=38.01-74.00
	M5	Ext.Dormund Eems	8.2	80-85	2.9	1051-1250	B=7.31-8.30 L>=74.01
IVa	M6	Rhine-Heme	9.5	80-85	2.9	1251-1750	B=8.31-9.60 L=38.01-86.00
	M7	Ext. Rhine-Heme	9.5	105	3	1751-2050	B=8.31-9.60 L>=86.01
IVb							
Va	M8	Large Rhine	11.4	110	3.5	2051-3300	B= 9.61-11.50 L=38.01- 111.00
	M9	Ext. Large Rhine	11.4	135	3.5	3301-4000	B= 9.61-11.50 L>= 111.01
Vb							
VIa	M10	Ref. vessel 13.5 * 110 m	13.5	110	4.0	4001-4300	B=11.51-14.30 L=38.01- 111.00
	M11	Ref. vessel 14.2 * 135 m	14.2	135	4.0	4301-5600	B=11.51-14.30 L>= 111.01
	M12	Rhinemax Vessel	17.0	135	4.0	>=5601	B>= 14.31 L>= 38.01
VIb							
VIc							
VIIa							

Appendix 1 RWS classification of inland navigation fleet [28]

CEMT Class	RWS Class	Pushed convoys (Barges)				
		Characteristics of reference vessel			Classification	
		Beam(m)	Length(m)	Draught (m)	Cargo capacity (t)	Beam and length (m)
0						
I	BO1	5.2	55	1.9	0-400	B<=5.20 L= all
II	BO2	6.6	60-70	2.6	401-600	B=5.21-6.70 L=all
III	BO3	7.5	80	2.6	601-800	B=6.71-7.60 L=all
	BO4	8.2	85	2.7	801-1250	B=7.61-8.40 L=all
IVa	BI	9.5	85-105	3	1251-1800	B=8.41-9.60 L=all
IVb						
Va	BII-1	11.4	95-110	3.5	1801-2450	B=9.61-15.10 L<=111.00
	BIIa-1	11.4	92-110	3.5	2451-3200	B=9.61-15.10 L<=111.00
	BIIL-1	11.4	125-135	4.0	3201-3950	B=9.61-15.10 L=111.01-146.00
Vb	BIIL-2l	11.4	170-190	3.5-4.0	3951-7050	B=9.61-15.10 L>=146.01
VIa	BII-2b	22.8	95-145	3.5-4.0	3951-7050	B=15.11-24.00 L<=146.00
VIb	BII-4	22.8	185-195	3.5-4.0	7051-12000	B=15.11-24.00 L=146.01-200
VIc	BII-6l	22.8	270	3.5-4.0	12001-18000	B=15.11-24.00 L>=200.01
VIIa	BII-6b	34.2	195	3.5-4.0	12001-18000	B>=24.01 L=all

Appendix 2 RWS classification of inland navigation fleet [28]

CEMT Class	RWS Class	Coupled units (Convoys)				
		Characteristics of reference vessel			Classification	
		Beam(m)	Length(m)	Draught (m)	Cargo capacity (t)	Beam and length (m)
0						
I	C1l	5.05	77-80	2.5	<=900	B<=5.20 L= all
	C1b	10.1	38.5	2.5	<=900	B=9.61-12.60 L<= 80.00
II						
III						
IVa						
IVb	C2l	9.5	170-185	3.0	901-3350	B=5.11-9.60 L=all
Va						
Vb	C3l	11.4	170-190	3.5-4.0	3951-7250	B=9.61-12.60 L>=80.01
VIa	C2b	19	85-105	3.0	901-3350	B=12.61-19.10 L<=136.00
	C3b	22.8	95-110	3.5-4.0	3351-7250	B>19.10 L<=136
VIb	C4	22.8	185	3.5-4.0	>=7251	B>12.60 L>=136.01
VIc						
VIIa						

Appendix 3 RWS classification of inland navigation fleet [28]

Name	Type of cargo			
	DryBulk	WetBulk	Remaining	Container
Alblasserdam, BCTN	No	No	No	Yes
Autriche haven	Yes	No	Yes	Yes
BNR Bouwstoffen	Yes	No	No	No
Coentunnel, haven	Yes	No	No	No
Dokhaven	No	No	Yes	No
Fokker, haven van	No	No	Yes	No
Gert van Lienden	Yes	No	No	No
Groot Ammers, Hartog	No	No	Yes	No
Haven Oranjesluizen	Yes	No	Yes	No
Haventje van Drongelen	Yes	No	No	No
Haventje van Dussen	Yes	No	No	No
Havikerwaard bv	Yes	No	No	No
Insteekhaven Lochem	Yes	No	No	No
Kampen, Peters	No	No	Yes	No
Koedoodhaven	Yes	No	Yes	No
Lochem, Holterman	No	No	Yes	No
Loshaven Clauscentrale	Yes	No	No	No
Meeuwen, rijksloswal	Yes	No	No	No
Peerenboom	Yes	No	No	No
Petroleumhaven Avia Weghorst te Enschede	No	Yes	No	No
Rotterdam, Van Nieuwpoort	Yes	No	No	No
Scheepswerf Ravestein bv	No	No	Yes	No
Straalgrit de Klein	Yes	No	No	No
Tebezo grond en wegenbouw	Yes	No	Yes	No
Triferta	Yes	No	No	No
Uilenvlietsehaven	Yes	No	No	No
Uitlaathaven Centrale Harculo	No	Yes	No	No
Werkhaven IJsseloog	Yes	No	Yes	No
Zuilichem, Van Oord	No	No	Yes	No

Appendix 4 Ports in key waterways

Name	TransitTime_min	WaitTime_min	LockLength_m	LockWidth_m
Rozenburgsesluis	15	32	306.36	24
Zeesluis Farmsum	11	12	121	11.5
Prinses Margrietsluis	9	21	260	15.9
Henriettesluis	12	25	80	13
Sluis 0	12	24	116.5	26.4
Noordersluis, IJmuiden	13	20	375	47.3
Houtribsluizen	9	11	196	18
Driel, sluis	14	24	260	18
Amerongen, sluis	16	26	260	18
Hagestein, sluis	13	21	220	18
Oostersluis	11	19	190	16
Gaarkeukensluis	10	18	190	16
Prinses Irenesluis	13	19	305	21
Prins Bernhardsluis	13	18	305	21
Hansweert, sluis	15	21	280	24
Westsluis,Terneuzen	30	30	290	38
Volkeraksluizen	8	16	316.4	24
Krammersluizen	25	31	280	24
Julianasluis	6.6	11	110	12
St. Andries, sluis	18.5	32	110	14
Oranjesluizen	11	9	111	17.5
Kreekraksluizen	11	26	318	24
Macharen, sluis	13	24	90	13.5
sluis Born	13	12	168	16
sluis Maasbracht	13	12	142	16
sluis Heel	12	15	142	16
sluis Belfeld	11	11	174.2	15.3
sluis Sambeek	11	11	174.2	15.3
sluis Grave	12	24	142	16
Prinses Maxima Sluizen	9	21	260	15.9
Weurt, sluis	9	19	264	16
Sluis Eefde	10	36	133	12
Sluis Delden	10	24	133	12
Sluis I	14	29	120	14
Sluis II	14	26	65	16
Sluis III	16	30	65	16
Sluis Hengelo	23.4	32	133	12
Sluis Schijndel	10	20	105	12.6
Prinses Beatrixsluizen	13	17	225	18

Appendix 5 Details of locks in key waterways [25]

Name	ServiceTime_min	Width_m
Calandbrug, verkeers-/spoorbrug	5	100
Harmsenbrug	5	79
Suurhoffbrug, verkeers-/spoorbrug	5	100
Woldbrug	5	79
Eelwerderbrug	5	79
Bloemhofbrug	5	79
Driebondsbrug	5	79
Borgbrug	5	79
Oudeschouw, brug	5	70
Spannenburg, brug	5	70
Uitwellingerga, brug	5	70
Stroobos, brug	5	70
Blauforlaet, brug	5	90
Kootstertille, brug in N369	5	70
Schuilenburg, brug	5	70
Burgumerdaam, brug	5	70
Fonejachtbrug	5	70
Van Brienenoordbrug	5	100
Orthenbrug	10	50
Kasterenbrug	5	50
Den Dungensebrug	5	50
Stadsbrug, Kampen	5	250
Oude IJsselbrug, Zutphen	10	250
IJsselspoorbrug, Zutphen	5	250
Ketelbrug	5	250
Ramspolbrug	5	80
Busbaanbrug	5	70
Gerrit Krol-brug	5	70
Dorkwerderbrug	5	70
Aduarderbrug	5	70
Brug Zuidhorn	5	70
Paddepoelsterbrug	5	70
Brug Eibersburen	5	70
Postbrug	5	100
Vlakespoorbrug	10	100
Vlakebrug	5	100
Sas van Gent, brug	5	100
Sluiskil, verkeers-/spoorbrug	5	100
Schellingwouderbrug	5	100
Spijkenisserbrug	5	100
Grotebrug, spoorbrug	10	100
Dordrecht, brug	5	100
Botlekbrug, verkeers-/spoorbrug	5	100
Merwedebrug, Gorinchem	5	150
Merwedebrug, Papendrecht	5	150
Alblasserdamsebrug	5	150
Amertakbrug	5	79
Brug Dr. Deelenlaan	5	79
Brug Waalstraat	5	79
Brug Lijnsheike	10	79
Brug Heikantsebaan	5	79
Dollegoorbrug	5	70
Eilandsbrug	5	70
Eshuisbrug	5	79

Name	ServiceTime_min	Width_m
Meppelerdiepbrug	5	79
Baanhoekspoorbrug	5	150
St. Servaasbrug	5	79
Maastricht, spoorbrug	5	79
Eilandbrug, Kampen	5	250
Hefbrug Gouwsluis	5	70
Gouwespoorbrug, Alpen aan den Rijn	5	70
Hefbrug Boskoop	5	70
Hefbrug Waddinxveen	5	70
Coenecoopbrug	10	70
Gouwespoorbrug, Gouda (viersporig)	10	70
Gouwespoorbrug, Gouda (enkelspoor)	5	70
Spoorbrug Grou	5	70

Appendix 6 Movable bridges in key waterways

label	CEMT	Load Type	Speed km_h	Empty Depth	Average Depth	MaximumLoadWeight
M0	1	0	12	1.2	2.06	139
M0	1	1	12	1.2	2.06	139
M1	2	0	15	1	2.19	367
M1	2	1	11	1	2.19	367
M2	3	0	16	1	2.31	577
M2	3	1	10	1	2.31	577
M4	4	0	16	1.2	2.41	951
M4	4	1	11	1.2	2.41	951
M5	4	0	16	1.2	2.4	1171
M5	4	1	11	1.2	2.4	1171
M6	5	0	17	1.2	2.57	1497
M6	5	1	12.5	1.2	2.57	1497
M7	5	0	18	1.2	2.65	2026
M7	5	1	11.5	1.2	2.65	2026
BO1	1	0	12	1.5	1.84	100
BO1	1	1	12	1.5	1.84	100
BO2	1	0	12	1.65	2.43	420
BO2	1	1	12	1.65	2.43	420
BO3	1	0	12	2	2.42	640
BO3	1	1	12	2	2.42	640
BO4	1	0	12	2	2.47	946
BO4	1	1	12	2	2.47	946
BI	5	0	15	2.06	2.72	1478
BI	5	1	13	2.06	2.72	1478
BII-1	6	0	16	2.1	3.18	2227
BII-1	6	1	13	2.1	3.18	2227
BII-2L	7	0	16	2.16	3.05	5495
BII-2L	7	1	12	2.16	3.05	5495
BII-2B	8	0	16	2.2	3.13	5601
BII-2B	8	1	12	2.2	3.13	5601
BII-4	9	0	16	1.8	3.57	11186
BII-4	9	1	12	1.8	3.57	11186
BII-6L	10	0	16	1.8	3.54	16757
BII-6L	10	1	12	1.8	3.54	16757
BII-6B	10	0	16	1.7	3.58	16493
BII-6B	10	1	10	1.7	3.58	16493
C1l	2	0	0	1	2.18	761
C1l	2	1	0	1	2.18	761
C1b	2	0	0	1	2.19	740
C1b	2	1	0	1	2.19	740
C2l	5	0	16	1.2	2.81	1806
C2l	5	1	11	1.2	2.81	1806
C2b	8	0	14	1.2	2.76	2260

label	CEMT	Load Type	Speed km_h	Empty Depth	Average Depth	MaximumLoadWeight
C2b	8	1	10.5	1.2	2.76	2260
C3l	7	0	16	1.5	3.57	5236
C3l	7	1	12	1.5	3.57	5236
C3b	8	0	14	1.5	3.63	5454
C3b	8	1	10.5	1.5	3.63	5454
C4	9	0	15	1.5	3.68	8145
C4	9	1	12.5	1.5	3.68	8145
M3	4	0	16	1	2.31	796
M3	4	1	11.5	1	2.31	796
M10	8	0	18	1.6	3.56	3932
M10	8	1	15.5	1.6	3.56	3932
M11	8	0	18	1.6	3.55	5186
M11	8	1	15.5	1.6	3.55	5186
M12	8	0	18	1.6	3.57	5900
M12	8	1	15.5	1.6	3.57	5900
M8	6	0	18	1.4	3.14	2689
M8	6	1	12.5	1.4	3.14	2689
M9	6	0	18	1.4	3.08	3900
M9	6	1	12.5	1.4	3.08	3900

Appendix 7 Ship speed according to ship type and loading

Label	Cargo Type	LaborCosts	MaintenanceCosts	InsuranceCosts	InterestCosts	HarborFees	OtherCosts
BI	remaining	48.33	3.06	4.83	1.17	1.96	7.06
BI	wet bulk	40.92	2.49	5.65	1.67	1.6	4.84
BI	dry bulk	51.35	3.29	4.49	0.96	2.11	7.96
BI	container	66.02	3.3	1.72	0.51	0.74	15.21
BII-1	remaining	51.87	3.38	5.14	1.29	2.78	7.25
BII-1	wet bulk	53.16	2.58	5.79	1.82	2.19	4.66
BII-1	dry bulk	51.35	3.71	4.88	1.07	3.02	8.31
BII-1	container	85.77	3.43	1.75	0.54	1.01	14.64
BII-2B	remaining	59.87	5.19	9.99	2.93	6.24	12.55
BII-2B	wet bulk	58.51	5.62	12.33	4.02	4.36	10.96
BII-2B	dry bulk	60.42	5.02	9.03	2.49	7.01	13.2
BII-2B	container	94.41	7.46	3.53	1.09	2.01	34.47
BII-2L	remaining	59.63	5.65	10.15	2.98	6.12	12.79
BII-2L	wet bulk	58.51	5.62	12.33	4.02	4.36	10.96
BII-2L	dry bulk	60.09	5.66	9.26	2.55	6.84	13.54
BII-2L	container	94.41	7.46	3.53	1.09	2.01	34.47
BII-4	remaining	76.28	9.46	16.19	6.33	10.65	20.57
BII-4	wet bulk	74.82	9.4	25.04	8.89	8.63	15.18
BII-4	dry bulk	76.87	9.48	12.58	5.28	11.48	22.77
BII-4	container	120.72	12.49	6.44	2.04	3.98	47.73
BII-6B	remaining	84.86	12.29	19.64	9.16	15.57	25.43
BII-6B	wet bulk	80.66	12.55	36.22	13.85	12.84	18.39
BII-6B	dry bulk	86.57	12.18	12.87	7.25	16.68	28.3
BII-6B	container	130.15	16.67	8.52	2.82	5.92	57.84
BII-6L	remaining	84.86	12.29	19.64	9.16	15.89	25.46
BII-6L	wet bulk	80.66	12.55	36.22	13.85	12.84	18.39
BII-6L	dry bulk	86.57	12.18	12.87	7.25	17.14	28.35
BII-6L	container	130.15	16.67	8.52	2.82	5.92	57.84
BO1	remaining	32.03	2.25	1.2	0.26	0.49	3.17
BO1	wet bulk	39.02	1.41	0.67	0.17	0.34	1.07
BO1	dry bulk	29.17	2.59	1.41	0.29	0.55	4.03
BO1	container	62.95	1.87	0.22	0.06	0.15	3.37
BO2	remaining	34.12	2.44	1.21	0.27	0.45	3.43
BO2	wet bulk	39.02	1.58	0.73	0.21	0.56	1.16

BO2	dry bulk	32.11	2.78	1.4	0.3	0.41	4.35
BO2	container	62.95	2.1	0.26	0.08	0.26	3.64
BO3	remaining	34.88	2.43	1.29	0.3	1.2	3.6
BO3	wet bulk	39.3	1.6	0.77	0.22	0.62	1.19
BO3	dry bulk	33.07	2.77	1.5	0.33	1.43	4.58
BO3	container	63.41	2.12	0.28	0.09	0.28	3.74
BO4	remaining	34.37	2.7	1.57	0.36	1.48	3.74
BO4	wet bulk	39.3	1.94	0.85	0.27	0.87	1.35
BO4	dry bulk	32.35	3.01	1.86	0.4	1.72	4.72
BO4	container	63.41	2.58	0.33	0.12	0.4	4.26
C1b	remaining	28.37	3.05	1.68	0.36	1.34	4.11
C1b	wet bulk	27.67	2.23	1.96	0.42	1.78	3.68
C1b	dry bulk	28.65	3.39	1.57	0.33	1.16	4.28
C1b	container	44.64	1.46	0.91	0.22	1.27	6.12
C1l	remaining	28.37	3.05	1.68	0.36	1.21	4.09
C1l	wet bulk	27.67	2.23	1.96	0.42	1.78	3.68
C1l	dry bulk	28.65	3.39	1.57	0.33	0.98	4.26
C1l	container	44.64	1.46	0.91	0.22	1.27	6.12
C2b	remaining	42.79	4.76	8.27	1.95	3.35	8.17
C2b	wet bulk	36.14	3.24	7.62	2.01	3.71	4.19
C2b	dry bulk	45.5	5.38	8.54	1.92	3.2	9.8
C2b	container	58.31	3.23	4.03	1.1	2.6	8.87
C2l	remaining	42.79	4.76	8.27	1.95	3.65	8.2
C2l	wet bulk	36.14	3.24	7.62	2.01	3.71	4.19
C2l	dry bulk	45.5	5.38	8.54	1.92	3.63	9.84
C2l	container	58.31	3.23	4.03	1.1	2.6	8.87
C3b	remaining	50.53	4.7	12.83	3.54	3.93	10.21
C3b	wet bulk	36.91	4.04	20.51	6.2	5.6	5.84
C3b	dry bulk	56.1	4.97	9.69	2.45	3.25	12
C3b	container	59.55	4.61	8.16	2.12	4.31	11.94
C3l	remaining	50.53	4.7	12.83	3.54	5.5	10.36
C3l	wet bulk	36.91	4.04	20.51	6.2	5.6	5.84
C3l	dry bulk	56.1	4.97	9.69	2.45	5.46	12.21
C3l	container	59.55	4.61	8.16	2.12	4.4	11.94
C4	remaining	63.78	5.95	14.43	4.76	10.06	12.96
C4	wet bulk	41.53	6.38	26.27	9.55	9.7	7.56
C4	dry bulk	72.87	5.77	9.59	2.81	10.21	15.17
C4	container	72.87	6.22	10.01	3.01	6.42	15.43

M0	remaining	21.54	1.18	0.26	0.05	0.38	1.64
M0	wet bulk	20.43	0.83	0.43	0.09	0.55	1.62
M0	dry bulk	22	1.33	0.19	0.04	0.3	1.65
M0	container	24.62	1.07	0.17	0.03	0.87	1.28
M1	remaining	23.54	1.57	0.93	0.2	0.62	2.14
M1	wet bulk	25.48	1.11	0.98	0.21	0.88	1.84
M1	dry bulk	22.75	1.76	0.9	0.19	0.51	2.26
M1	container	25.46	1.42	0.78	0.17	1.49	1.75
M10	remaining	57.79	2.48	12	3.43	4.59	3.62
M10	wet bulk	58.76	2.18	12.26	4.42	2.46	2.9
M10	dry bulk	57.39	2.6	11.89	3.03	5.46	3.91
M10	container	56.33	2.11	10.14	2.93	4.93	2.9
M11	remaining	57.79	2.64	12.59	3.86	5.68	4.03
M11	wet bulk	58.76	2.33	12.77	5.12	6.09	3.23
M11	dry bulk	57.39	2.76	12.52	3.35	5.51	4.35
M11	container	56.33	2.24	10.68	3.24	4.97	3.23
M12	remaining	57.79	2.9	13.59	4.72	5.68	4.73
M12	wet bulk	58.76	2.57	13.16	6.27	6.4	3.79
M12	dry bulk	57.39	3.04	13.76	4.09	5.39	5.11
M12	container	56.33	2.46	11.73	3.96	4.86	3.79
M2	remaining	26.19	1.47	1.12	0.25	1.09	2.13
M2	wet bulk	27.34	1.35	1.43	0.3	1.15	2.1
M2	dry bulk	25.72	1.52	1	0.22	1.06	2.14
M2	container	26.08	1.66	1.46	0.31	1.98	2.1
M3	remaining	26.83	1.56	1.48	0.32	1.34	2.3
M3	wet bulk	28.15	1.36	1.74	0.37	1.4	2.29
M3	dry bulk	26.3	1.64	1.38	0.3	1.32	2.3
M3	container	26.39	1.71	2.04	0.43	2.22	2.29
M4	remaining	26.52	1.76	2.25	0.48	1.51	2.51
M4	wet bulk	27.71	1.7	2.31	0.49	1.48	2.51
M4	dry bulk	26.04	1.79	2.22	0.47	1.53	2.51
M4	container	26.96	2.06	2.86	0.6	2.67	2.59
M5	remaining	30.38	1.94	3.16	0.67	1.99	2.99
M5	wet bulk	31.69	1.87	3.02	0.64	1.93	2.99
M5	dry bulk	29.85	1.96	3.22	0.68	2.02	2.99
M5	container	34.9	1.66	4.04	0.86	2.45	2.17
M6	remaining	33.4	1.92	5.86	1.26	2.35	2.83
M6	wet bulk	35.36	1.93	7.39	1.64	2.36	2.79

M6	dry bulk	32.61	1.91	5.23	1.11	2.35	2.84
M6	container	35.61	1.91	5.01	1.06	2.87	2.42
M7	remaining	39.55	2.28	7.87	1.74	2.61	3.42
M7	wet bulk	43.31	2.24	7.97	1.82	2.56	3.28
M7	dry bulk	38.01	2.29	7.83	1.71	2.63	3.48
M7	container	50.6	1.69	5.08	1.11	4.25	2.25
M8	remaining	44.28	2.32	11.08	2.72	3.23	3.52
M8	wet bulk	53.86	2.12	11	3.03	3.01	2.68
M8	dry bulk	40.36	2.4	11.11	2.6	3.32	3.87
M8	container	53.16	1.88	7.85	1.88	4.34	2.45
M9	remaining	54.61	2.1	9.96	2.81	3.87	3.05
M9	wet bulk	58.37	2.16	11.86	3.92	4.21	2.81
M9	dry bulk	53.08	2.07	9.19	2.35	3.73	3.15
M9	container	55.84	2.14	8.87	2.34	3.6	2.81

Appendix 8 Ship cost according to ship type and cargo type