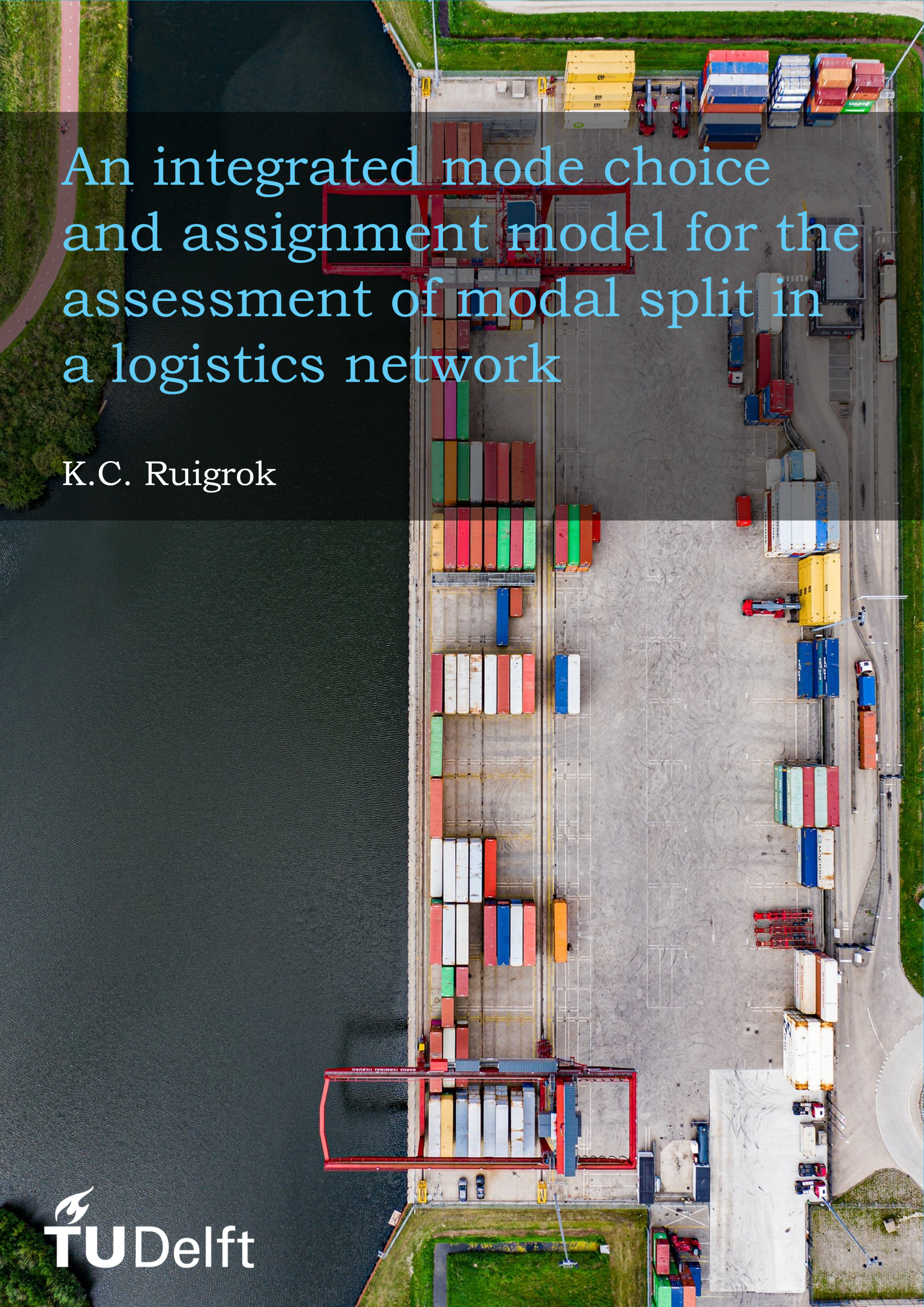
An integrated mode choice and assignment model for the assessment of modal split in a logistics network

K.C. Ruigrok



TU Delft

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by

K.C. Ruigrok

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Preface

I proudly present this thesis as my final work to obtain my masters degree in mechanical engineering. This thesis represents the culmination of years of studying, tests, research and more. A period of my life with ups and downs and one that am happy and proud of to have successfully concluded.
I would like to thank Bilge Atasoy, whose expertise, patience and understanding helped me immensely throughout the graduation process. Last but certainly not least, I would like to thank my family and friends for all their support and understanding. I love you all.

Kars Ruigrok
June 2025

Abstract

Inland container transport can be done via road transport, rail transport or Inland Waterway Transport (IWT). Currently the majority of containers is transported via road transport. Which leads to high CO2 emissions and more congestion on the road network. Shifting container transport from road transport to IWT can reduce both of these problems. In order to test innovations to aid this shift, a model should be made to predict their impact on the transport flow.
Literature indicates that most transport models follow the four step approach of trip generation, trip distribution, mode choice and trip assignment. These final steps: mode choice and assignment, are often done sequentially. However, the lack of interaction between these steps make the model less realistic. This thesis aims to create a new model by combining the mode choice and assignment steps and testing the impact of several transport mode attributes on the modal split using this new model.
A new integrated mode choice and assignment model is developed using multi objective optimisation. The first objective minimised the cost of the services assigned to the containers and the second objective maximised the probability of the chosen transport modes. Comparing it with the sequential model, it showed that while the sequential model could assign containers to a transport mode which capacity was already met, the interaction between the mode choice and assignment steps prevented this problem in the new integrated model.
The integrated mode choice and assignment model was then used to test the impact of three transport mode attributes on the modal split. Based on literature the three most important attributes are: cost, capacity and frequency. To increase the use of IWT these three attributes were tested as follows: increasing the cost of road transport, increasing the capacity of IWT services and increasing the frequency of IWT services.
Results showed that increasing road cost can significantly increase the modal share of IWT. However due to IWT already having the lowest cost in most cases, it has almost no effect on the cost minimisation objective. Increasing capacity of IWT services does increase the modal share of IWT but only due to the fact that more containers can be assigned to the IWT services before the capacity is met. It does not cause shipments to switch from using road or rail transport to using IWT. Increasing the frequency of IWT services is tested two ways. First, while keeping the overall capacity unchanged so only the frequency is altered and secondly, by simply adding additional barge movements which cause the frequency to increase but also the capacity. While keeping the overall capacity unchanged the results showed almost no shift in the modal split. Without keeping the capacity unchanged the increase in frequency and capacity showed a significant increase in the modal share of IWT. A final test, combining the increase in road transport cost and the increase in frequency, showed that a 10% increase of both attributes results in an increase of 4,4% for the modal share of IWT.
This study showed that an integrated mode choice and assignment model is more accurate than a sequential model and that a small change of the right attributes in a transport network can have a noticeable impact on the modal split.

Contents

1
Introduction

A large percentage of manufactured goods is transported in containers these days. The global container throughput has increased massively the past 30 years and reached a worldwide throughput of over 858 million TEU in 2023[28]. A significant part of the transport journey of these containers is considered inland transport, which is transport between the ocean ports and the inland origins or destinations. While geographically this inland transport might look like a small part of the transport, research shows that inland transport can be up to 80% of the total cost of the container transport[21]. The optimisation of inland container transport is therefore an interesting research subject.

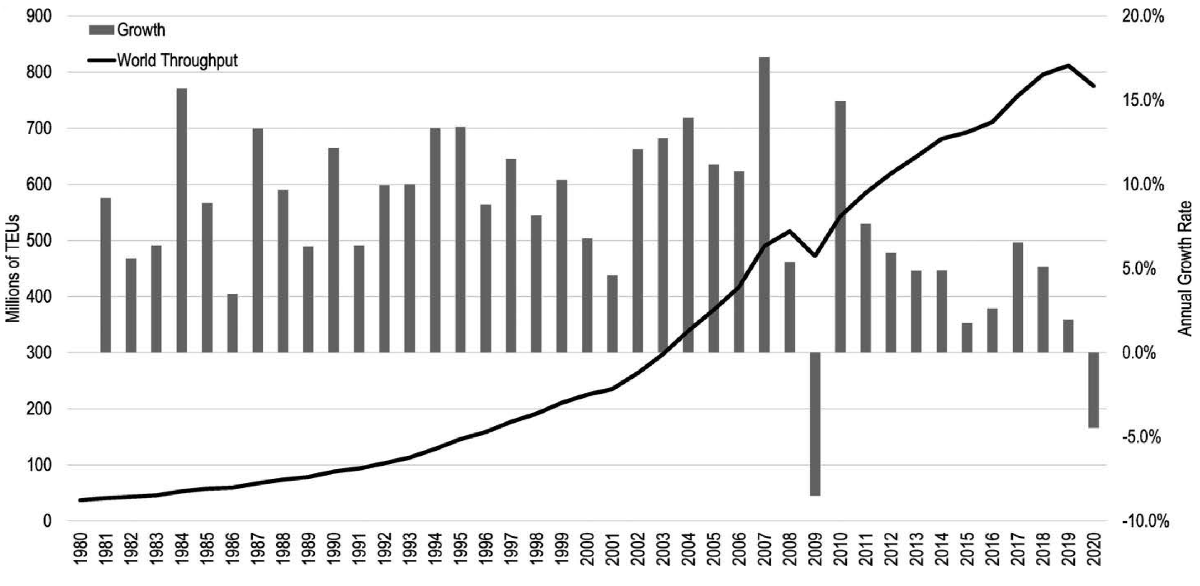


Figure 1.1: World container throughput[20]

Apart from the economic side, there is also the sustainability side. A continuing growth in container freight as shown in Figure 1.1 and a forecast of 1,0% growth per year[24] will also result in an increase of CO_2 emissions by transporting these containers. To this day inland container transport is still often being done using trucks. This causes congestion on the road network and high CO_2 emissions. Inland waterway transport (IWT) is 4.6 times more energy efficient than road transport[10], a shift from road transport to IWT would thus reduce both of these issues, yet truck transport is still preferred over IWT[15].

1.1. Research Motivation

This graduation project is carried out in collaboration with project NOVIMOVE: Novel inland waterway transport concepts for moving freight effectively. Their focus is to enhance the logistics system density by studying several innovations. One of the goals of the project is a logistics simulation model [15] of the freight transport along the Rhine-Alpine corridor to test the new concepts for improving the logistics operations such as: use of vessel trains and feeder vessels, cargo reconstruction and smooth navigation through bridges and locks. This graduation project will look into how the mode choice and assignment sub-models can be improved and how altering different attributes affect the modal split and can increase the mode share of IWT. This will guide the development of the innovations as critical attributes will be identified. The currently used sub-models within the NOVIMOVE simulation model[25] first looks at the mode choice preferences of the shippers before assigning the containers to the available services using cost minimization. This can result in a sub-optimal distribution due to containers firstly being assigned to a transport mode before certain attributes of the available services, such as frequency and capacity, are taken into account. A new model, which will take the preferences of the shippers and the freight forwarder into account at the same time based on the trade-offs between them, would result in a more realistic and optimal distribution of the container flow.

1.2. Research Scope

This research focuses on hinterland container transport and the scope of this research will thus be the transport of containers between deep-sea ports and the inland destinations or origins via road, rail and inland waterway transport. The transport between the terminals and the customer and the sea-bound transport to and from the ports are outside of the scope of this graduation project.

The geographical scope of project NOVIMOVE is the Rhine-Alpine corridor. As this is a very large network, this graduation project will focus on a section of this network. This section will include the Ports of Rotterdam and Antwerp and the inland terminals along the Rhine-Alpine corridor which transport to either of these ports. Depending on the available data the geographical scope of this project will be specified later on in the project (See section 4.1).

1.3. Problem Definition

The problem can be defined from the point of view of a freight forwarder. Shippers request an amount of freight to be transported from an origin to a destination. Each shipment has certain attributes such as: quantity of containers, pick up and delivery locations, pick up and delivery time windows, etc. The containers can be transported by different transport modes across the arcs in the network. For each arc the available modes are given, as certain modes can not be used to transport along certain arcs. Each mode has its own set of attributes such as: Capacity, Costs, Transport time, Availability, Frequency, etc. The flow along each arc can be defined as the amount of containers transported with a certain transport mode. Changing the attributes of the transport modes will have an effect on this container flow.

In order to distribute the container flow across such a network, the current model designed for project NOVIMOVE contains two sub-models. The first determines the transport mode for each shipment based on the preference of the shippers. The other sub-model assigns the shipment to the specific service of the chosen transport mode (e.g., the specific barge service for IWT). This is done using cost minimisation. The goal of this research is to understand the impact certain attributes have on the container flow of each transport mode. To do so, the existing sub-models are analysed and it is concluded that the way they are used has some limitations. The main limitation is that the utility of the shippers (i.e., mode choice preferences) is not considered simultaneously with the information from the available services (e.g., capacity, departure frequency) which can lead to sub-optimal assignment of the container flow. (e.g. When 100 containers are assigned to IWT but the capacity of IWT services is only 70.) To further optimise the assignment of containers, an integrated mode choice and assignment model is proposed in this research, visualised in Figure 1.2. Therefore the problem is how to integrate the mode choice and assignment sub-models, so that the impact of certain transport mode attributes can be tested.

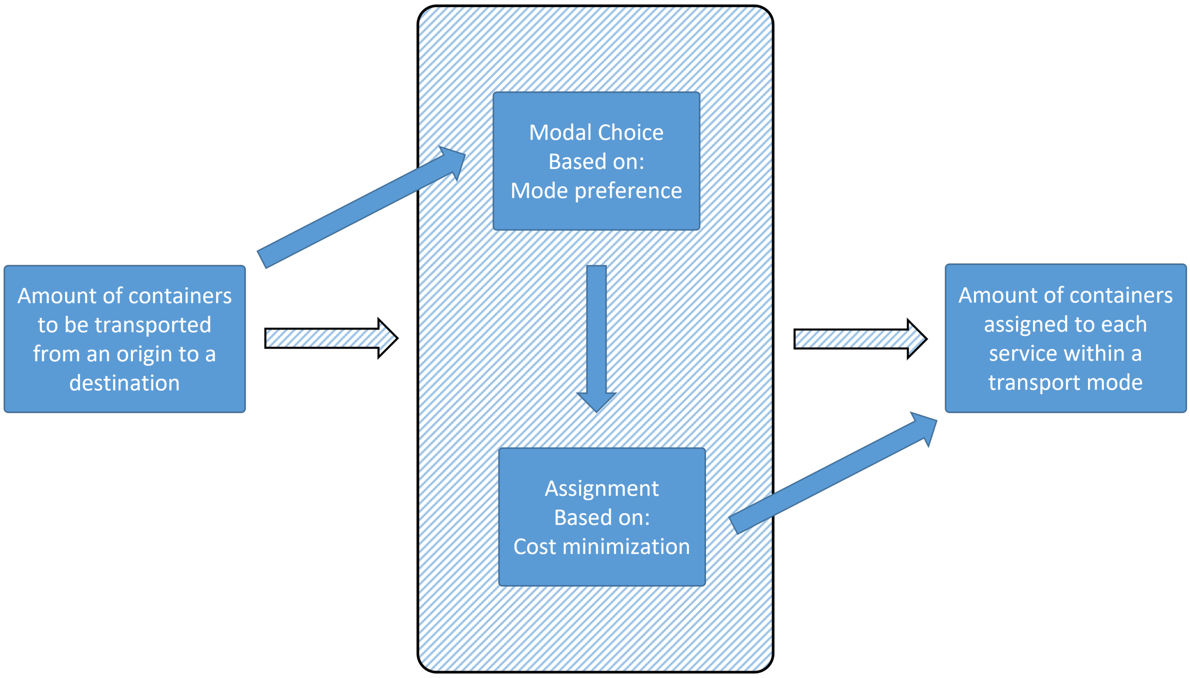


Figure 1.2: Flow diagram of the mode choice and assignment submodels, the shaded flow showing the in this research proposed integrated model flow

1.4. Research Questions

The main research question of this study is:

How to develop an integrated mode choice and assignment model for evaluating the impact of transport mode attributes on the modal split in a logistic network?

To answer the main research question, the main question is split in the following sub questions:

- RQ1: What are the most important transport mode attributes affecting mode choice for logistic networks?
- RQ2: How are mode choice and assignment modelled in other relevant studies?
- RQ3: How can the mode choice and assignment sub-models be enhanced, considering different preferences of stakeholders?
- RQ4: What is the impact of integrating mode choice and assignment compared to the sequential model?
- RQ5: How do transport mode attributes affect the modal split using the integrated model?

1.5. Research Method

With the problem defined and the research questions formed, the research method can be described. The work in this study is done according to the following steps:

- Research literature for studies into the effect of transport mode attributes on the modal split in a transport network and assignment models. [RQ1]
- Determine all the transport components and their attributes as well as relevant stakeholders. [RQ1]
- Research literature for relevant studies relating to freight flow assignment and mode choice models. [RQ2+3]
- Create a benchmark model using the current NOVIMOVE model. [RQ3+4]
- Develop an integrated model combining the mode choice and assignment tasks. [RQ3+4]
- Study available data for the case study. [RQ5]
- Create policy scenarios by altering the most important transport mode attributes. [RQ5]
- Evaluate the effects these scenarios have on the modal split using the integrated model. [RQ5]

After these steps a conclusion can be drawn and the main research question of this study can be answered.

1.6. Structure

This report is structured as follows; after the introduction an overview of the studied literature is given in Chapter 2. The benchmark model and new developed model are described further in Chapter 3. The data used for the case study and the experiments done together with their results are presented in Chapter 4. Finally this report finishes with some conclusions and recommendations in Chapter 5.

2
Literature Review

Research into multimodal freight transportation planning has been an increasingly interesting topic. In this chapter a brief overview of some relevant literature is given. Firstly the concept of multimodal transport itself is briefly discussed, followed by discussing some studies that looked into the effects of attributes of transport modes on hinterland transport planning. This will give us an idea of what attributes to alter in this study. Next, the most well known transport model, the four step model is explained and how it is still used to this day. Finally the latest research in multimodal transport is discussed along with how this study stands out. Studying this relevant literature gives an overview of the current state of research and answers the first two research questions of this study.

2.1. Multimodal Transport

Several different terminologies are used in the industry and literature when looking into transport using multiple modes. Unfortunately the definitions of these terminologies often differ per study. Reis [23] studied these definitions and discussed the key characteristics of these different terminologies in order to create unambiguous meanings and prevent misinterpretations in future research. The following definitions are based on this paper.

- **Multimodal transport** can be defined as transportation of freight or people from an origin to a destination by using at least two different transportation modes.

- An evolution of this is **intermodal transport**, three characteristics can be defined. First of all the use of a uniform loading unit, often containers, to ease transshipment and allow for standardising of equipment. This leads into the second characteristic, the integration of transport agents. Besides the technical integration by using uniform loading units, this also includes integration on an organisational level. The final characteristic is the door-to-door transport concept where the customer specifies an origin and destination but the path and modes used to transport the shipment are irrelevant as long as the shipment is transported in time.

- **Combined transport** is an evolution of intermodal transport, it focuses heavily on sustainable modes to reduce the environmental impact.

- **Co-modal transport** is derived from intermodal transport as well, here the focus is more on efficiency. The use of a single mode is also allowed in this definition.

- **Synchromodal transport** is the latest evolution of this transport concept and it adds the concept of real-time decision making. It aims to develop a sustainable and efficient transport chain with flexible mode choice based on real-time information.

A visualisation of the sequential relations between these terms can be seen in Figure 2.1.

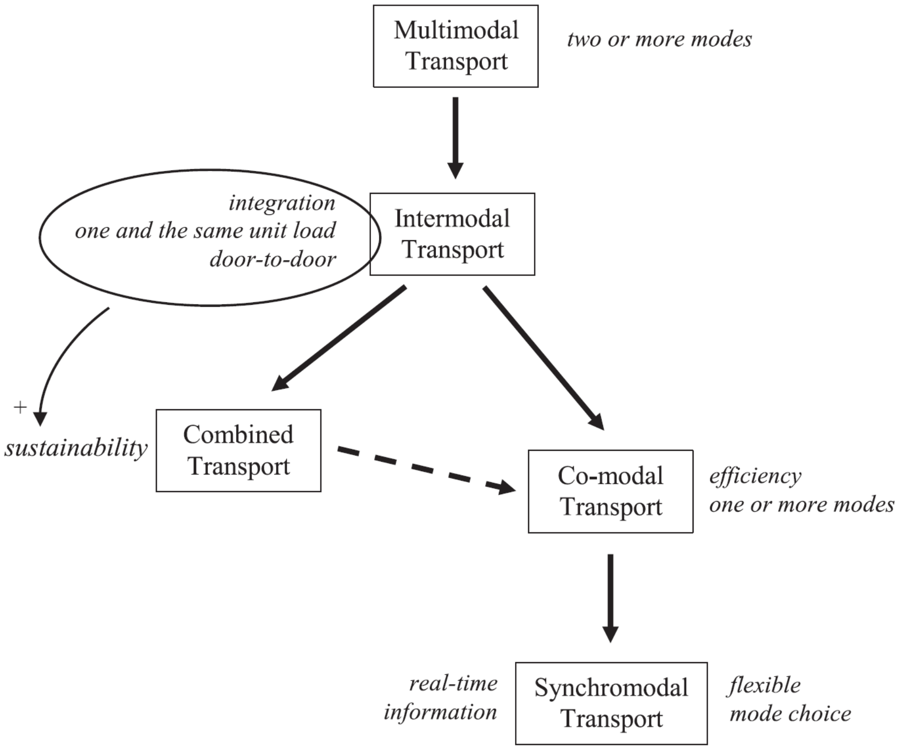


Figure 2.1: Visualisation of the sequential relations between transport chain terms by Reis [23]

Steadieseife et al. [26] used similar definitions where intermodal focuses on using the same loading units, co-modal on resource utilisation and synchromodal on real-time flexibility. Multimodal transport is used as the overarching term for these variations. Even though there are many papers written concerning multimodal transport the different variations are still not always clear. Based on the definitions mentioned, the transport network studied in this research can be characterised as an intermodal transport network. Although the term multimodal transport network will be used in the rest of this thesis to prevent any misinterpretations.

2.2. The Effects of Mode Attributes

Several studies can be found mentioning the effect of certain transport mode attributes in hinterland container transport. However, almost all of these studies looked at the impact these attributes have on the choice preferences of decision makers (e.g., freight forwarders) in the transport chain. Meers et al. [19] studied the modal choice preferences in short-distance hinterland container transport. Based on earlier literature they included price, transport time, reliability and frequency as main criteria in their study. Determining what transport attributes affect this choice the most. They concluded that road transport is still the main preferred transport mode and that higher service frequency at competitive costs and higher reliability than road transport could result in a modal shift away from road transport. Blauwens et al. [4] and Feo-Valero et al. [9] both showed that regarding modal choice for container shipments from seaports to hinterland, frequency is of key importance. Feo-Valero et al. [8] also reviewed various papers analysing the impact of attributes on mode choice. According to them transport cost, transport time and reliability regarding the delivery times are the most frequently considered transport mode attributes when determining the modal choice. Results of this study can also be seen in Figure 2.2. Tavasszy et al. [27] investigated the mode choice of freight transportation using a multi-criteria decision analysis. Their results indicated that transport cost and on-time reliability are the most important attributes, while CO2 emission reduction was viewed as least important. Bask and Rajahonka [1] conducted a literature review on the role of environmental sustainability (as a mode attribute) in modal choice of freight transport. The results of this review showed that although an emerging topic, most papers have not yet focused on environmental aspects of transport modes and focused mainly on cost efficiency and utility. Feo-Valero et al. [9] also noted that in their research no freight forwarder chose lower environmental impact as a reason to use rail instead of road transport.

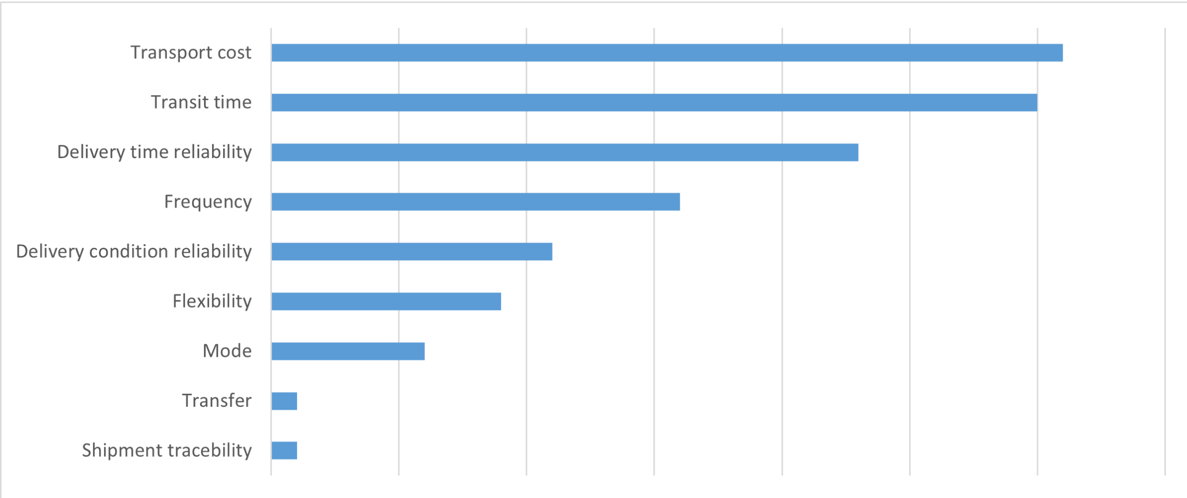


Figure 2.2: Graph showing the amount of papers in which each transport mode is considered by decision makers when choosing a transport mode, results of a literature study by Feo-Valero et al.[8]

2.3. The Four Step Model

A widely used transportation model is the four-step model, which is a systematic approach to forecasting travel demand and evaluating the performance of transportation systems. The four-step travel model is a sequential process that involves four stages: trip generation, trip distribution, mode choice, and trip assignment. These steps are designed to capture different aspects of travel behaviour and help, amongst others, transportation planners and policymakers make informed decisions about transportation policies and investments. This model has often been called the classic transport model [6] and the main structure of the model has remained mostly unaltered since the 1960s. The steps in the four-step model are described by McNally [18] as follows; In the trip generation step, the propensity to travel is estimated using data such as demographic, socio-economic, and land use data. Next in the trip distribution step, using the results of the trip generation, a trip matrix is created. These trips are defined as production-attraction or origin-destination pairs. The next step is the mode choice, here the generated trips are coupled to a specific transport mode. Finally in the last step the trips are assigned to a specific service of their previously determined transport mode. Most variants of the four-step model feed the output flows back to either the trip distribution or mode choice step. A flow diagram of the generic four-step model can be seen in Figure 2.3. The last two steps are discussed in more detail in the following as they are the focus of this study.

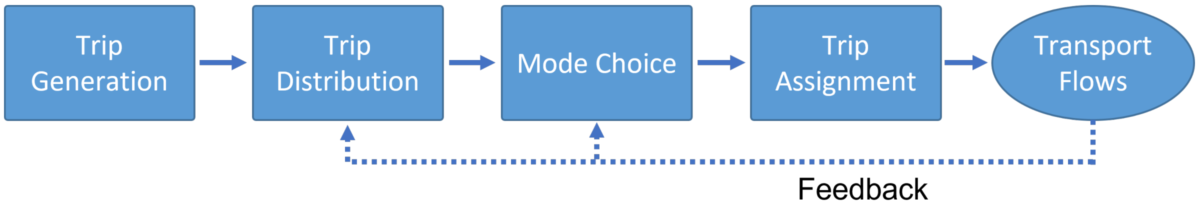


Figure 2.3: Flow diagram of the four step travel model

2.3.1. Mode Choice

As previously mentioned the mode choice model takes a set of trips and assigns each to a specific transport mode. One of the most commonly used models is a Multinomial Logit (MNL) model, the MNL model is a form of discrete choice modelling and based on the random utility maximisation principle firstly proposed by McFadden [17]. These types of models determine the utility of a certain mode and then calculate the probability of choosing that transport mode. Some variations of the MNL that are often used as well are the following. Nested Logit [11] and Mixed Multinomial Logit [16]. Specifically, the mixed MNL model is often used in freight transport planning as the coefficient in the model indicating the importance of a certain attribute is randomly distributed instead of fixed as in the traditional MNL. This can help mitigate the lack of detail when using aggregated data instead of precise shipment data, since shipment data is often hard to obtain. Other non-statistical models that use more recently developed computing methods are artificial neural network and machine learning. Lee et al. [13] showed that an artificial neural network model is more accurate compared to MNL as it can analyze more complex patterns and model nonlinearity. The downside is that it is a lot more complex compared to MNL. Zhao et al. [30] compared a machine learning model to MNL and results showed that machine learning is more accurate in predicting where MNL is more behavioral sound.

2.3.2. Assignment

As the last step of the four-step model, the assignment model takes the output of the mode choice model and the trips or OD-pairs matched with a certain transport mode and assigns each to a specific service of the transport mode. This step is at times also called route choice like in [7] this gives the final output of the model, being the specific trips for each container. The assignment step can be done simultaneously with the mode choice or separately. Both have its advantages and disadvantages. De Jong et al.[7] give a nice overview of these disadvantages and advantages of combining or separating the mode choice and assignment steps. The advantages of having a separate assignment stage are that the mode choice model can be disaggregate and allows interaction with passenger trips in case passenger and freight trips are assigned together. The disadvantages of a separate assignment stage however are the absence of interaction between demand and assignment, making the model less realistic as it can only be done iterative. In this case there is no disaggregate data and there is solely freight to transport, therefore a combined mode choice and assignment model can make the model more realistic.

2.4. Synchromodal Transport

As mentioned in section 2.1, synchromodal transport is the latest evolution of intermodal transport. The real-time decision making aspect makes synchromodal transport more attractive to shippers, as the ability to use multiple modes of transport or quickly switch transport modes in case of disruptions can improve reliability and reduce costs. This means shippers must relinquish their control over the shipping mode. Research, Khakdaman et al.[12], shows that over two third of shippers is willing to do so in return for lower costs or better services. Most of the current research into synchromodal transportation is focussed on some sort of cost minimization [2]. However, at this time most shippers still use unimodal transport and choose their modes of transport themselves. Therefore it is important to also take shipper preferences into account in order to persuade shippers to switch to synchromodal transport solutions. Zhang et al. [29] address the shippers preferences by using fuzzy set theory to convert the vague preferences to values that are then used in constraints in a multi objective optimization model. What sets this research apart is that fact that the multi objective optimization both minimizes the cost and maximizes the preferred transport mode of the shippers simultaneously.

2.5. Summary

Literature research shows that multimodal transport is an active field of research with many variations. The most important attributes to determine what transport mode is chosen by the decision makers are cost, time, reliability of transport time and transport frequency. The structure of the four-step travel model is still one of the most used templates for transportation models, although many variations of it exist. The mode choice and assignment steps are most often two separate steps, but they can be combined to create a better interaction between demand and assignment, making the model more realistic. Finally most of the current research is focussing on synchromodal transport. The addition of real-time decision making in case of disruptions for example, improves the reliability of transport time, making it more attractive to shippers to switch from unimodal to multimodal transport. Currently most shippers still have a preferred mode of transport, however not many studies include the shippers preferences in their models. The ones that do use it as a constraint in their cost minimization models. Using multi objective optimization to simultaneously minimize cost and maximize the preferred transport mode is what sets this research apart from the rest. How this model is created is described in the next chapter.

3
Methodology

In this chapter the creation of the model used in this study is described. First the current transport sub-models used for project NOVIMOVE are explained as they form the base of this study. Next the benchmark model created from these sub-models is described and validated. Finally the integrated mode-choice assignment model is explained in the last section of this chapter.

3.1. Background Transport Model

The main model created for project NOVIMOVE is a simulation model, designed to simulate the freight flow along the Rhine-Alpine corridor. Shobayo et al.[25] developed three sub-models to assign each container to a specific transport service, these are: Cost and time sub-model, Mode choice sub-model and Assignment sub-model. A flowchart of the interactions of the sub-models with the main simulation model can be seen in Figure 3.1

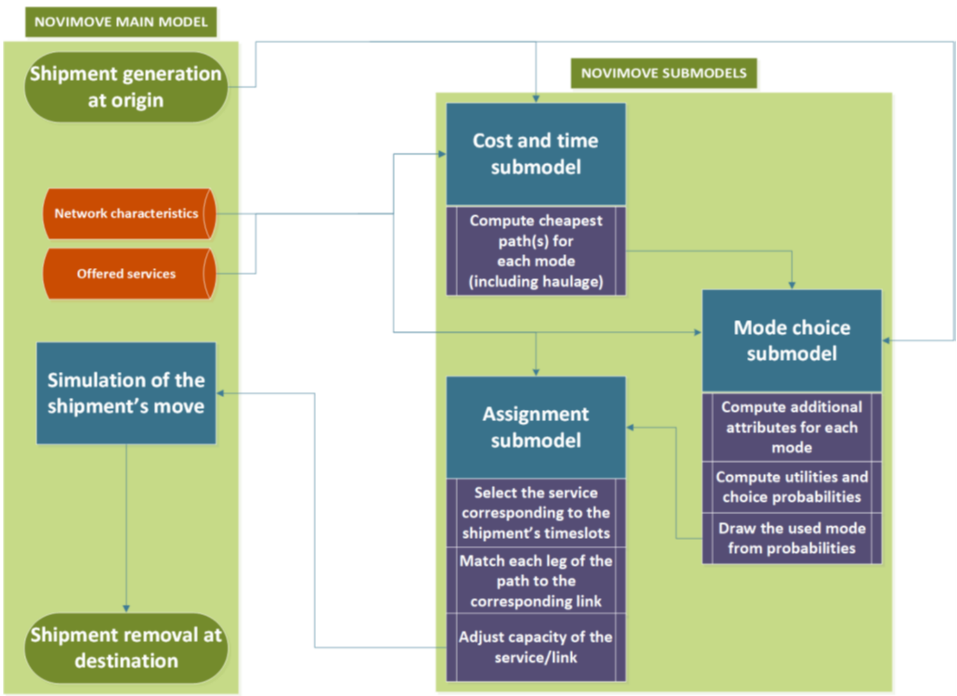


Figure 3.1: NOVIMOVE simulation model structure [25]

In this section, these three sub-models are explained as they form the benchmark model for this study.

3.1.1. Cost and Time Sub-model

As the name suggests, the cost and time submodel calculates the time and cost needed to transport freight along the paths of the network for each of the different transport modes. The generalised cost for each mode is calculated using equation 3.1.

$$C_{gen} = C_{tran} + C_{hand} + C_{time} + C_{rel} + C_{tot,ext} \tag{3.1}$$

Where;
C_{gen} = Generalised cost
C_{tran} = Transport cost
C_{hand} = Handling cost
C_{time} = Time cost
C_{rel} = Reliability cost
$C_{tot,ext}$ = Total external cost

This base cost function is further specified for each individual transport mode. The total external cost is made up of the accident, air pollution, climate change, noise, congestion and infrastructure costs. Further details on the cost and time sub-model can be found in Shobayo et al. [25]. The output of this sub-model is a list of the cost and time for transport between every Origin-Destination pair (further mentioned as OD-pairs).

3.1.2. Mode Choice Sub-model

The mode choice sub-model is used to predict the transport mode that will be used to transport a shipment from its origin to its destination. To do this the sub-model uses a variation of the Multinomial Logit (MNL). The utility function U_m of a transport mode and the probability P_m of choosing transport mode m are, as mentioned in Shobayo et al. [25], formulated as:

$$U_m = V_m + \epsilon_m = \alpha_m + \sum_{i \in I} \beta_{i,m} * X_{i,m} + \epsilon_m \tag{3.2}$$

$$P_m = \frac{e^{Um - \epsilon_m}}{\sum_m e^{U_m - \epsilon_m}} \tag{3.3}$$

Where;
I = Set of attributes influencing the mode choice (e.g. cost, time, reliability, etc.) indexed by i
M = Set of available transport modes indexed by m
V_m = Systematic utility function of mode m
α_m = Alternative Specific Constant of mode m
$X_{i,m}$ = Value of the attribute i for mode m
$\beta_{i,(m)}$ = Coefficient expressing the importance of attribute i (can vary according to the considered mode m or not)
ϵ_m = Error term for mode m to account for the unobserved factors influencing the outcome (follows an Extreme Value distribution)

There are several attributes that have an influence on the mode choice for a certain transport route. Two of the most often used attributes, cost and time, are calculated in the previous sub-model. Other attributes that were looked at include: reliability, frequency, accessibility, number of transfers, safety, environmental impact, shipping direction and population density. The systematic utility function for this sub-model will use the generalised cost as mentioned in equation 3.1. This generalised cost already includes several attributes namely: reliability, safety, time and environmental impact. The systematic utility functions for each mode are calculated as follows:

$$V_{IWT} = \alpha_{IWT} + \beta_{C,IWT} * C_{gen,IWT} + \beta_f * F_{IWT} \tag{3.4}$$

$$V_{Rail} = \alpha_{Rail} + \beta_{C,Rail} * C_{gen,Rail} + \beta_f * F_{Rail} \tag{3.5}$$

$$V_{Road} = \alpha_{Road} + \beta_{C,Road} * C_{gen,Road} + \beta_d * D^{pop} \tag{3.6}$$

Where;
$C_{gen,m}$ = Generalised costs for mode m
F_m = Frequency of mode m
D^{pop} = Average population density of origin and destination zones

The α and β coefficients are estimated using likelihood maximisation. In order to do this, one alternative specific constant α had to be normalised, in this case α_{IWT} is set to zero. The estimation results can be seen in Table 3.1, a further detailed explanation can be found in Majoor [15].

Table 3.1: Estimation results of the α and β coefficients.

Coefficient	Value
α_{Rail}	-1.46
α_{Road}	0.536
$\beta_{C,IWT}$	-10.2
$\beta_{C,Rail}$	-7.32
$\beta_{C,Road}$	-4.65
β_f	-0.998
β_d	0.0146

With the probability for each mode known, a random drawing procedure is used to assign each container to a mode for every OD-pair.

3.1.3. Assignment Sub-model

After the transport mode is predicted for each OD-pair, the assignment sub-model can now assign each shipment to a specific service for each transport mode. Solving the assignment problem is often done using cost minimization (Beuthe et al. [3]; Crainic et al. [5]; Lou et al. [14]), where for each shipment the service with the lowest overall cost is selected until the capacity for said service is met or the service departs. In order to use the cost minimization method, sufficiently detailed information about the services and network is vital. In this study this is only the case for the IWT network as the road and rail networks are both modelled at a lesser detailed level. Therefore only the IWT assignment is done using cost minimization while road and rail assignment is done using heuristics. Below the assignment methods are briefly explained for each transport mode.

Road

The assumption is made that trucks are always available. The use of the road transport part of the assignment sub-model is solely to determine the amount of shipments send by truck along each link of the network.

Rail

Shipments send by rail will be assigned according to the first-come first-served principle. Incoming shipments are assigned to the next departing rail service. If the capacity of this rail service is met, the shipment will simply be assigned to the following departing service.

IWT

As there is enough information regarding the IWT services (i.e. barges) and the IWT network, the cost minimization method can be used. Doing so each container will be assigned to a specific barge service. Each service is specified by origin and destination at terminal level, barge type and frequency. The cost and time sub-model calculates the time and cost for each service. The waiting times at the origin port are also used for the cost minimization. To convert the waiting and travel times in monetary units, they will be multiplied by the Value Of Time (VOT). The following minimization equation determines which service a given container will be assigned to:

$$\min_{s \in S}(c_s^{trans} + VOT * (\Delta t_s^O + \Delta t_s^D)) \tag{3.7}$$

Where;
S = Set of available services
c_s^{trans} = Transport costs for service s [€]
Δt_s^O = Difference of departure time of service s compared to the earliest departing service in S [h]
Δt_s^D = Difference of arrival time of service s compared to the earliest arriving service in S [h]

Figure 3.2 shows an example of how Δt_s^O and Δt_s^D are determined when there are three services available.

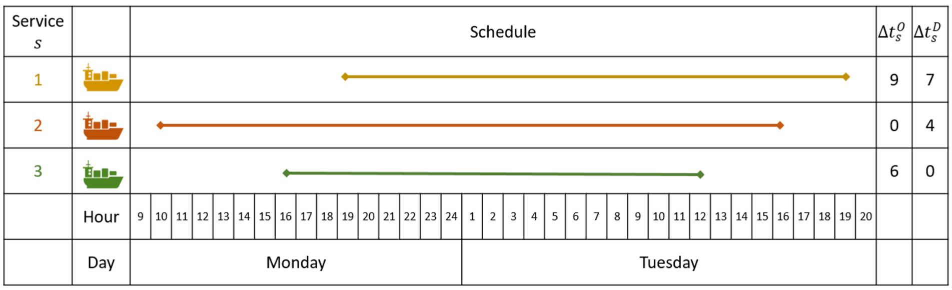


Figure 3.2: Example of determining Δt_s^O and Δt_s^D [15].

Transport via rail or IWT often includes pre- or post-haulage via trucks. This section of road transport is not included in the model as the transport is along relatively small distances and the road network is represented at a high level. Thus the shipments along the rail and IWT network will enter and exit the network at their respective terminals.

3.2. Benchmark Model

The goal of this study is to create a new model which combines the mode choice and assignment step. To experiment with this new model, a benchmark model must be made to compare the new integrated mode-choice and assignment model with the currently used version. To create this benchmark model the mode choice sub-model and the assignment sub-model are implemented as they are described in section 3.1. The cost and time sub-model will not be altered in this study and will therefore not be implemented. The output of this sub-model, the transport cost and time between each OD-pair, will still be used as input for both models.
Two changes are made to the benchmark model to make it more realistic. Firstly, in some cases extra barges were created in order to send all containers assigned to IWT by the mode choice sub-model. Now, if all barges are filled to max capacity, the remaining containers are held until a next barge arrives. The second alteration is that barges were departing immediately after max capacity was reached. This caused the problem that barges were sent earlier than the input data showed. As the frequency of barge services is modelled by holding the barge at the origin for a set amount of days before creating the next one, this altered the frequency of the barge services. Therefore, fully loaded barges are now held for the correct amount of days based on the frequency input. As can be seen by the modal split results in Table 3.2 these changes make the benchmark model more realistic as the result is much closer to the actual modal split according to collected data[15].

Table 3.2: Modal split according to collected data[15], the original benchmark and the altered benchmark model

	IWT	Rail	Road
Collected Data	18%	6%	76%
Original benchmark model	40%	10%	50%
Altered benchmark model	20%	3%	77%

Validation of the Benchmark Model

In order to validate the Mode Choice of the research model, it is compared with the original NOVIMOVE sub-models. The two adaptations mentioned above are implemented in the NOVIMOVE sub-models as well to make sure both models work the same. To compare the models the random drawing procedure used to randomly assigned the containers to each mode is replaced with a simple uniform distribution. This is done to ensure the input for both models is exactly the same. After running both models with the same OD input, the outputs are compared. The results show that the amount of containers assigned to each OD per mode are exactly the same. The amount of containers assigned to each mode by both models can be seen in Appendix C. The output shown is for one day for all OD-pairs used in this research.
The assignment part of the research model is validated using the same uniform distribution as input. The model is ran for a week to also account for holding containers at the origin due to the frequencies of the barges departing. The results are almost identical to the NOVIMOVE model and are shown in Appendix C. Two discrepancies are noticed, in one case there are two ships of the same class and departure frequency servicing the same OD-pair. According to the model there is no preference between the two. In this case the NOVIMOVE sub-models selected the barge with lower capacity first, filled it and then shipped the remainder of the containers on the other barge. The research model selected the other barge first, which has

a higher capacity and filled it with all waiting containers. Thus eliminating the need of sending the other barge. The other discrepancy is due to the fact that in the NOVIMOVE model, an extra barge is created when not all containers can fit on the departing barges. This occurred here and the containers were equally distributed along the original barge and the newly created one. The research model fills the departing barge till its capacity and holds the remainder of containers to be send on the next departing barge.

3.3. Integrated Mode Choice and Assignment Model

Along with the two changes already implemented in the benchmark model, this new model will combine the mode-choice and assignment in one step to make it more realistic. As mentioned earlier, the assignment step uses cost minimization to select a service and the mode choice is done using probability maximization, where the amount of containers assigned to the mode with the highest probability is maximized. In order to optimize both these objectives simultaneously a multi objective optimization model is made. The mathematical model looks as follows:

Mathematical Model

Sets:

P	Set of OD-pairs indicated by i
S	Set of services indicated by j
M	Set of transport modes indicated by m

Parameters:

q_i	Amount of containers to be transported between OD-pair i
c_j	Cost of transporting a container with service j
p_{im}	probability of containers transported with transport mode m between OD-pair i
u_j	Capacity of service j
o_i	Origin of OD-pair i
o_j	Origin of service j
d_i	Destination of OD-pair i
d_j	Destination of service j
$bigM$	A large enough positive number
δ_{jm}	Indicates the transport mode m of service j

Decision variables:

x_{ij}	Binary variable: $\begin{cases} 1, & \text{if containers are assigned to service } j \text{ between OD-pair } i \\ 0, & \text{otherwise} \end{cases}$
y_{ij}	Integer variable denotes the amount of containers from OD-pair i assigned to service j
z_{im}	Integer variable denotes the amount of containers from OD-pair i transported with mode m

Minimize:

$$\sum_{i \in P} \sum_{j \in S} c_j y_{ij} \tag{3.8}$$

Maximize:

$$\sum_{i \in P} \sum_{m \in M} p_{im} z_{im} \tag{3.9}$$

Subject to:

$$\sum_{j \in S} x_{ij} \geq 1 \qquad \forall i \in P \tag{3.10}$$

$$\sum_{j \in S} y_{ij} = q_i \qquad \forall i \in P \tag{3.11}$$

$$\sum_{i \in} y_{ij} \leq u_j \qquad \forall j \in S \tag{3.12}$$

$$x_{ij} o_i = x_{ij} o_j \qquad \forall i \in P, j \in S \tag{3.13}$$

$$x_{ij} d_i = x_{ij} d_j \qquad \forall i \in P, j \in S \tag{3.14}$$

$$y_{ij} \leq bigM x_{ij} \qquad \forall i \in P, j \in S \tag{3.15}$$

$$\sum_{j \in S} y_{ij} \delta_{jm} = z_{im} \qquad \forall i \in P, m \in M \tag{3.16}$$

$$\begin{aligned} x_{ij} &\in \{0,1\} \qquad \forall i \in P, j \in S \\ y_{ij} &\in \mathbb{Z} \qquad \forall i \in P, j \in S \\ z_{im} &\in \mathbb{Z} \qquad \forall i \in P, m \in M \end{aligned} \tag{3.17}$$

The first objective (3.8) minimizes the cost of the services being used and the second objective (3.9) tries to maximize the the use of the transport mode with the highest probability. To optimise these objectives the following constraints are used: Constraint (3.10) states that containers from each OD-pair must be assigned to at least one service. Constraint (3.11) makes sure that all the containers for each OD-pair are assigned to a service. Constraint (3.12) denotes that the amount of containers assigned to a service can not exceed the capacity of the corresponding service. Constraints (3.13) and (3.14) determine that the origin and destination of the OD-pair should match those of the service. Constraint (3.15) then states that containers should only be assigned if a service is being used. Constraint (3.16) defines the amount of containers assigned to each transport mode for each OD-pair. Finally constraint (3.17) describes the decision variables.

The problem is solved using Gurobi optimization software [22] which uses the weighted sum method to combine both objective functions resulting in the combined objective function (3.18). As the second objective needs to be maximized instead of minimized, W_2 needs to be negative.

$$Minimize: \qquad W_1 \sum_{i \in P} \sum_{j \in S} c_j y_{ij} + W_2 \sum_{i \in P} \sum_{m \in T} p_{im} z_{im} \tag{3.18}$$

3.3.1. Verification Tests

To test the model a small section of the data from the case study is used, consisting of 4 O-D pairs. The input data is shown in Table 3.3 and consists of: the origin and destination of the shipment, the weekly quantity of containers transported between the O-D pair, the generalised cost for each mode and the weekly capacity of each transport mode. The capacity for road transport is set at 100000 as it is assumed there is always road transport available.

Table 3.3: Small section of the case study data used for testing the model

O	D	Containers	$C_{GEN,IWT}$	$C_{GEN,Rail}$	$C_{GEN,Road}$	Cap_{IWT}	Cap_{Rail}	Cap_{Road}
NL33	DEA1	36673	256	428	431	9806	4680	100000
NL33	DEA2	3164	309	465	528	2072	300	100000
BE21	CH03	217	498	796	1462	968	1800	100000
BE21	DEA2	1820	322	449	422	1194	0	100000

The model uses Gurobi optimization software [22] to calculate the flow on a weekly basis as the collected data is weekly as well.
Based on the generalised costs in Table 3.3 it is expected that the Cost minimization objective will firstly fill the IWT services till max capacity. The capacity for IWT and Rail transport can be found in Table 3.4. The results of only using the cost minimization function in Table 3.5 confirm that this is the case.
For the Probability maximization objective it is expected that the model chooses the modes with the highest probability, as underscored in Table 3.4, first, before moving to the next highest probability. The results of only using the Probability maximization objective show that this is indeed true.
Finally when using both the cost minimization and probability maximization objectives a combination of the two single objectives is expected. The results show this as well, for example: Looking at the Multi objective optimization in Table 3.4, OD-pair (NL33-DEA2) shows that IWT is filled to capacity first, which is the lowest cost transport mode but not the mode with the highest probability. The remainder of the containers is then transported by road, which has the highest probability but also the highest cost of all modes.

Table 3.4: Probabilities for each transport mode of the test input

O	D	P_{IWT}	P_{Rail}	P_{Road}
NL33	DEA1	**0.526**	0.142	0.332
NL33	DEA2	0.408	0.075	**0.517**
BE21	CH03	**0.76**	0.122	0.118
BE21	DEA2	0.237	0	**0.763**

Further verification tests show the model works as expected. Table 3.6 shows the input of some of the verification tests, where the availabilities of certain transport modes are altered for one of the OD-pairs from the test input from Table 3.3. The results are shown in Table 3.7, only the cost minimization objective is used as its behaviour is most predictable.
With all transport modes available, the model fills the cheapest transport mode first till capacity is met and than moves to the next cheapest mode. When IWT is not available as transport

Table 3.5: Test output showing the amount of containers transported by IWT, Rail and Road for each O-D pair using either only cost minimization, only probability maximization or multi objective optimization.

Only cost minimization

O	D	IWT	Rail	Road
NL33	DEA1	9806	4680	22187
NL33	DEA2	2072	300	792
BE21	CH03	217	0	0
BE21	DEA2	1194	0	626

Only probability maximization

O	D	IWT	Rail	Road
NL33	DEA1	9806	0	26867
NL33	DEA2	0	0	3164
BE21	CH03	217	0	0
BE21	DEA2	0	0	1820

Multi objective optimization

O	D	IWT	Rail	Road
NL33	DEA1	9806	0	26867
NL33	DEA2	2072	0	1092
BE21	CH03	217	0	0
BE21	DEA2	0	0	1820

mode, e.g. the capacity is set to zero, no containers are assigned to this mode but instead the second cheapest mode is filled first. This shows that constraint 3.15 is correctly implemented and no containers are assigned to a service that is not available.
When there is no road transport available however, there is no solution available. Constraints 3.10 and 3.12 tell that every container must be assigned to a service and the the amount of containers can not exceed the capacity of the service. In this case the available capacity is less then the containers that need to be transported. The model gives no solution, indicating the correct implementation of the constraints.

Table 3.6: Input of the verification tests with 1) the original capacities 2) zero capacity for IWT 3) zero capacity for road transport

O	D	Containers	$C_{GEN,IWT}$	$C_{GEN,Rail}$	$C_{GEN,Road}$	Cap_{IWT}	Cap_{Rail}	Cap_{Road}
NL33	DEA1	36673	256	428	431	9806	4680	100000
NL33	DEA1	36673	256	428	431	0	4680	100000
NL33	DEA1	36673	256	428	431	9806	4680	0

Table 3.7: Output of the verification tests using only the cost minimization objective function

O	D	IWT	Rail	Road
NL33	DEA1	9806	4680	22187
NL33	DEA1	0	4680	31993
NL33	DEA1	*No Solution*		

3.3.2. Sequential vs Integrated Mode Choice and Assignment

The switch from sequential mode choice and assignment sub-models to an integrated mode choice and assignment model was made to allow interaction between the mode choice and assignment steps. As explained earlier, a sequential approach lacks the capability to check the capacity of the services of a transport mode before choosing the transport mode for a shipment. In this case, this can lead to the issue where more containers are designated to a transport mode than the available capacity of the services for that transport mode. Table 3.8 compares the output for two OD-pairs between sequential mode choice and assignment, as used in the NOVIMOVE sub-models, and the new integrated mode choice and assignment model, as described in this section. This clearly shows that the sequential model can assign more containers to IWT and rail transport than the capacity of the transport modes. As for the integrated model, due to the mode choice and assignment steps happening simultaneously, no more containers can be assigned to a transport mode than the capacity of that transport mode, as constraint 3.12 dictates. Therefore, with the integrated model, we avoid having unserved demand as we include the capacity considerations upfront. The modal split in the given examples makes it look like road transport is used more with the integrated model. However, this very much depends on the characteristics of the specific case at hand. The attributes of the different modes play a key role and in different OD-pairs this could have been the other way around.

Table 3.8: Amount of containers assigned to each transport mode using sequential and integrated mode choice and assignment steps

Location		Cost			Capacity		Assigned containers			Unserved Demand	
O	D	IWT	Rail	Road	IWT	Rail	IWT	Rail	Road	IWT	Rail
Sequential mode choice and assignment sub-models											
NL33	DEA1	256	428	431	9806	4680	19348	5182	12143	9542	502
NL33	CH03	475	852	1581	1316	1140	1417	100	86	101	0
Integrated mode choice and assignment model											
NL33	DEA1	256	428	431	9806	4680	9806	0	26867	0	0
NL33	CH03	475	852	1581	1316	1140	1316	287	0	0	0

3.4. Summary

The transport model by Shobayo et al. [25] can be split into three sub-models: the cost and time sub-model, the mode choice sub-model and the assignment sub-model. A benchmark model is developed based on these mode choice and assignment sub-models. Two changes are made in the assignment sub-model to make the model more realistic: (1) no extra barges are created to send all containers assigned to IWT and (2) barges are only send according to the collected frequencies and not send immediately when fully loaded. This benchmark model is validated against the model by Shobayo et al. [25] to show the model works as expected and has a realistic output. The reason this benchmark model is developed, is to compare the new integrated mode-choice assignment model to and to determine the weights of the combined objective function. The integrated mode-choice assignment model will combine the separate mode-choice and assignment sub-models into a single step, to make the model more realistic. This results in two objective functions: maximize the probabilities for choosing a transport mode and minimize the cost of the transport services used. Using multi objective optimization and the weighted sum method this results in the objective $Minimize: \ W_1 \sum_{i \in P} \sum_{j \in S} c_j y_{ij} + W_2 \sum_{i \in P} \sum_{m \in T} p_{im} z_{im}$ where W_2 is negative as the probabilities need to be maximized. In the next chapter these weights are determined by comparing results with the benchmark model.

4 Case Study

With the model now defined and verified we can look at the case study and the experiments that were done. In this chapter the data for this case study is described first and the scenarios for the experiments are explained. Next the results of these experiments are discussed for each scenario.

4.1. Data

As mentioned in the introduction, the scope of project NOVIMOVE is the Rhine-Alpine corridor. The data considering the freight flow along this corridor, collected by partners of project NOVIMOVE is at NUTS-2[1] level. Using the transport routes between all these NUTS-2 zones would result in a very large dataset that would be too big for this study. After consulting with members of project NOVIMOVE, the busiest and most frequently used transport routes were selected. The chosen data consists of transport routes where either the origin or destination of the route was one of the major sea ports along the corridor, being either the port of Antwerp or the port of Rotterdam. A visualisation of the geographical scope can be seen in Figure 4.1. After some further study and test runs of the model some OD-pairs where found that did not have more detailed data at port-level for the IWT part of the model. This missing data was either because it couldn't be obtained by the NOVIMOVE-partner or because it was not relevant to project NOVIMOVE. As the main focus of this study is the assignment of containers to IWT at port-level, the OD-pairs where no data was available at port-level were removed from the scope of this study. A full list of all the OD-pairs can be found in Appendix B.

[1] Nomenclature of Territorial Units for Statistics (NUTS) is a European classification system for subdivisions of countries used for logistic purposes, in the Netherlands NUTS-2 zones are the 12 provinces.

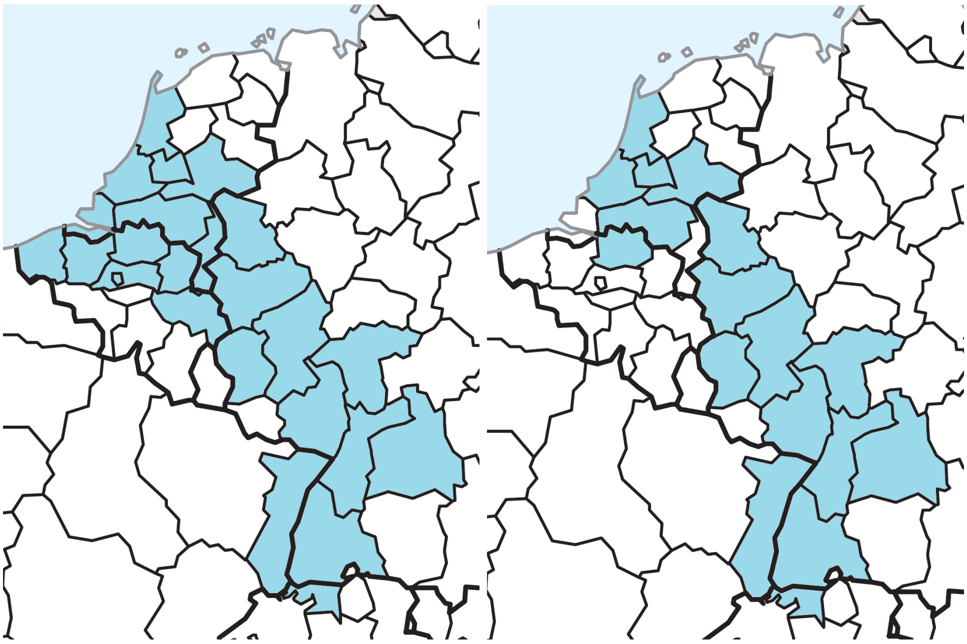


Figure 4.1: F.l.t.r. The suggested geographical scope and the final geographical scope used in this study.

4.2. Experimental Setup

The goal of this research is to determine how certain attributes of transport modes can effect the modal split of the container transport. Based on the literature study; cost, time, reliability and frequency are the most important decision makers when choosing a transport mode. Three attributes were selected to alter: Cost, Capacity and Frequency. As the aim for inland container transport is to increase the modal share of IWT, these attributes are altered in such a way that they would increase the usage of IWT.

- **Cost**
  For this experiment the cost of road transport is being increased to make road transport less attractive and in return IWT more attractive. A possible real life implementation of this would be to increase taxes on road transport of containers.

- **Capacity**
  For the second experiment the capacity of the individual IWT services is increased to allow more containers to be transported using IWT. Increasing the capacity of individual IWT services in real life could be done by either increasing the size of the barges or by using multiple barges departing at the same time as if a single IWT service.

- **Frequency**
  Finally the frequency of IWT services is increased to allow more frequent servicing for IWT. This is tested two ways, once by keeping the capacity constant and once by allowing the capacity to increase together with the frequency. In reality these scenarios mean that increasing the frequency without increasing capacity would be replacing a large barge by multiple smaller barges that together have the same capacity as the original larger barge. Not keeping the capacity constant however can simply be realised by increasing the number of barges that service a certain OD-pair or decreasing the time it takes for a barge to service an OD-pair so it can travel the route more frequently.

- **Combined policy**
  Based on the results of these experiments a final, combined policy is tested that would be more realistic to implement.

For all the experiments, all other attributes remain unchanged in order to see the impact each individual attribute has on the modal split. These experiments are not meant to be realistic solutions to increase the modal share of IWT, but to determine the impact that an individual attribute has. Each experiment is further explained in the following respective sections.

Determination of Weights
Before the experiments can be run, the weights for the combined objective function must be determined. In order to determine which weights for the objective functions are most realistic, the output of the CMA model is compared with the benchmark model. Several different weights between only cost minimization ($W_2 = 0$) and only probability maximization ($W_1 = 0$) are tested and the resulting modal split, is compared to the modal split of the benchmark model in Figure 4.2. This figure shows that the weights: $W_1 = 1$; $W_2 = -1500$ result in a modal split that comes closest to the modal split of the benchmark model. Therefore these weights will be used in the experiments along with $W_1 = 1$; $W_2 = 0$ and $W_1 = 0$; $W_2 = -1$ to highlight both objective functions individually, only cost minimization and only probability maximization respectively.

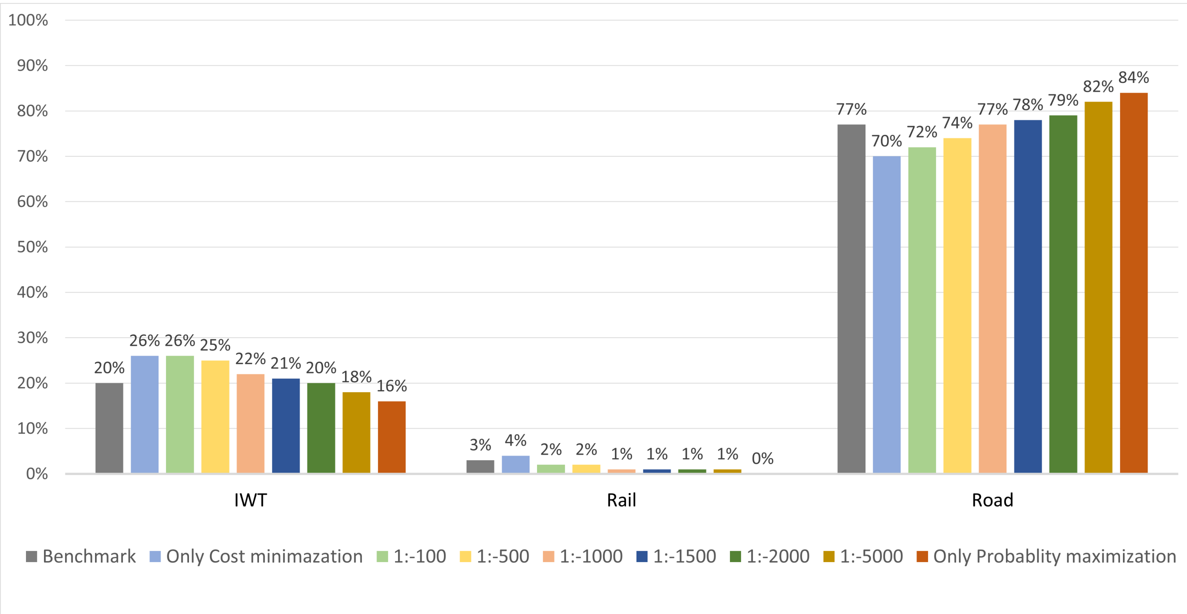


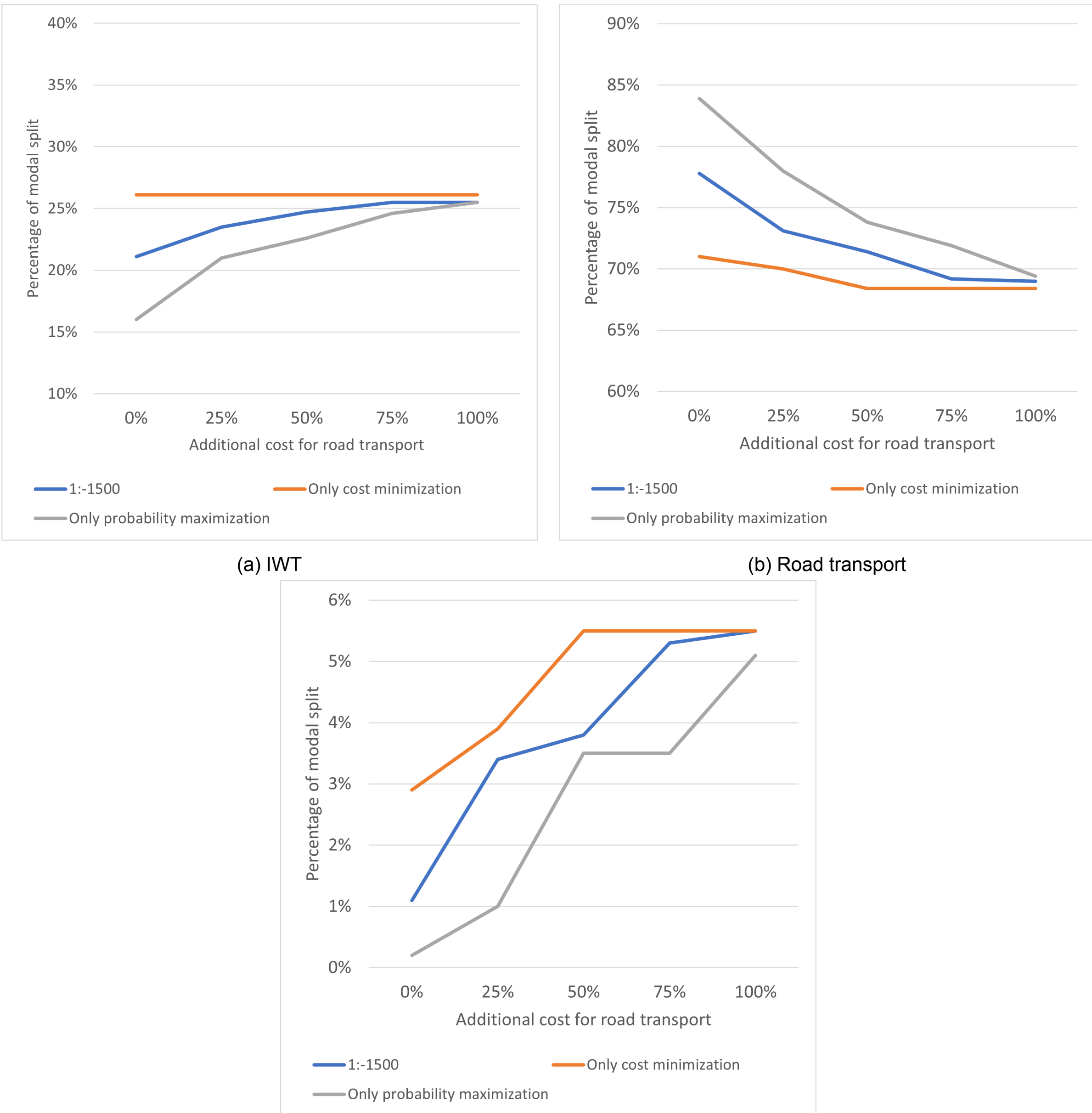
Figure 4.2: Weights of objectives

4.3. Experimental Results

In this section the results are presented of the scenarios defined in the previous section. Additionally some more realistic scenarios are described and their results are discussed as well.

4.3.1. Increasing Road Transport Costs

The first attribute that is altered is the cost of road transportation. The general cost for road transportation is increased by 25%, 50%, 75% and 100% to determine the effect this has on the modal split. The results of this experiment can be seen in Figure 4.3 (Note that in this and following figures the scale of the rail transport graph is different then the IWT and road graphs, to increase the readability).



(a) IWT

(b) Road transport

(c) Rail transport

Figure 4.3: Change in percentage of modal split for increasing the cost of road transport

At first glance, it can be seen that the IWT percentage of the modal split increases as the Road

transport percentage decreases. An increase in cost of 25% for road transportation, already shows an increase in IWT transport of 2,4% and a decrease of road transport of 4,7%. Looking at the individual objective functions, it is clear that the increase in cost of road transportation has the most effect on the probability maximization. The runs where only the cost minimization function was used show no change in the IWT percentage. This makes sense when looking into the data, as it shows that IWT transport is already the transport mode with the lowest cost for almost all OD-pairs. Thus, increasing the cost of road transport has no effect on choosing the least expensive transport mode.
Table 4.1 shows the distribution of containers across transport modes for three OD-pairs. Highlighted are the moment where the increase in road transport cost leads to a switch in mode choice for each OD-pair. For the first two OD-pairs, at 25% and 50% increase of road transport cost, the OD-pairs switch from using only road transport to first using IWT transport and sending the remainder with road transport. The last OD-pair only switches after increasing the cost of road transport by 100%, from using IWT and road transport to also using rail transport. Road transport will always remain needed in this scenario as the capacity of IWT and rail transport is less than the demand. Increasing the cost of road transport thus has a limit at which point the capacities of IWT and rail transport are met and the remaining containers have to be sent via road transport regardless of the cost, which can be seen in Figure 4.3b as the graph bottoms out.

Table 4.1: Containers transported by each transport mode for increasing the cost of road transport.

OD-pair		Increase of road transport cost 0%			25%			50%		
O	D	IWT	Rail	Road	IWT	Rail	Road	IWT	Rail	Road
NL33	NL22	0	0	23191	**1854**	0	**21337**	1854	0	21337
NL33	NL31	0	0	10889	0	0	10889	**944**	0	**9955**
NL33	NL41	2440	0	32014	2440	0	32014	2440	0	32014

Table 4.1: Continued

Increase of road transport cost 75%			100%		
IWT	Rail	Road	IWT	Rail	Road
1854	0	21337	1854	0	21337
944	0	9955	944	0	9955
2440	0	32014	2440	**300**	**31714**

4.3.2. Increasing IWT Service Capacity

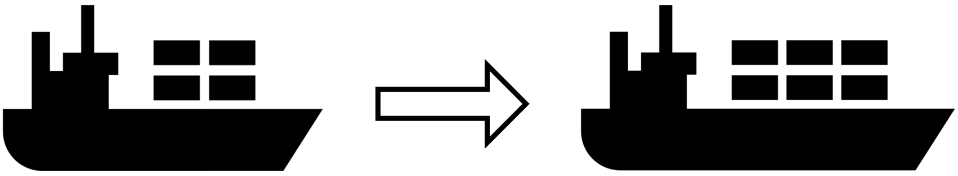
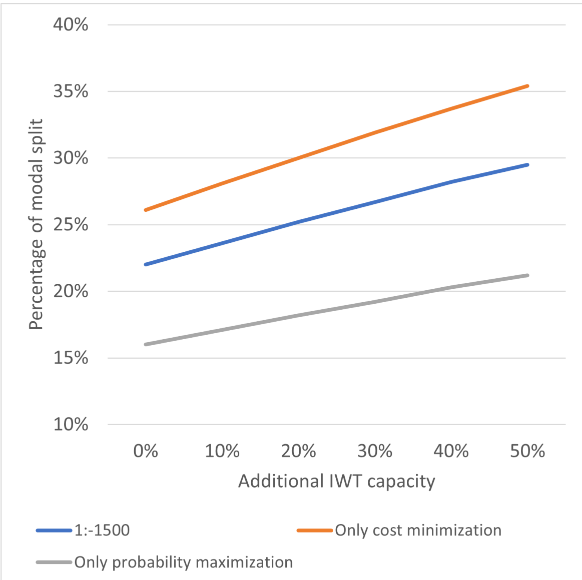
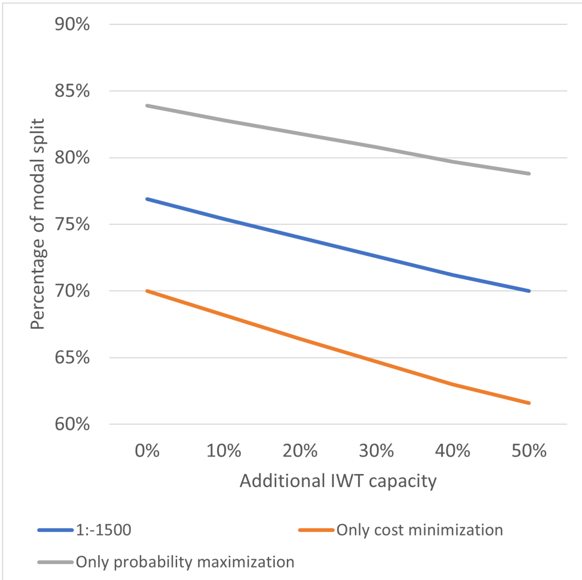


Figure 4.4: Illustration indicating the increase in capacity.

The second attribute that has been tested is the capacity. This is done by increasing the amount of containers each individual ship can transport by steps of 10%. Figure 4.4 shows that in reality this can be done by increasing the barge sizes. As can be seen in Figure 4.5a increasing the capacity of IWT services significantly increases the modal share of IWT. Looking closer at the results however, we see that increasing the capacity does not result in choosing IWT over another transport mode, but it allows for the OD-pairs where IWT is the preferred transport mode to send more containers before the maximum capacity is met and they need to switch to an alternative transport mode. This can be explained as neither objective function is influenced by the Capacity of IWT barges. The cost is not altered so cost minimization objective remains the same and capacity is not an attribute of calculating the probability of choosing a transport mode therefore the probability maximization objective remains similar as well. The increase is more when looking at only cost minimization (9%) versus only probability maximization (5%). This can be explained as IWT is the transport mode with the lowest cost for almost all OD-pairs and thus the preferred transport mode when only using the cost minimization objective.



(a) IWT



(b) Road transport

Figure 4.5: Change in percentage of modal split for increasing the capacity of IWT services

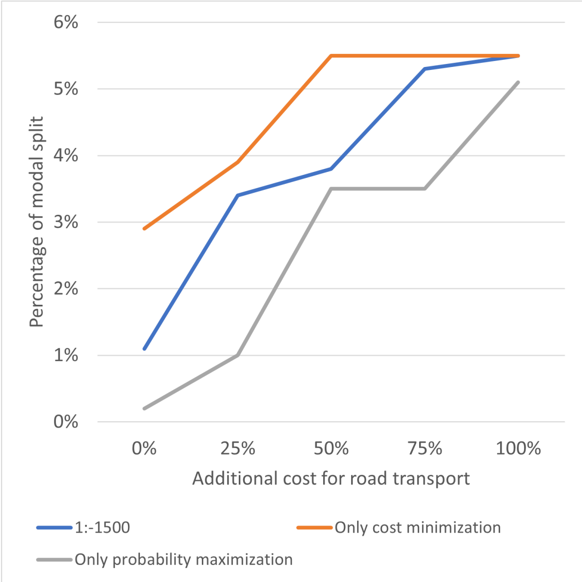


Figure 4.5: Change in percentage of modal split for increasing the capacity of IWT services (cont.)

4.3.3. Increasing IWT Service Frequency

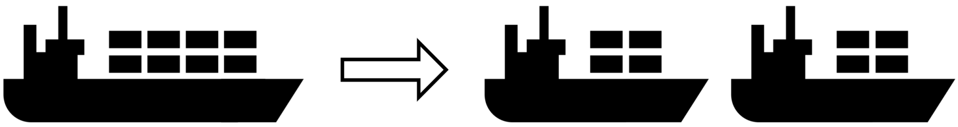
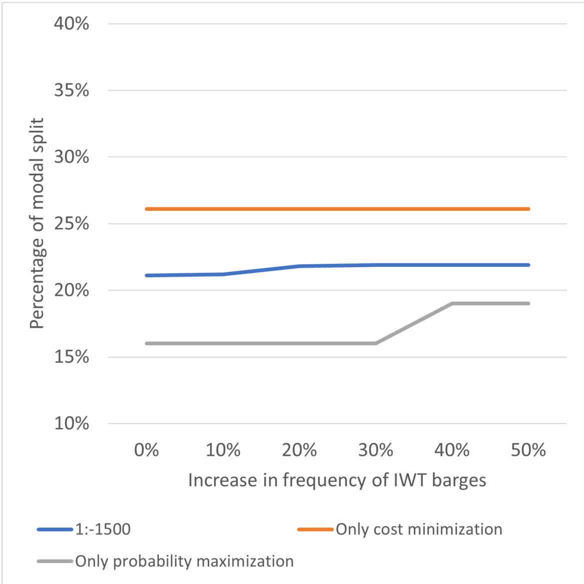
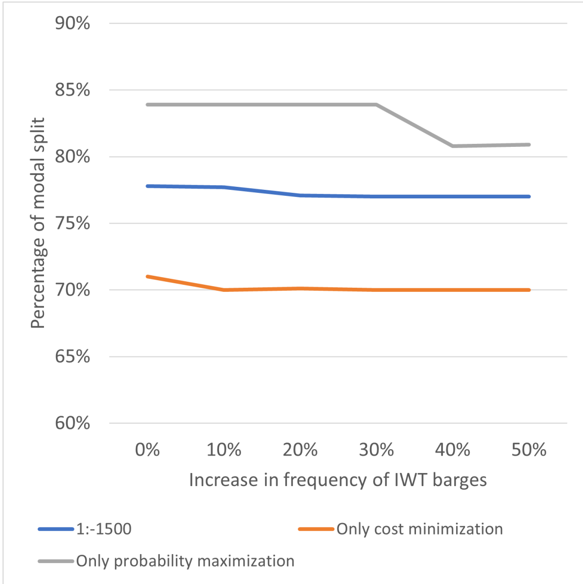


Figure 4.6: Illustration showing the increase in frequency while keeping the total capacity constant

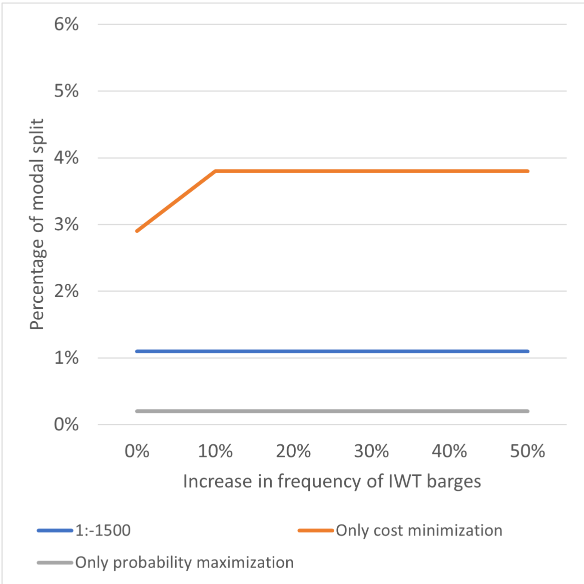
Finally the last attribute tested is the frequency of IWT services. The frequency is increased by steps of 10% and then rounded up to an integer. Increasing the frequency of IWT services means that per week more barges can be used between each OD-pair, however this means the capacity and cost increase as well by adding these barges. In order to solely determine the effect of the frequency, the cost and capacity are reduced as the frequency increases, so that the overall capacity and cost for the barges remain the same during the experiment. An illustration of this can be seen in Figure 4.6, again, this is not a realistic scenario but an academic analysis to guide future decisions where the barge sizes are smaller but the total capacity is the same. The results are shown in Figure 4.7, it is clear that frequency on its own does not have a high impact on the modal split. The large shift for just the probability maximization objective is due to a single high volume OD-pair shifting preference from road transport to IWT.



(a) IWT



(b) Road transport



(c) Rail transport

Figure 4.7: Change in percentage of modal split for increasing the frequency of IWT services

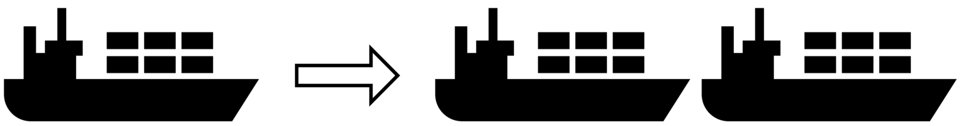
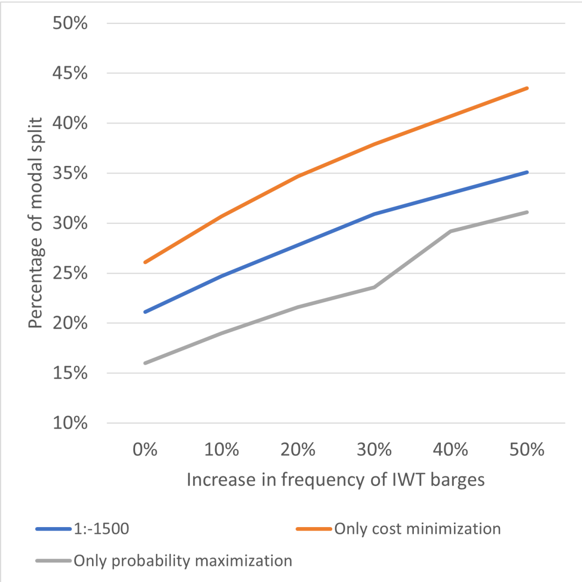
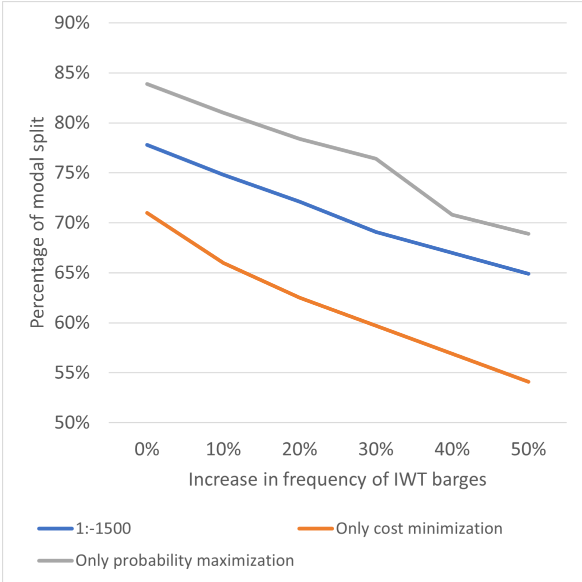


Figure 4.8: Illustration showing the increase in frequency while letting the capacity increase as well

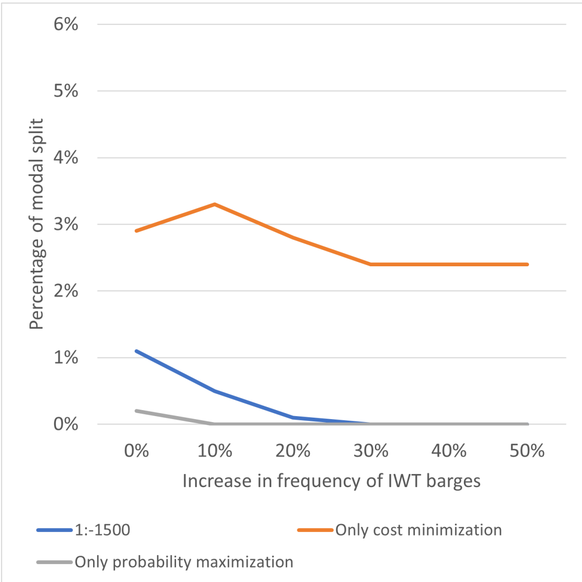
To demonstrate why the capacity and cost were reduced when increasing the capacity, the same experiment was done without this compensation as illustrated in Figure 4.8. In this case increasing the frequency of IWT services would be done by simply increasing the amount of barge movements per week with the same barge sizes and thus this also increases the overall capacity and cost. The results in Figure 4.9a show that, as expected, adding more barges significantly increases the IWT mode share. An increase in frequency of just 10% resulting in an IWT mode share increase of 3,6%.



(a) IWT



(b) Road transport



(c) Rail transport

Figure 4.9: Change in percentage of modal split for increasing the frequency of IWT services without compensating capacity and cost.

Looking at the data in Table 4.2, the results show that for some OD-pairs such as NL33-DE13 the increase in capacity for IWT allows more containers to be transported via IWT before an alternative mode has to be chosen due to maximum capacity. For other OD-pairs like NL33-DEA1 the increase can lead to a switch of preference, here seen at 30% increase where containers are transported by IWT instead of Road transport. These results indicate that increasing the frequency of IWT only has a positive effect on the modal share of IWT if it is implemented by increasing the amount of barge movements and thus increasing the IWT overall capacity simultaneously.

Table 4.2: Containers transported by each transport mode for increasing the frequency of IWT and overall capacity.

		Increase in IWT service frequency								
OD-pair		0%			10%			20%		
O	D	IWT	Rail	Road	IWT	Rail	Road	IWT	Rail	Road
NL33	DE13	348	300	507	696	300	159	1044	111	0
NL33	DEA1	0	0	1841	0	0	1841	0	0	1841

Table 4.2: Continued

Increase in IWT service frequency								
30%			40%			50%		
IWT	Rail	Road	IWT	Rail	Road	IWT	Rail	Road
1155	0	0	1155	0	0	1155	0	0
1841	0	0	1841	0	0	1841	0	0

4.3.4. Combined Policy

While increasing a single attribute such as capacity or frequency is not a very realistic scenario, increasing the frequency by adding additional barge movements and increasing the road cost are options that could be implemented as of today. A form of tax could be applied for using road transportation and this money could be even used to invest in IWT. Therefore a combined policy of reducing the cost of road transport and increasing the IWT frequency by increasing the number of barge movements, is tested. The results of four scenarios are shown in Figure 4.10. The frequency and road cost are increased by 10% and 20%, an increase of 10% for both already results in an IWT mode share increase of 4,4%, growing to 9,1% for a 20% increase in frequency and road cost.

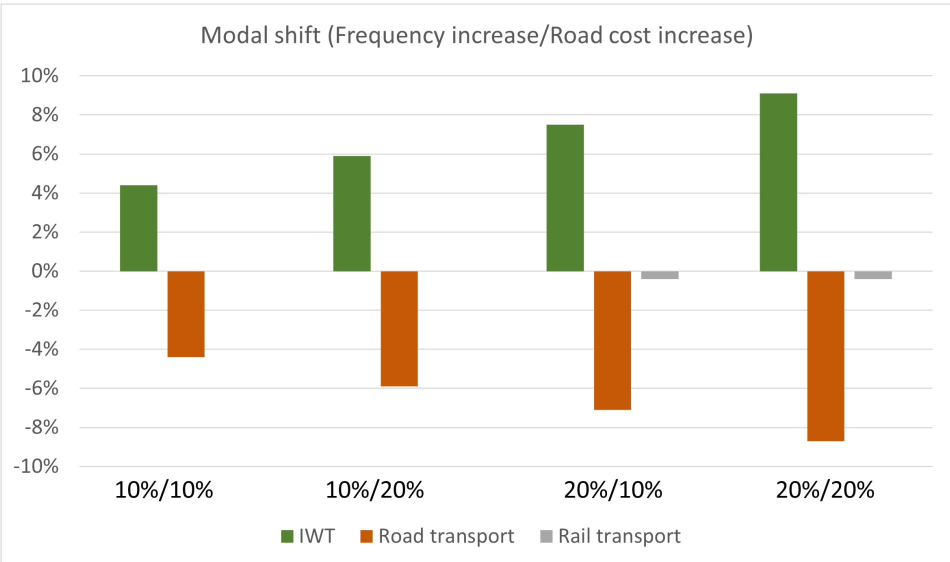


Figure 4.10: Modal shift for increasing the frequency and road costs by 10% and/or 20%

Looking closer at the data for each individual OD-pair, it is clear that these increases have more impacted on some OD-pairs then on others. Four OD-pairs stand out, each of which has an increase of more than 1000 containers transported by IWT. These are: transport in both directions between South Holland and North Brabant in the Netherlands, transport from South Holland in the Netherlands to Antwerp in Belgium and transport from Antwerp in Belgium to Düsseldorf Germany. When looking at the first scenario where road cost and frequency of IWT are increased by 10%, it would require 13 additional barge movements to increase the frequency of these OD-pairs. The result of increasing the frequency of just these four OD-pairs is that the mode share of IWT will increase by 2.1%.

4.4. Summary

In this chapter the case study is described and the results of the different experiments are presented. Three attributes were altered and the impact on the modal split is discussed. The first attribute was the cost of road transport, the results of which showed that an increase of 25% resulted in a 2,4% increase of the IWT mode share and a 4,7% decrease of the road transport mode share. The results also showed that increasing the road cost had no effect on the IWT mode share when only using the cost minimization objective as IWT already was the transport mode with the lowest cost. The capacity of IWT was the second attribute that was increased. An increase in IWT capacity showed a linear increase in the IWT mode share. However, this increase in capacity did not result in OD-pairs switching to IWT from another transport mode as neither objective function has capacity as input. The final attribute that was increased, was the frequency of IWT. First, only the frequency was increased with smaller barges and capacity and cost remained unchanged. This resulted in nearly no change in the modal split. When capacity and cost were not kept unchanged while increasing the frequency, which translates to the real life scenario of adding additional barges of similar sizes, there was a significant increase in the mode share of IWT. Finally some more realistic scenarios were tested with a combination of policies, where the cost of road transport and frequency of IWT were increased by 10% and/or 20%. The results showed that an increase of 10% for both attributes resulted in an mode share increase of 4,4% for IWT. Closer analysis showed that 4 OD-pairs had a significant higher impact on the mode shift. Only increasing the road cost and IWT frequency for these four OD-pairs already resulted in an IWT mode share increase of 2,1%. With these results the next chapter will conclude this thesis with future research directions0.1cm.

5

Conclusion and Future Research

This chapter concludes this thesis by answering the main research question and discussing the implications of it in section 5.1. In section 5.2 some recommendations for future research are given, both on the scientific side and the practical side.

5.1. Conclusion

The main research question of this study was: *How to develop an integrated mode choice and assignment model for evaluating the impact of transport mode attributes on the modal split in a logistic network?* To answer this question, five sub questions were asked which are all answered in the following paragraphs.

What are the most important transport mode attributes affecting mode choice for logistic networks?
How are mode choice and assignment modelled in other relevant studies?
Chapter 2 discusses current research on the effect of transport mode attributes and the way mode choice and assignment models are developed. Literature research shows that most research regarding the effect of transport mode attributes looked at the impact these have on the mode choice preference and not on the modal split. From these studies we learn that the most important attributes for choosing a transport mode are cost, time, reliability of transport time and transport frequency. The most used method for transport models is still the four-step model. While mode choice and assignment are often separate sub models it is also possible to combine them, to create a more realistic model.

How can the mode choice and assignment sub-models be enhanced, considering different preferences of stakeholders?
Firstly the existing model is adapted by removing the option where extra barges were created to meet the demand and by no longer allowing barges to be sent earlier then the frequency dictates. Next, based on literature research the transport model is made more realistic by combining the mode choice and assignment sub-models into one model. This is done by creating a multi objective optimization model that simultaneously minimises cost, the freight forwarders preference, and maximises the use of transport modes with highest probability of being chosen by shippers.

What is the impact of integrating mode choice and assignment compared to the sequential model?

Collected data showed the current modal split being 18%, 6% and 76% for IWT, rail transport and road transport [15]. The sequential model was over 20% off, mainly due to several functions distributing containers assigned to modes that had their maximum capacity reached. After removing these extra functions, the modal split of the benchmark model was within 3% of the collected data. As shown in Table 3.8 the lack of interaction between the mode choice and assignment steps caused more containers to be assigned to transport modes than the capacities allowed. The integrated mode choice and assignment model did not have this problem as the interaction between mode choice and assignment steps does not allow a mode to be chosen for a container, which already has reached its capacity of the amount of containers assigned to it. Thus the integrated model has no need for additional functions to distribute unserved demand.

How do transport mode attributes affect the modal split using the integrated model?
The three transport mode attributes tested in this thesis are the cost of road transport, capacity of IWT and the frequency of IWT. Results show that increasing the cost of road transport mainly increases the mode share of IWT for the probability maximization objective. It does not influence the cost minimization much as road transport is already the most expensive option in most cases. Increasing capacity of IWT does increase the mode share of IWT. However, it does not effect the objective functions, the increase is due to the extra available capacity for IWT before another mode must be chosen. Increasing the frequency while keeping capacity and cost unchanged has very little effect on the modal split. When capacity and cost are not kept the same while increasing frequency, a significant increase in the mode share of IWT can be seen. Finally some combined scenarios with combined strategies are tested, these results show that a 10% increase of road cost and frequency will result in an 4,4% increase of the mode share of IWT. Further investigation shows that increasing this for only 4 OD-pairs already increases the mode share of IWT by 2,1%.

As mentioned in the introduction, a modal shift from road transport to IWT would help reduce traffic congestion and CO2 emissions. The final results show that with just a 10% increase in frequency and road cost (via emission tax for example), already results in a 4,4% modal shift from road transport to IWT. Although a 4,4% shift might not sound like much, looking at the results from other innovations these results fit perfectly in the range of 5,5% to 6% for innovative vessels and 0,5% to 1% for modular mobile terminals [24]. In order to have a significant impact on the mode share of IWT, different attributes should be considered at the same time in a holistic way. This may translate to regulations on road costs in the form of taxes or subsidies for IWT. But also investments in the availability of the IWT services should be considered in parallel to that. Right analysis on these interactions between the impact of attributes is expected to guide future policy developments.

5.2. Recommendations for Further Research

As with all studies, while working on this thesis there were some limitations and some assumptions made. Therefore there are a couple of suggestions for future research. They are split in scientific recommendations regarding the model and data, and more general recommendations to further increase the choice for IWT over road transport.

Scientific recommendations

- The four OD-pairs mentioned that have the largest modal shift could be further researched. A more detailed study at NUTS-3 level could tell where specific barges should be added to cause the biggest modal shift.
- The collected data although detailed for IWT, didn't have the same detailed level for rail and road transport. As the focus was on IWT this data was good enough for this thesis. However, for future research a more detailed dataset for each transport mode could yield more realistic results.
- One of the assumptions made during this thesis was the constant availability of road transport. While this ensures that every container is always transported, this is not a realistic scenario. A more detailed road transport assignment in the model would thus create a more realistic output.
- The systematic utility function for IWT is based on the generalised cost and frequency for each OD-pair. However frequency and cost differ for each OD-pair also per Barge type. A different probability calculation that takes this into consideration would make the model more realistic. Other attributes could also be added to a new probability function such as environmental impact.

Further recommendations

- This thesis showed that increasing the cost of road transport causes a modal shift from road transport towards IWT. Further research could be done into how exactly the cost for road transport could be increased, with a tax system for example.
- Literature research showed that CO2 emissions and environmental impact are of very little importance to shippers. With climate change being a topic that is getter more and more important. Making shippers more aware of the large decrease in emissions caused by switching from road transport to IWT along with the financial benefit of lower emission taxes, could increase the probability of shippers using IWT.
- While adding additional barges to shipping routes shows to improve the use of IWT, it can cause issues at ports. Inland barges often have to wait due to limited or lack off, dedicated space and equipment. Increasing the accessibility of barges at ports could thus be a topic for future research.
- In order to increase capacity or frequency of IWT services, additional barge movements or new barges have to be introduced. Research should be done into new technologies, investments, etc. as well as the possibility of introducing new or more barges. As some waterways have restrictions to prevent operating more or bigger barges.

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A

Scientific paper

An Integrated Mode Choice and Assignment Model for Assessing Modal Split in Logistics Networks

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***Abstract*—This study proposes an integrated mode choice and assignment model that combines the final steps in the classical four-step transport modelling approach. Using multi-objective optimisation, the model minimises service costs while simultaneously maximising the probability of mode selection. Compared to traditional sequential models, the integrated model prevents over-assignment to modes exceeding capacity. The model was then used to asses three key transport mode attributes—cost, capacity, and frequency—to evaluate their effect on the modal split, with a focus on increasing Inland Waterway Transport (IWT). Results showed that increasing road costs and IWT service frequency (with associated capacity growth) had the most impact on shifting modal share towards IWT. These findings demonstrate the potential of this integrated model to better evaluate policy impacts and inform transport planning.**

I. Introduction

Containerised inland transport plays a critical role in the logistics chain, often accounting for up to 80% of total transport cost [1]. Despite the sustainability benefits and cost advantages of Inland Waterway Transport (IWT), the majority of containerised inland transport continues to rely on road haulage. This results in growing challenges, such as increased congestion on road networks and heightened carbon emissions. To study the modal split in these transport networks, several transport models are developed. Traditional transport models apply the four-step method—trip generation, trip distribution, mode choice, and assignment—often in a sequential manner. However, separating mode choice and assignment limits realism due to lack of interaction between demand and capacity constraints.

This paper introduces a novel integrated model that simultaneously incorporates both steps, ensuring realistic and capacity-aware mode allocation. We evaluate this model by comparing its output against a sequential benchmark model and conduct a scenario analysis on three transport attributes—cost, capacity, and frequency. The study is carried out in collaboration with project NOVIMOVE, which aims to enhance the logistical performance and modal share of IWT along the Rhine-Alpine corridor.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on the effects of transport mode attributes on modal split and freight mode choice and assignment modelling. Section 3 details the mathematical structure of the model, including. Section 4 presents and discusses the results from multiple policy scenarios. Finally, Section 5 provides conclusions and suggests directions for future research.

II. Literature

A. The Effects of Mode Attributes

Several studies can be found mentioning the effect of certain transport mode attributes in hinterland container transport. However, the vast majority of these studies looked at the impact these attributes have on the choice preferences of decision makers (e.g., freight forwarders) in the transport chain. Feo et al. [2] conclude that transport cost, transport time and reliability regarding the delivery times are the most important attributes when choosing a transport mode. Blauwens et al. [3] and Feo et al. [4] indicate that frequency is of key importance as well. The main attributes that would cause a modal shift towards IWT are higher service frequency and higher reliability according to Meers et al [5].

B. Mode Choice and Assignment

Mode choice and assignment are the two final steps in the widely used four step model. Traditional approaches typically use a Multinomial Logit (MNL) model for mode choice and separate assignment based on cost minimisation. The MNL model is a form of discrete choice modelling and based on the random utility maximisation principle firstly proposed by McFadden [6]. Variants of the MNL that are often used include nested logit [7] and mixed multinomial logit [8]. More recently developed computing methods are artificial neural networks and machine learning. Lee et al. and Zhao et al. showed that although machine learning and artificial neural network models are more accurate, they are far more complex and MNL is more behavioral sound.

The assignment step uses the output of the mode choice and assign the demand to the specific service of the chosen transport mode. This step can be done sequentially or simultaneously with the mode choice. An overview by De Jong et al. [9] states that advantages of sequential mode choice and assignment are that the model can be disaggregate and allows for interaction of freight trips with passenger trips. Disadvantages however are the absence of interaction between demand and assignment, resulting in less realistic results due to only iterative operation.

Recent advances focus on integrated or synchromodal transport planning [10] [11]. Literature highlights the importance of real-time flexibility and behavioural modelling, though few integrate mode choice and assignment simultaneously. This research addresses that gap.

III. Methodology

The new integrated mode choice and assignment model is a multi objective model where the first objective minimises transport costs. The second objective maximises the utility-based probability of choosing a specific transport mode. The utility function of the mode choice sub-model by Shobayo et al. [12] is used for calculating the probabilities for the mode choice. These are calculated using the generalised costs for each mode, the frequency for IWT and rail transport and the average population density of origin and destination for road transport. The sub-models by Shobayo et al. [12] are sequential mode choice and assignment sub-models and are used to compare the new integrated model against. The sets and parameters are summarized in table I. It is assumed that there is always road transport available therefore the capacity of road transport is infinite.

Three decision variables are used; x_{ij} is a binary variable which denotes if there are containers assigned to service j between OD-pair i. Next, y_{ij} is an integer variable denoting the amount of containers from OD-pair i that are assigned to service j. Finally z_{im} is an integer variable denoting the amount of containers from OD-pair i transported with mode m. The complete mathematical model is then formulated as follows.

$$min \sum_{i \in P} \sum_{j \in S} c_j y_{ij} \tag{1}$$

$$max \sum_{i \in P} \sum_{m \in M} p_{im} z_{im} \tag{2}$$

TABLE I: Sets and parameters

Sets	
P	Set of OD-pairs indicated by i
S	Set of services indicated by j
M	Set of transport modes indicated by m
Parameters	
q_i	Amount of containers to be transported between OD-pair i
c_j	Cost of transporting a container with service j
p_{im}	probability of containers transported with transport mode m between OD-pair i
u_j	Capacity of service j
o_i	Origin of OD-pair i
o_j	Origin of service j
d_i	Destination of OD-pair i
d_j	Destination of service j
$bigM$	A large enough positive number
δ_{jm}	Indicates the transport mode m of service j

subject to:

$$\sum_{j \in S} x_{ij} \geq 1 \qquad \forall i \in P \tag{3}$$

$$\sum_{j \in S} y_{ij} = q_i \qquad \forall i \in P \tag{4}$$

$$\sum_{i \in} y_{ij} \leq u_j \qquad \forall j \in S \tag{5}$$

$$x_{ij} o_i = x_{ij} o_j \qquad \forall i \in P, j \in S \tag{6}$$

$$x_{ij} d_i = x_{ij} d_j \qquad \forall i \in P, j \in S \tag{7}$$

$$y_{ij} \leq bigM x_{ij} \qquad \forall i \in P, j \in S \tag{8}$$

$$\sum_{j \in S} y_{ij} \delta_{jm} = z_{im} \qquad \forall i \in P, m \in M \tag{9}$$

$$\begin{aligned} x_{ij} \in \{0,1\} \qquad & \forall i \in P, j \in S \\ y_{ij} \in \mathbb{Z} \qquad & \forall i \in P, j \in S \\ z_{im} \in \mathbb{Z} \qquad & \forall i \in P, m \in M \end{aligned} \tag{10}$$

The first objective (1) minimizes the cost of the services being used and the second objective (2) tries to maximize the the use of the transport mode with the highest probability. To optimise these objectives the following constraints are used: Constraint (3) states that containers from each OD-pair must be assigned to at least one service. Constraint (4) makes sure that all the containers for each OD-pair are assigned to a service. Constraint (5) denotes that the amount of containers assigned to a service can not exceed the capacity of the corresponding service. Constraints (6) and (7) determine that the origin and destination of the OD-pair should match those of the service. Constraint (8) then states that containers should only be assigned if a service is being used. Constraint (9) defines the amount of containers assigned to each transport mode for each OD-pair. Finally constraint (10) describes the decision variables.

The problem is solved using Gurobi optimization software [13] which uses the weighted sum method to combine both objective functions resulting in the combined objective function (11). As the second objective needs to be maximized instead of minimized, W_2 needs to be negative.

$$Min \quad W_1 \sum_{i \in P} \sum_{j \in S} c_j y_{ij} + W_2 \sum_{i \in P} \sum_{m \in T} p_{im} z_{im} \qquad (11)$$

After the model was verified, it was compared against the sequential mode choice and assignment sub-models using NOVIMOVE's dataset. Entering the same dataset in both models clearly showed the benefits of the integrated approach. As can be seen in Table II the sequential sub-models allow more containers to be assigned to a mode then the capacity of that mode allows, which leads to unserved demand. Due to interaction between the assignment and mode choice steps, this can't happen using the integrated model.

TABLE II: Amount of containers assigned to each transport mode using sequential and integrated models

Location		Capacity		Containers Assigned		
O	D	IWT	Rail	IWT	Rail	Road
Sequential mode choice and assignment sub-models						
NL33	DEA1	9806	4680	**19348**	**5182**	12143
NL33	CH03	1316	1140	**1417**	100	86
Integrated mode choice and assignment model						
NL33	DEA1	9806	4680	9806	0	26867
NL33	CH03	1316	1140	1316	287	0

IV. Case Study

A case study was done with the dataset from project NOVIMOVE, consisting of locations along the Rhine-alpine corridor with either origin or destination at the port of Rotterdam or port of Antwerp. Based on literature three of the most important transport mode attributes are altered to try and increase the mode share of IWT. This resulted in the following policy scenarios that are tested.

1) **Road Cost Increase:** The cost of road transport is increased to make road transportation less attractive. This could be implemented by increasing taxes on road transport of containers.
2) **IWT Capacity Increase:** The capacity of IWT services is increased to allow more containers to be shipped with each service. Implementation could either be increasing the barge size or using multiple barges departing at the same time as if a single IWT service.
3) **IWT Frequency Increase:** The frequency of individual IWT services is increased. This is done two times, once while keeping the total capacity constant, to only see the effect of only the frequency itself. Secondly by allowing the capacity to increase with the increase in frequency. Increasing frequency but keeping capacity constant can be implemented, although unlikely in reality, by replacing a large barge by multiple smaller barges that combined equal the capacity of the large barge. Increasing frequency without keeping capacity constant can simply be done by increasing the amount of barge movements.
4) **Combined Policy:** A combined policy based on the results of the first experiments is tested that would be more realistic to implement.

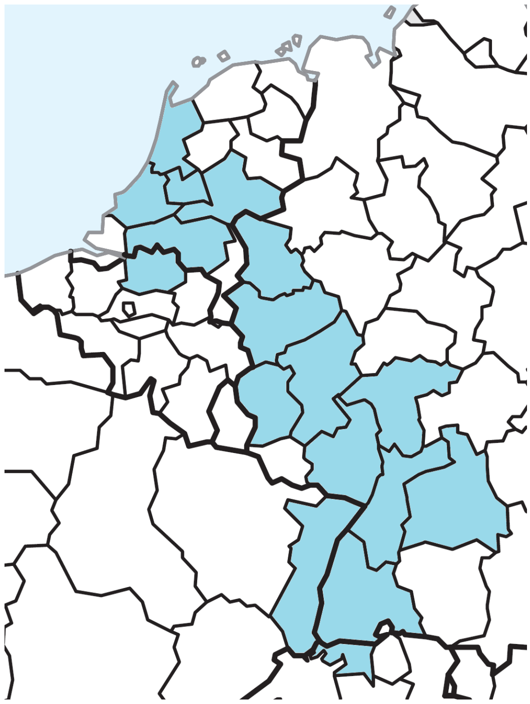


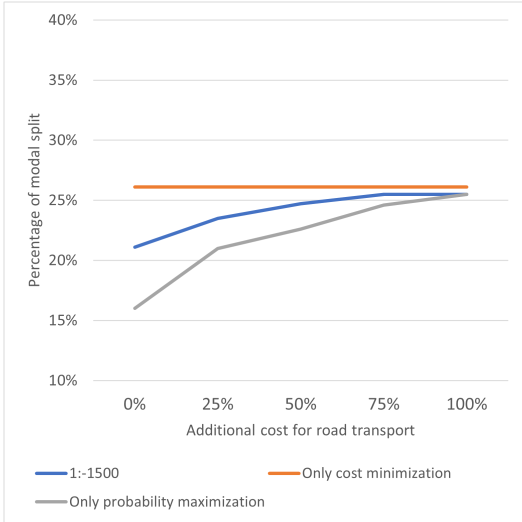
Fig. 1: Locations at NUTS-2 level used for the case study

In order to determine the weights for the combined objective function 11 the modal split was calculated with various weights and compared against the modal split of the sequential benchmark model. The weights $W_1 = 1$, $W_2 = -1500$ were chosen for testing the policy scenarios along with $W_1 = 1$, $W_2 = 0$ and $W_1 = 0$, $W_2 = -1$ to determine the impact on the cost minimisation and probability maximisation objectives individually.

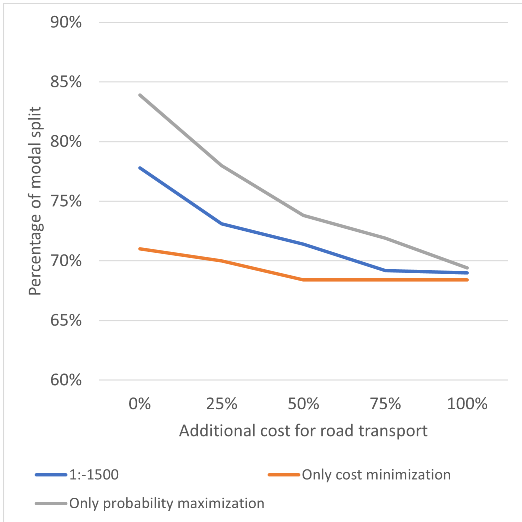
V. Results

The graphs in this section show the impact of the tested scenarios on the modal share of IWT and Road transport. The effect on rail transport is omitted as it is a very small percentage and less relevant. The full results are available in [14].

1) **Road Cost Increase** The results of increasing the cost of road transport can be seen in Figure 2 Raising costs by 25% led to up to 2.4% increase in IWT share. When only using the cost minimisation objective, the IWT mode share does not change. This is due to the fact that IWT is already the mode with the lowest cost for nearly all OD-pairs. The shape of the graphs shows that using the combined objective, the mode share converges to that of using only cost minimisation. At that point the cost of road transport is so high that IWT is nearly always chosen over road transport and now the capacity of IWT is preventing the IWT mode share to increase further.
2) **IWT Capacity Increase** Figure 3 clearly shows an increase in IWT mode share. However a closer look at the results showed that the increase in capacity does not result in OD-pairs choosing IWT over another transport mode. The mode share increases because the OD-pairs where IWT is the preferred mode of transport, can transport more containers before the capacity is met and another transport mode must be chosen to transport the remaining containers. This can be explained as neither objective function is influenced by IWT service capacity.
3) **IWT Frequency Increase** Without increasing the capacity, increasing the frequency has hardly any effect on the modal split. However by allowing the capacity to increase as well, there is a significant increase in the IWT mode share, shown in Figure 4. A frequency increase of just 10% increases the IWT mode share by 3.6%.
4) **Combined Policy** Increasing just a single attribute such as only capacity or frequency of IWT services is not a realistic scenario. However increasing IWT frequency through additional barge movements and increasing the cost of road transport could more easily be implemented. A combined policy is tested where road transport costs and IWT frequency are increased by 10% and 20%. The results shown in Figure 5 show that just a 10% increase in road cost and IWT frequency resulted in a 4.4% IWT share increase.

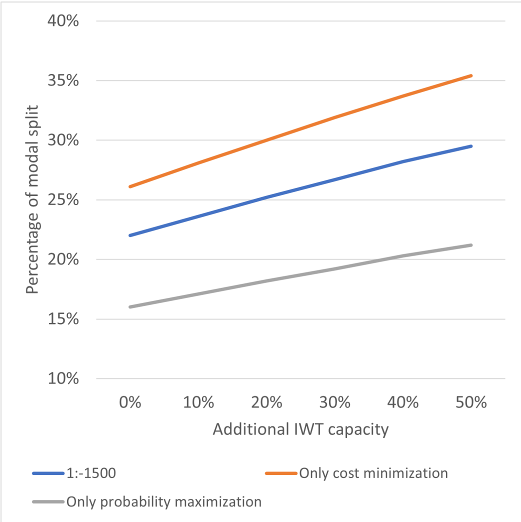


IWT

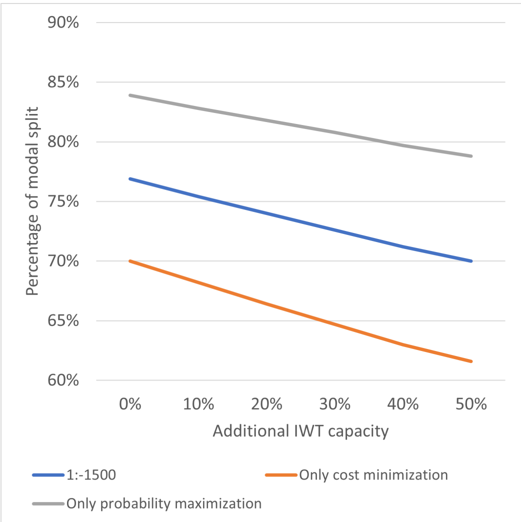


Road transport

Fig. 2: Change in percentage of modal split for increasing the cost of road transport



IWT



Road transport

Fig. 3: Change in percentage of modal split for increasing the capacity of IWT services

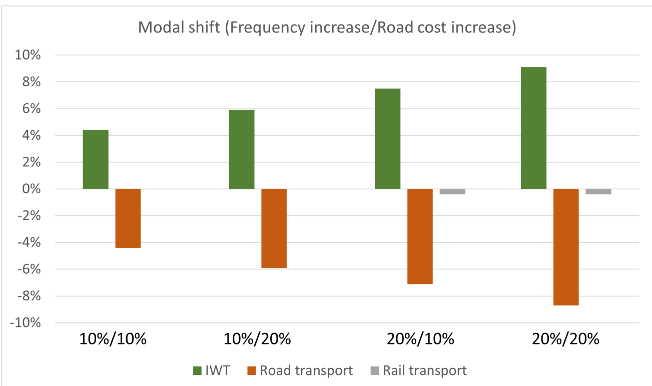
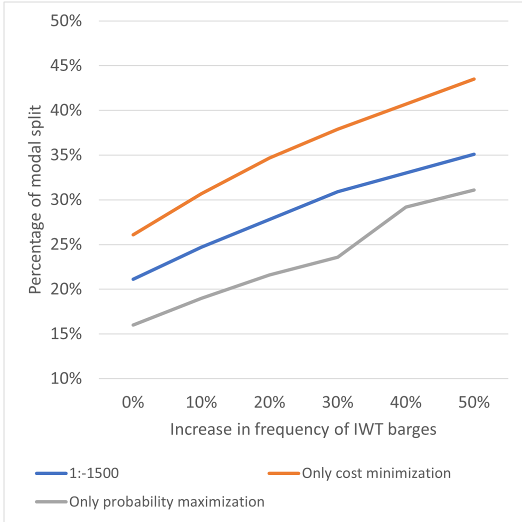
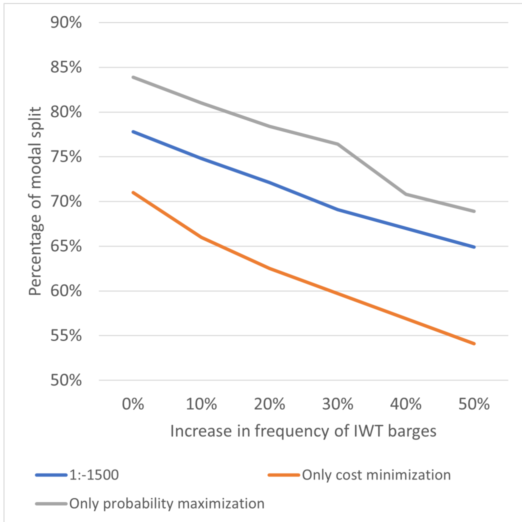


Fig. 5: Modal shift for increasing the frequency of IWT service and cost of road transport by 10% and 20%



IWT



Road transport

Fig. 4: Change in percentage of modal split for increasing the frequency of IWT services while keeping the same barge size, i.e. increasing the total capacity

VI. Conclusions and Future Work

This paper presents an integrated mode choice and assignment model for assessing modal split in logistics networks. By simultaneously executing the mode choice and assignment steps as opposed to sequentially, the model showed that no demand can be left unserved. Several transport mode attributes are tested as well to assess their effect on the modal split. Results show that in order to have a significant impact on the mode share of IWT, different attributes should be considered at the same time in a holistic way. This model could be used by policy makers to provide an indication of how certain policies will affect the modal split in a logistics network There are improvements that can be made to the model. The assumption that road transport capacity is infinite is not very realistic, therefore a more accurate road transport assignment will allow for more realistic results. The probability calculation can be improved as well by using service specific costs and frequency instead of the generalised costs and frequency. Other attributes such as environmental impact could be introduced as well.

Acknowledgment

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B

OD Dataset

Table B.1: Set of OD-pairs used in this research

Location NUTS2	Location Port
BE21	ANR
CH03	BSL
DEA1	DMG
	DUI
	DUS
	EMM
	ESU
	KRE
	NSS
DEA2	BON
	CGN
	LEV
DE11	STR
DE12	MHG
DE13	KEH
	WLR
DE71	GHM
	GIG
DEB1	AND
	KOB
DEB2	TRI
DE3	GER
	LUH
	MAI
	WOE
	WOR
FRF1	NEF
	SXB
NL22	NIJ
	TIE
NL31	UTC
NL32	AMS
	BEV
	VEL
	ZAA
NL33	ABL
	GOR
	RTM
NL41	BZM
	HTB
	MOE

C

Validation outputs Research model vs NOVIMOVE model

Table C.1: Amount of containers assigned to each mode for both the NOVIMOVE model and the copy made for this research given a uniform input.

OD-pair		NOVIMOVE model			Research model		
Origin	Destination	IWT	Rail	Road	IWT	Rail	Road
NL33	CH03	89	7	4	89	7	4
NL33	DEA1	53	14	33	53	14	33
NL33	DEA2	41	8	51	41	8	51
NL33	DE12	70	8	22	70	8	22
NL33	DE13	82	5	13	82	5	13
NL33	DE71	74	7	19	74	7	19
NL33	DEB1	52	6	42	52	6	42
NL33	DEB2	0	18	82	0	18	82
NL33	DEB3	57	8	35	57	8	35
NL33	FRF1	86	5	9	86	5	9
NL33	NL22	33	3	64	33	3	64
NL33	NL31	33	3	64	33	3	64
NL33	NL32	22	49	29	22	49	29
NL33	NL41	57	4	39	57	4	39
NL33	BE21	66	6	28	66	6	28
NL33	BE24	0	12	88	0	12	88
NL33	BE33	0	13	87	0	13	87

BE21	CH03	77	12	11	77	12	11
BE21	DEA1	35	6	59	35	6	59
BE21	DEA2	23	5	72	23	5	72
BE21	DE11	58	5	37	58	5	37
BE21	DE12	50	6	44	50	6	44
BE21	DE13	63	8	29	63	8	29
BE21	DE71	54	6	40	54	6	40
BE21	DEB1	30	5	65	30	5	65
BE21	DEB2	42	5	53	42	5	53
BE21	DEB3	36	5	59	36	5	59
BE21	FRF1	71	7	22	71	7	22
BE21	NL31	30	3	67	30	3	67
BE21	NL32	39	2	59	39	2	59
BE21	NL33	66	7	27	66	7	27
BE21	NL41	30	6	64	30	6	64
BE21	BE10	0	71	29	0	71	29
BE21	BE24	0	9	91	0	9	91
CH03	NL33	97	3	0	97	3	0
CH03	BE21	92	6	2	92	6	2
DEA1	NL33	46	15	39	46	15	39
DEA1	BE21	32	6	62	32	6	62
DEA2	NL33	35	7	58	35	7	58
DEA2	BE21	20	5	75	20	5	75
DE11	BE21	80	4	16	80	4	16
DE12	NL33	56	8	36	56	8	36
DE12	BE21	39	6	55	39	6	55
DE13	NL33	69	6	25	69	6	25
DE13	BE21	50	7	43	50	7	43
DE71	NL33	63	7	30	63	7	30
DE71	BE21	45	6	49	45	6	49
DEB1	NL33	41	6	53	41	6	53

DEB1	BE21	24	5	71	24	5	71
DEB2	NL33	0	22	78	0	22	78
DEB2	BE21	61	5	34	61	5	34
DEB3	NL33	45	8	47	45	8	47
DEB3	BE21	28	5	67	28	5	67
FRF1	NL33	95	3	2	95	3	2
FRF1	BE21	90	4	6	90	4	6
NL22	NL33	33	3	64	33	3	64
NL31	NL33	33	2	65	33	2	65
NL31	BE21	30	3	67	30	3	67
NL32	NL33	22	49	29	22	49	29
NL32	BE21	40	2	58	40	2	58
NL41	NL33	56	4	40	56	4	40
NL41	BE21	31	6	63	31	6	63
BE10	BE21	0	71	29	0	71	29
BE24	NL33	0	11	89	0	11	89
BE24	BE21	0	9	91	0	9	91
BE33	NL33	0	11	89	0	11	89

Table C.2: Container assignment to barges for inland waterway transport by the NOVIMOVE model and the copy made for this research

OD-NUTS2		OD-Ports			NOVIMOVE model		Research model	
Origin	Destination	Origin	Destination	Day	Barge	Containers	Barge	Containers
NL33	DEA1	RTM	DUI	1	M8	53	M8	53
BE21	NL33	ANR	RTM	1	C3b	66	C3b	66
DEA1	NL33	DUI	RTM	1	M8	46	M8	46
NL41	NL33	HTB	RTM	1	M8	56	M8	56
NL33	NL41	RTM	HTB	2	M8	57	M8	57
DEA1	BE21	DUI	ANR	2	M11	64	M11	64
DEB2	BE21	TRI	ANR	2	M6	90	M6	90
NL33	BE21	RTM	ANR	2	C3l	132	C3l	132
BE21	DEA1	ANR	DUI	2	M11	70	M11	70
NL33	DEA1	RTM	DUI	2	M8	53	M8	53
NL33	NL22	RTM	TIE	2	M8	66	M8	66
BE21	NL33	ANR	RTM	2	M9	66	M9	66
DEA1	NL33	DUI	RTM	2	M8	46	M8	46
NL22	NL33	TIE	RTM	2	M8	66	M8	66
NL31	NL33	UTC	RTM	2	M8	66	M8	66
NL41	NL33	BZM	RTM	2	M7	56	M7	56
NL33	NL41	RTM	HTB	2	M8	57	M8	57
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
FRF1	BE21	NEF	ANR	6	C3l	62	C3l	270
FRF1	BE21	SXB	ANR	6	M8	208	-	-
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
DEB1	NL33	KOB	RTM	6	M9	144	M9	272
DEB1	NL33	KOB	RTM	6	M9	143	-	-
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮