Economic Models for Inland Navigation in the Context of Climate Change

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Economic Models for Inland Navigation in the Context of Climate Change

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What has a beginning, has an end.
What has a beginning, has a reason.
Knowing all reason was a promise
that was given to mankind at the beginning.
In search for wisdom they would end.

- E. D.

PREFACE

(page 1)

preface

(page 2)

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION[1]

1.1 Context

Climate change may be defined as a structural change in weather patterns, in terms of precipitation, wind and temperature. It is also a topic that currently arises frequently in the daily news. While there is still much uncertainty, the scientific consensus is that climate will change as a result of human activity and will have an influence on many aspects of life on earth in the coming decades. In the key *Climate Change 2007*-report of the Intergovernmental Panel on Climate Change (IPCC), some of the most important conclusions are that the average global temperature has increased by 0.76 °C in the past century, and will most probably increase by another 1.1 to 6.4 °C in this century, depending on which measures are taken to cope with climate change. In addition, sea level has increased in the 20th century by 17 cm, and is expected to increase by another 18 to 59 cm over the course of the 21st century. This increase is accelerating as a result of the melting of icecaps on Greenland and Antarctica. The warming of the earth is mainly caused by the emission of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4), the levels of which have increased significantly due to human activities since the start of the Industrial Revolution (ca. 1750).

Climate change is expected to make certain aspects of life on earth quite problematic, although there are counterexamples such as tourism[2]. Floods, droughts, hurricanes and bad harvests may be the kind of natural disasters expected to be associated with climate change. In an economic sense, production in the new environment after climate change may be more costly, partly due to the costs of adaptation. Increased variation and less predictability of the weather may also have an increasing effect on costs.

Markets that are frequently mentioned in the context of climate change include, for example, agriculture, tourism and transport. Inland navigation, however, is a topic that appears less in the headlines. For example, not many people are aware of the true importance

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[1] A summary of the results in this dissertation are published in Demirel et al., (2010), Climate change and inland navigation between the Netherlands and Germany: An economic analysis, Chapter 2 in the book: *The Social and Behavioural Aspects of Climate Change: Linking Vulnerability, Adaptation and Mitigation*, edited by Pim Martens and Chiung Chang, Greenleaf Publishing.

[2] For a review on the social and behavioural aspects of climate change, see Martens and Chang (2010).

of inland navigation for countries along the Rhine river in North-Western Europe. So it is likely that few people give consideration to the possible impacts of climate change for this mode of transport. Interestingly, neither is there much scientific work on the transport economic aspects of inland navigation either (see Section 1.2). This also holds for the effect of climate change on inland navigation (see Section 1.3).

While mitigation of the effects of climate change to prevent a worsening of the situation, adaptation to climate change seems inevitable for the actors affected. Governments, private sectors and consumers will all have to take sound measures to adapt to the conditions after climate change. For the inland navigation market this would include a considerable range of adaptation strategies such as: barge-size/design adjustment, fleet-composition adjustment, infrastructure adjustment, adjustments in contract-design, modal-shift; and adjustment in stock-keeping behaviour and relocation by customers.

The remainder of this introduction proceeds as follows. In Section 1.2, we describe the importance of inland navigation as a mode of transport in North-Western Europe. In Section 1.3 we examine the impact of climate change on inland navigation in Western Europe. In Section 1.4, we briefly discuss the imbalance theme in freight transport. In the concluding Section 1.5, we present the motivation, the research questions addressed and the outline of the remaining chapters of this dissertation.

1.2 Inland navigation

1.2.1 Importance

Inland navigation is a mode of transport that has certain unique qualities over other modes such as rail and road transport. It has a cost advantage, it is more reliable, and can transport large volumes. However, there are also disadvantages, such as no door-to-door-receipt-and-delivery possibility and lower speed.

The importance of inland navigation as a transport mode for countries in North-Western Europe can best be understood from the figures on modal split. Table 1.1 shows for example that *within* the Netherlands, for both domestic and international transport, more than one-third of all tonne kilometres are transported by inland navigation. For Belgium this is more than one-seventh.

Table 1.1: Modal split in tonne-kilometres for Western European countries (in percentages) in 2008

Country	Inland Navigation	Road	Rail
The Netherlands	34.7	59.9	5.4
Belgium	15.8	69.1	15.1
Luxemburg	3.3	94.2	2.5
Germany	12.3	65.5	22.2
France	3.5	80.6	15.9

Source: Eurostat, 2010.

To get an idea of the volume of transport *between* countries, we present the figures for transport between the Netherlands and Germany. In 2006, 127 million tonnes were transported from the Netherlands to Germany by road, rail, and inland navigation. From Germany to the Netherlands this was 73 million tonnes. Of these volumes, transport by inland navigation accounted for 58 per cent (78.0 million tonnes) of all transport, measured in tonnes, from the Netherlands to Germany. From Germany to the Netherlands, this was 41 per cent (32.3 million tonnes) (CBS, 2010; TLN, 2007). The reason that there is such an imbalance in the volume of tonnes transported in both directions is that the Port of Rotterdam is the main port of entry for bulk materials such as coal, iron ore, and agricultural products moving into its hinterland. The flow of primary products of this type in the opposite direction is considerably smaller.

Transport by inland navigation in North-Western Europe mainly occurs along the Rhine (see Figure 1.1 for a map of the river Rhine and the Rhine area). In 2006, transport along the Rhine accounted for 63 per cent of total volume transported by inland navigation in Europe (CCNR, European Commission, 2007).

Figure 1.1: Map of the river Rhine in Western Europe.

The north-south route between France, Belgium and the Netherlands carried about 15 per cent of the volume and the east-west route in North Germany, linking Eastern Europe and the German North Sea ports to the industrial Ruhr area, about 4 per cent. Finally, the Main-Danube route, from the south of Germany to the Black Sea carried about 10 per cent (CCNR and European Commission, 2007). The Rhine is so important because it connects the seaports of Rotterdam, Amsterdam and Antwerp with the main industrial areas in Germany. In 2006, about 320 million tonnes were transported on the Rhine corridor (CCNR and European Commission, 2007).

1.2.2 Literature overview

Not only within the climate change literature but also within the transport literature, transport by inland navigation is a topic on which less is published than other modes. The main reason is probably that inland navigation only takes place on a large scale in certain geographical areas in the world. The most important are parts of Europe (the Rhine and Danube Rivers and their tributaries), the US (the Great Lakes area and the Mississippi River), and China (the

Yangtze and the Pearl River). The literature that relates inland navigation to climate change is discussed in Section 1.3.

A good start to the literature overview on inland waterways is provided by Dupuit (1844). Transport along canals was once the most important mode of transport in newly industrializing countries: a well-known example of this is the period of the Canal Mania in Britain between 1790 and 1820 (Burton and Taylor, 1993). Dupuit was a French engineer who was responsible for benefit-cost analyses for public works such as canals and bridges. The benefit-cost analyses for these projects posed important intellectual challenges. As a consequence, he was the first to introduce economic concepts like marginal utility and consumer surplus (see Ekelund and Hébert, 1976). Another remarkable study is that of Fogel (1964) on the history of economic growth of the United States in the 19th century. While railroads are often claimed to be one of the main contributors to the economic development of the US during this period, Fogel claims that if the investments in railroads had been made in the inland waterway network, a similar growth effect would have resulted.

Other scientific work on inland waterways, which dates from the beginning of the 20th century, was descriptive and US oriented. Later in the 20th century, topics covered include: infrastructure (Patton, 1956; Johnson, 1911; Chisholm, 1907); competition with railroads (Kelso, 1941; Fisher, 1915; Johnson 1909); and policy and regulation issues (Johnson, 1911; Wilcox, 1931). Between 1955 and 1970, we could hardly find any scientific studies on transport by inland navigation.

From 1970, studies become more analytical. For example, Case and Lave (1977), Bongaerts and van Schaik (1984), Miljkovic et al. (2000) and Yu et al. (2006) use econometric techniques to investigate the determinants of transport costs. Polak and Koshal (1980) study the effect of progress in technology on the costs of inland waterway transport; Hong and Plott (1982) examine the effect of regulation on freight prices, volume and efficiency; and Babcock and Lu (2000) make short-term forecasts for the number of tons of grain that is transported on the Mississippi River. Inland navigation appears in the transport network approach that is followed by Beuthe and Jourquin. In Beuthe and Jourquin (2006), they review the NODUS model, where transport by inland navigation is one of the modes in a multi-modal transport network model.

With the growth of container transport, more literature has been written on this part of the inland navigation market. Examples are Konings (2003; 2006; 2007; 2009), Notteboom (2007a; b), and Notteboom and Konings (2004). The next section discusses the vulnerability of inland navigation to climate change in the geographical area of North-Western Europe. In that section we also give a brief review of the existing literature (for a more detailed review, see Jonkeren and Rietveld, 2009).

1.3 Climate change and inland navigation

Predictions about the future state of the climate are often made with the use of climate change scenarios, where probabilities about the likelihood of scenarios may or may not be reported. In its Special Report on Emission Scenarios' of SRES, the IPCC reports scenarios which are mainly based on assumptions about future development of demography, the world economy, use of ‘clean’ technology, and degree of globalization. For the Netherlands, climate change scenarios have been developed by the KNMI (The Royal Netherlands Meteorological Institute). In 2006, KNMI produced scenarios for the year 2050, and these are summarized in Table 1.2.

Table 1.2: KNMI scenarios for 2050 relative to 1990

Scenario	Global temperature increase in 2050	Change of atmospheric circulation
M	+1°C	Weak
M+	+1°C	Strong
W	+2°C	Weak
W+	+2°C	Strong

Source: KNMI (2006).

Possible future water levels on the Rhine can be derived on the basis of these climate scenarios. In Figure 1.2 we present the predicted water discharge (in cubic metres per second) within one year in 2050 at the Dutch town of Lobith, situated on the Rhine close to the border between the Netherlands and Germany. The four solid lines correspond to the four presented scenarios above, and the dotted line corresponds to the current situation. It can be seen that especially the M+ and W+ scenarios predict low water levels between May and December. All scenarios predict higher water levels between January and May.

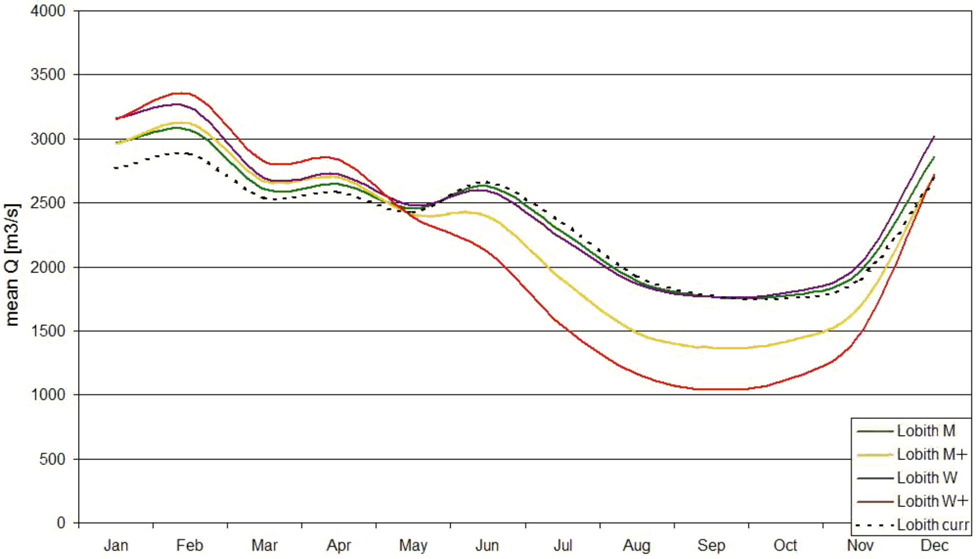

Figure 1.2: Predicted water discharges on the Rhine at Lobith in 2050 for different scenarios
Source: Te Linde, 2007.

Traditionally, transport has entered the climate change discussion as one of the main generators of climate change due to the emission of greenhouse gases. Therefore, most of the discussion has been about mitigation strategies to reduce the emission of greenhouse gases. The implications of climate change for the transport sector has received less attention, but is a topic that is being increasingly researched. For example, for a recent review on the effects of climate change on transport, see Koetse and Rietveld (2009).

This dissertation focuses on the effects of climate change on freight transport by inland navigation in particular. Climate change may affect transport by inland navigation positively. This is seen, for example, in the Arctic area where water transport is becoming possible as a result of shorter ice periods (Johanessen et al., 2004; Somanathan et al., 2007).

Other areas in the world, for example, the North-West European area, which is the focus of this study, are expected to experience the harmful side of climate change. When climate change means lower water levels, the carriers’ capacities are reduced because a minimum distance between the barge and the riverbed must be maintained.

For North-America, the literature on the effect of climate change on inland navigation can be summarized as follows. Marchand et al. (1988) estimate the increase in average annual shipping costs due to climate change in the Great Lakes – St. Lawrence area in Canada. They find an increase of 5 per cent between 1979 and 2035. However, this study may be considered outdated as other climate scenarios have since been developed. For the same region, Millerd (2005) estimates an average increase of 8 per cent of shipping costs between 2001 and 2030. For the Middle Mississippi River, Olsen et al. (2005) estimate losses in shipper savings due to low water levels, where shipper savings is defined as the difference between the costs of shipping by inland navigation and the (second) cheapest alternative. They estimate an annual loss of $77 million per year on average between 1933 and 2002. For the year 2100 they predict losses of $118, $10 and $24 million per year depending on the climate scenario used.

In Europe, as was stated in the previous section, inland navigation in North-Western Europe mainly takes place along the Rhine. Some properties of the Rhine which have, historically, made it attractive for transport, such as stability of water levels and sufficient depth, now seem to be vulnerable to climate change. For this river, climate change is expected to manifest itself in more extreme low water-level periods in summer and more extreme high water-level periods in winter (Middelkoop et al., 2000, 2001; Te Linde, 2007). Haasnoot et al. (2009), and Offermans et al. (2009) propose a society management based method to evaluate adaptations in the water system to climate change. The IAMM model they develop presents possible adaptation paths, such as changes in barge size and dredging intensity, over the course of a century. However, they do not report economic welfare figures for, or optimality of, the strategies against low water, as we do in Chapter 2. For 2050, by means of interviews and simulation, Nomden and Van Deursen (1999) estimate an increase of 10 per cent in the unit cost of transport by inland navigation for the Rhine area. In the summer of 2003 water levels dropped so much that navigation was only possible at low freight capacities for a long period of time (almost 6 months), and the transport cost per tonne increased accordingly. For that year, Jonkeren et al. (2007) estimate a welfare loss of €91 million for the Kaub[3] spot market. Royal Haskoning (2007) arrive at a similar welfare loss,re-estimating the model in RWS-RIZA et al. (2005).

High water levels increase flood risk and cause difficulties with bridges and motorways, especially for container transport. In cases of extreme high water levels, navigation may be halted completely. This is, however, extremely rare (see RWS-Infocentrum Binnenwateren, 2009).

Other negative aspects of climate change may be increases in the mean and possibly in the standard deviation of the arrival times of barges (this may be summarized under the heading reliability). High water levels result in an increase in the number of blockades, and

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[3] Kaub, is a place along the Rhine that is the most important bottleneck in terms of capacity due to low water.

low water levels decrease capacity and result (under inelastic demand) in more traffic. Both have a negative impact on the mean arrival time. For example, for the year 2020, Quispel and Visser (2007) predict that waiting times at certain locks in the Rhine area will increase by 23 per cent due to climate change. However, Beuthe and Bouffioux (2008) report that reliability may not be as important for customers of inland navigation as compared with, for example, road transport.

As mentioned above, low water levels cause low freight capacities, but maybe also lower speeds, and therefore increased freight prices per tonne transported. High water levels may cause navigation halts due to flood risk and for safety reasons.

Both extreme low water levels and high water levels are harmful in terms of economic welfare. Jonkeren (2009) estimates a welfare loss of €227 million following from an increase of the transport cost caused by low water levels for the whole Rhine area. High water levels leading to a ban on water transport do not occur frequently, which is why the focus in this dissertation is on the effects of low water levels.

By taking adaptation measures, the harmful impacts of climate change on this market can possibly be decreased. These measures may be categorized into public, carrier, and customer measures. *Public measures* include mainly infrastructure investments such as dredging, canalizing and building reservoirs. *Carrier measures* include changes in fleet composition, barge design or barge size. *Customer measures* may include changes in stock-keeping behaviour, and relocation to locations that depend less on transport by inland navigation. Changes in contract design, especially in low-water clauses, is an adaptation where both carriers and customers play a role.

1.4 Imbalances in inland navigation markets

In freight transport, imbalance in good flows between regions is a commonly observed phenomenon. As an example from the inland navigation market, in 2006, 126 million tonnes of goods were transported from the Netherlands to countries abroad, while the opposite flow was 64 million tonnes (CBS, 2010). Freight prices and transported volumes are to some extent determined by the degree of imbalance in demand for transport between regions, which will be analysed in more detail in Chapters 3 and 4.

While demand for transport is direction-specific, a large share of the transport cost is *joint*. As carriers often have incentives to return to the location of origin, this means that the cost for a return trip is made together with the fronthaul trip (see Pigou, 1913). This situation, where carriers face the risk of finding no backhaul (or passengers) for the return trip because of low(er) demand for transport on the return journey, is frequently referred to as *the backhaul problem.*

The ‘backhaul problem’ is a well-known phenomenon in transport economics, both in freight and passenger transport studies. It arises in situations where the volume of transported goods or persons is not in balance between two (or more) locations, which means that transport flows are mainly in one (or more) dominant direction(s). Since the inland navigation market has a large number of suppliers and costs of entry into these markets are low, one might assume competition to model freight imbalances in this market. On the other hand we observe that market frictions, such as lack of information on the time and location of demand and supply, play a role in freight price formation in this transport market. This lack of information also expresses itself in search and waiting times. In order to deal with these issues, and to enrich the literature in this field, we deviate from the standard competitive model for backhaul (see Boyer, 1998; Felton, 1981), and develop a matching model in this context.

The backhaul problem often leads to a lower load factor in low demand directions. Carriers may follow different strategies to cope with the backhaul problem. Different pricing of fronthaul and backhaul trips may be used by carriers to keep flows balanced to some extent. Other strategies may for example be *waiting* (when the imbalance in demand is only temporary), or *triangular routing*, which means that carriers do offer not only bi-directional services but also transport services via additional nodes in a network (see Button, 2001).The focus in this dissertation is on pricing and waiting.

Freight prices determine, among other things, the demand for the transported goods. For example, in Krugman (1991), freight prices influence trade and therefore regional and international transport demand. Freight prices not only depend on costs of transport but are also determined by direction-specific demand. In economic terms, we can say that freight prices are endogenous with respect to transport demand. In a recent paper Takahashi (2010) studies imbalance in a New Economic Geography setting. Takahashi concludes that differences in freight prices are the result of differences in the economic size of regions. Larger regions pay a higher freight price. Differences in freight price, therefore, have the effect that regions become more equal in economic size. Imbalance in a context with location shift of firms and agglomeration, and endogenous freight prices is studied by Behrens et al. (2009). However no distinction is made between fronthaul and backhaul prices.

As we will show, the imbalance feature is also relevant for transport by inland navigation, and it has specific implications for the consequences of climate change on this sector. Changes in policy, or environmental changes such as climate change, have different economic impacts for regions when there is an imbalance in transport flows. In this dissertation, which studies the combined effects of climate change and freight imbalance, we shed light on policy questions, such as how to share the burden of a climate-related infrastructure improvement in a transnational context. A common practice is that each country pays for the infrastructure improvements located on its own territory. However, in the case of backhaul problems the benefits of the improvement are distributed in a rather uneven way: one country will receive a larger share of the benefits than the other. Knowledge concerning how the benefits are spread between the two locations (countries) helps us to arrive at a proper division of infrastructure costs. This is relevant for those countries along the Rhine or Danube where water management costs to improve the navigability have to be shared between countries, and where benefits are unevenly spread because of the backhaul problem.

1.5 Research questions, relevance and outline of the dissertation

The inland navigation market of North-Western Europe faces potential problems due to climate change. Different measures may be taken by governments, carriers, and customers to cope with the negative effects of climate change. The effects of climate change on the inland navigation market may also be different for regions with different demand for transport by inland navigation. The research carried out in this dissertation can be seen as an investigation into adaptation strategies and the interaction-effects of imbalance and climate change on the inland navigation market. This gives rise to the following two main research questions for this dissertation:

1. What is the optimal barge-size adjustment for barge operators to cope with climate change, and what are the implications of climate change for investments in inland waterway infrastructure by the public sector?

2. What is the impact of climate change on freight prices in the inland navigation market in the presence of direction dependent freight imbalances?

This dissertation is, on the one hand, relevant as a contribution to scientific literature, while, on the other hand, it can support (societal) decision making. As stated earlier, there is still a gap in the scientific literature on the transport economic aspects of inland navigation in general. This dissertation contributes to this literature by approaching the field in a climate change context. In addidition, the incorporation of imperfect information to the backhaul literature can be seen as a contribution to the economic theory. We show that imbalance leads to different impacts of climate change in different regions (even though the climate change may be the same for these regions).

As a contribution to decision making, the adaptation strategies that are evaluated from a welfare economic perspective can be mentioned. Both private decision making (choice of barge size) and public decision making (choice of amount to invest in infrastructure) are supported, by providing the optimal values to be chosen for the instruments available. By taking the imbalance issue into account, this study gives insights into how to achieve a fair division of the costs of potential infrastructural investments on an international level.

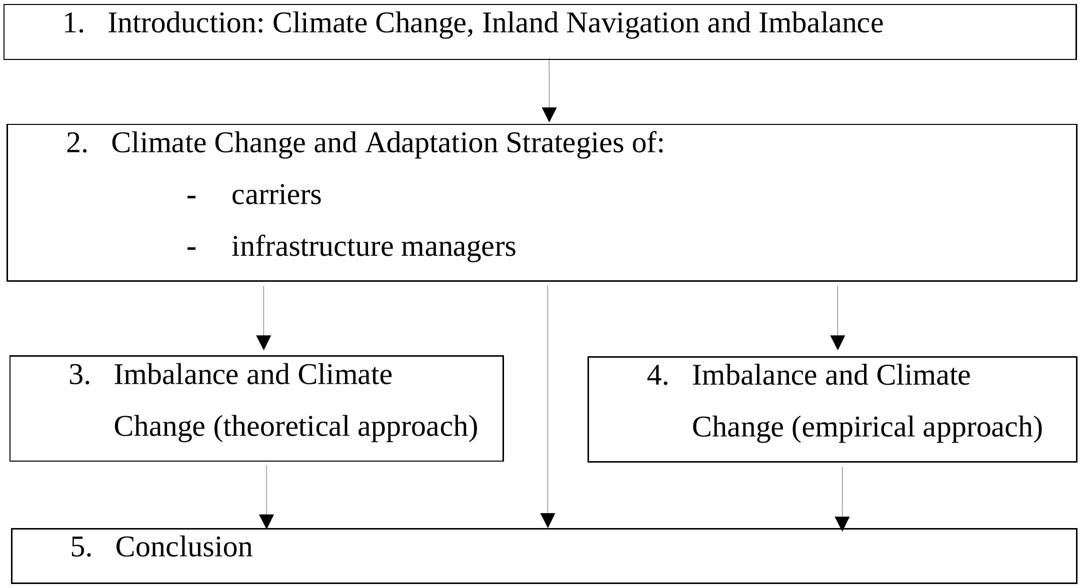

Figure 1.3: Schematic representation of the outline of the dissertation

In Chapter 2, Research Question 1 is addressed by formulating a micro-economic model and deriving optimality conditions for instruments to cope with climate change. In addition, numerical results are given for the case of the Rhine market. Research Question 2 is addressed in Chapter 3 by a mainly theoretical investigation into imbalance and its implications for climate change impacts, and then by an empirical analysis of the Rhine market in Chapter 4. In Chapter 3 a matching model is used to derive, theoretically, the effect of directional flow imbalances on freight prices in an imperfect information setting. After establishing this effect, climate change is taken into account, and the interaction between climate change and imbalance is presented. In Chapter 4, imbalance is studied empirically for the case of the Rhine market in Western Europe. Chapter 5 concludes. The outline of the dissertation is shown schematically in Figure 1.3.

CHAPTER 2

PRODUCTION UNCERTAINTY IN THE INLAND NAVIGATION MARKET: CLIMATE CHANGE, OPTIMAL BARGE SIZE, AND INFRASTRUCTURE INVESTMENTS

2.1 Introduction

In many markets, supply is by its very nature affected by weather conditions. Important examples are agriculture, tourism, and transport. For these markets, weather conditions can be regarded as an exogenous source of production uncertainty which results in a highly correlated shocks in output for producers within certain geographical areas. Production uncertainty encompasses *market uncertainty*, where market prices for inputs and/or outputs are uncertain, and *technological uncertainty*, where the amount of the output to be obtained is uncertain (see Gravelle and Rees, 1992, pp. 643-670).[4] Markets that are affected by weather conditions will also be exposed to climate change, which may be defined as a structural shift in weather conditions.[5]

The most studied form of production uncertainty in the economic literature is weather uncertainty and its influence on the agricultural market. An essential feature of the agricultural market is that the outputs of agricultural firms are strongly correlated with weather shocks, at least at a regional level and for similar products. For example, Solomou and Wu (1999) measure weather effects on agricultural output in Western-Europe for the period 1850-1913. They find that weather shocks explain between one-third and two-thirds of the variation in agricultural output.

In this chapter we study (in addition to optimal infrastructure investment) the welfare effects of choosing an optimal barge size, which shows similarity to the optimal input choice in the agricultural economics literature that is first developed in the 1970s. A key study is Feder (1980), who studies the optimal scale of operation for cultivating modern crops under new technology and uncertainty. He derives both the optimal amount of fertilizer and optimal

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[4] ‘Technological uncertainty’ is also called ‘output uncertainty’ in the literature (see Saha 1994). Pope and Kramer (1979) also use the term ‘production uncertainty’ for what we call ‘technological uncertainty’.

[5] For example, for the inland navigation market, the relevant effect of climate change is the expected change in the statistical properties of water levels, which determine available capacities for transport.

amount of land to be used in an agricultural production process. Pope and Kramer (1979) also derive optimal input choice under uncertainty, and conclude that an increase in uncertainty may lead to an increased usage of inputs. While our model setting shows similarities with these studies, we particularly focus on models with closed form solutions. This has a number of advantages. For example, it facilitates the interpretation of the theoretical results. Moreover, it simplifies the numerical analyses. We use the model to study the effects of public intervention on welfare in the inland navigation sector.

Transport is a market which is strongly influenced by weather conditions. Weather variables, such as rainfall, snow, ice, and wind, have different, but mostly negative, impacts on the output of the different transport modes. For an empirical overview of the effects of weather (and climate change) on transport, see Koetse and Rietveld (2009). They conclude that: (i) most studies focus on passenger transport rather than freight transport; (ii) the effect of extreme weather on transport accidents has received most attention; (iii) most studies deal with the effect of short-term variations in weather, whereas studies that consider long-term impacts are rare.

The inland navigation market, is strongly affected by weather conditions, as rainfall and temperature (through evaporation) have an influence on water levels. As mentioned in the introduction, extremely high water levels may lead to navigation halts on rivers, as navigation becomes too dangerous because of flood risk, and may give problems with infrastructure like bridges and motorways. Extreme low water levels reduce available freight capacities for carriers, as a minimum distance must be maintained between the barge and the bottom of the river. Both extreme low and high water levels lead to economic welfare losses due to limitations in supply. For empirical estimates of welfare losses due to low water levels, see Jonkeren et al. (2007).

In recent years, the River Rhine in Western Europe has been the main example of a river that is potentially affected by climate change. The Rhine is the most important waterway in Europe. About 70 per cent of all inland waterway transport in the former EU-15 Member States is carried via the Rhine (see Jonkeren et al., 2007). As a result of climate change, water levels on this river may become structurally lower in summer and higher in winter. Also more variation in water levels in summer is predicted for the future.[6]

The choice of barge size may function as an instrument to cope with water-level uncertainty.[7] While one advantage is that a larger barge makes it possible to benefit from

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[6] For evidence see a study on future water-level discharges on the Rhine by Te Linde (2007).

[7] In the analysis we keep barge-design constant, which may be a topic for further research.

returns to scale, a disadvantage is that large barges are relatively more affected by low water levels than small barges. Under uncertainty in water levels, a trade-off between advantages and disadvantages must be made. Even now, when climate change is (only) expected, barge operators have to make investment decisions regarding the size of their barges that have long-lasting consequences.

However, optimal adjustment to climate change is not just a matter of private sector adjustment. The public sector in its role of the supplier of the waterway infrastructure might also contribute. An important question is what the optimal composition of the overall adjustment strategy is in terms of the shares of the private and the public sector. More in particular, we will address the potential contribution of both private and public actors when they act independently, and compare this with the case when a joint optimization takes place.

We formulate a theoretical model which determines market equilibrium and economic welfare under choice of optimal barge size and amount of infrastructure investment by the government. The number of active barge operators and the freight prices are also dependent on the degree of uncertainty in water levels. Higher freight prices may result because of a scarcity effect when capacity is reduced. Higher freight prices may or may not compensate barge operators for the reduction in capacity. For certain choices of the form of the Von Neumann-Morgenstern utility[8] function and the demand function, we are able to derive the optimal barge size analytically.

In Section 2.2 we present the theoretical framework for the inland navigation market under water-level uncertainty. In Section 2.3 we determine the equilibrium freight prices, the equilibrium number of barges active in the market and expected welfare. In Section 2.4 we derive the optimal barge size chosen by barge operators in the market. In Section 2.5 we present an analysis of infrastructure investment. Section 2.6 then gives the numerical presentation of the work described in Sections 2.2 to 2.5, including a sensitivity analysis with respect to climate change. Section 2.7 concludes.

2.2 Theoretical framework

In this section we formulate a theoretical framework to study the strategies of carriers and the government to cope with output uncertainty, as outlined in the Introduction. An abstract setting is chosen, where we assume demand for transport from one end point, e.g. a mainport,

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[8] See Von Neumann and Morgenstern (1944).

to the other end point, e.g. the hinterland. Transport occurs at discrete points in time at $t = 1, 2, \ldots, T$, where t is measured in a period of fixed length, e.g. a week. We will apply this setting to the inland navigation market, assuming output uncertainty due to water-level uncertainty, but it is of course applicable to any setting.

We now focus on the supply side. Barge operators are assumed to be identical, possess exactly one barge, and are risk averse. At $t = 0$, barge operators decide whether or not to enter the market. When $t > 0$, a barge operator cannot leave the market until $t = T$, so the number of barge operators N_B is fixed during this period.

For each barge operator, the effective (supply) capacity available for transport at time t, q_t, depends on the water level at t. When water levels are low, capacity is restricted, as a minimum distance must be maintained between the bottom of the river and the barge. Therefore, in the relevant range of water levels, capacity increases with water levels. We assume a discrete probability distribution of q_t, which is assumed to be independently and identically distributed at discrete moments in-time $t = 1,2, \ldots, T$.

We assume that a barge operator incurs only fixed costs C (including costs of transport). This may be justified as fixed costs account for the majority of a barge operator's total costs. For a trip beginning at time t, C is paid at the beginning of a period t, and the revenue is received at the end of the trip at time $t + 1$. We assume that freight prices for a trip beginning at time t are fully determined by supply and demand factors at time t. We assume a constant elasticity demand function for transport with elasticity ε. Aggregate demand Q_t in tonnes is then given by:

$$Q_t = N_B q_t = \alpha {p_t}^{\varepsilon}, \qquad \text{where} \qquad \alpha > 0,\ \varepsilon < 0, \qquad (2.1)$$

where p_t is the freight price per tonne. Hence, the inverse demand function may be written as:

$$p_t = \left(\frac{1}{\alpha} N_B q_t\right)^{\frac{1}{\varepsilon}}. \qquad (2.2)$$

Following conventions in financial economics, it is assumed that the barge operators' objective function depends on returns on investment (rather than profits)[9]. Periodical returns are defined by profits $p_t q_t - C$ relative to expenses C. So we denote the *periodical* return by

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[9] By using returns rather than profits, we are also able to derive analytical results.

$r_t = \frac{p_t q_t}{C} - 1$. We assume that there exist markets (e.g. stock markets), where barge operators reinvest their excess returns, that yield returns identical to the returns on their investment in the inland navigation market (we do not see this assumption as essential but this reduces the complexity of the model). The *overall* return R for the period between $t = 0$ and $t = T$ is then defined by $R = \prod_{t=1}^{T}(1 + r_t) - 1$.

In order to model the barge operator's preferences under uncertainty, we use the commonly employed expected utility approach.[10] In this model, economic agents base their decisions on the expected value of the utility given the probability distribution of the underlying uncertainty. We use a utility function that is logarithmic and exhibits decreasing relative risk aversion (DARA) [11]. This utility function is widely used and can be formulated[12] as:

$$U(R) = \ln(1 + R). \qquad (2.3)$$

Barge operators base their entry decision on the expected utility of entering, which is in expanded form equal to:

$$E[U(R)] = T\ \left(\frac{1}{\varepsilon}\ln N_B - \frac{1}{\varepsilon}\ln\alpha - \ln C + \left(1 + \frac{1}{\varepsilon}\right)E[\ln q_t]\right), \qquad (2.4)$$

where we used the assumption of an independent and identical distribution of capacities over time. The probability distribution of capacities is assumed to be discrete, where π_i denotes the probability that capacity q_i is realized, for possible state of the water levels $i = 1, .., m$. Furthermore, water-level states are assumed to be ordered in an increasing manner, meaning that a higher i means a higher water level. We also assume that a higher water level implies a higher capacity q_i per barge.

2.3 Equilibrium

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[10] For a theoretical introduction, see Mas-Colell et al. (1995).

[11] By 'exhibiting decreasing absolute risk aversion (DARA)', we mean that the Pratt-Arrow absolute risk aversion coefficient is decreasing, which is defined as $(y) = -U''(y)/U'(y)$, where A is the Pratt-Arrow relative risk aversion coefficient; U is the utility function; and y may be a quantity such as income or return. A *decreasing* absolute risk aversion coefficient means that the risk aversion decreases for higher levels of income or return, which was argued by Pratt (1964) to be quite in line with people's observed behaviour. For more details, see, e.g., Varian (1995).

[12] For an example where this type of utility specification is used, see Levy and Markowitz (1979).

The barge operators' utility of investing in risk-free assets is $U(R^f) = \ln(1 + R^f)$, where R^f denotes the *overall* risk-free interest rate; and r^f denotes the *periodical* risk-free interest rate, so $r^f = (1 + R^f)^{1/T} - 1$. The free entry condition implies that the expected utility which barge operators derive from their investment is equal to investing in risk-free assets. So the equilibrium condition on returns is $E[U(R)] = U(R^f)$.

This condition, combined with (2.4), yields the equilibrium number of barges, N_B:

$$N_B = \alpha\,(1 + r^f)^{\varepsilon}\, C^{\varepsilon} e^{-(\varepsilon+1)E[\ln q]} = \alpha\,(1 + r^f)^{\varepsilon}\, C^{\varepsilon} e^{-(\varepsilon+1)\sum_{i=1}^{m} \pi_i \ln q_i}$$

$$= \frac{\alpha\,(1+r^f)^{\varepsilon}\, C^{\varepsilon}}{\left(\prod_{i=1}^{m} {q_i}^{\pi_i}\right)^{(\varepsilon+1)}}\,. \qquad (2.5)$$

It is seen that N_B depends on the elasticity of demand ε, and the geometric mean of the barge capacity. If demand is elastic ($\varepsilon < -1$), N_B depends positively on the (geometric) mean of the capacity, and negatively if demand is inelastic ($-1 < \varepsilon < 0$). This implies that a higher capacity leads to less barges in the inelastic case, but to more barges in the elastic one.

Given (2.2) and (2.5), the price per tonne at time t becomes:

$$p_t = \frac{(1 + r^f)\, C}{\left(\prod_{i=1}^{m} {q_i}^{\pi_i}\right)^{\left(1+\frac{1}{\varepsilon}\right)}}\; {q_t}^{\frac{1}{\varepsilon}}\,.$$

This expression shows that both realized capacity at time t and the properties of the capacity distribution function play a role in the determination of the price per tonne at time t, since $\varepsilon < 0$, p_t depends negatively on realized capacity q_t. Furthermore, if demand is elastic ($\varepsilon < -1$), p_t depends negatively on the geometric mean of q_t, and vice versa if demand is inelastic ($-1 < \varepsilon < 0$). For the special case that $\varepsilon = -1$, one gets $p_t = (1 + r^f)C/q_t$, and prices per tonne do not depend on the geometric mean of the capacity in a certain period.

To compare the effects of different interventions to cope with water level uncertainty or, to be more specific, the increasing probability of low water levels due to climate change, we are interested in expected welfare $E[W]$. In the welfare analysis, the profits of barge operators can be neglected as these can be gained by investments in risk-free assets. Therefore $E[W]$ can be calculated as:

$$E[W] = \frac{D - D^{T+1}}{1 - D} E[CS_t],$$

where CS_t denotes the consumer surplus at time t derived from transport on the market analysed, and $D = (1 + r^f)^{-1}$ is the weekly discount factor. We consider changes in expected welfare $\Delta E[W] = E[W] - E[W_0]$, where $E[W_0]$ is the expected welfare in a reference case. This expression can be written as[13]:

$$\Delta E[W] = E[W] - E[W_0] = \frac{D^{T+1} - D}{D-1} (E\,[CS] - E_0\,[CS_0])$$

$$= \frac{D^{T+1} - D}{D-1} \left(\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}} \left(N_B{}^{\left(\frac{1}{\varepsilon}+1\right)} E\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right] - N_{B0}{}^{\left(\frac{1}{\varepsilon}+1\right)} E_0\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right] \right) \right). \qquad (2.6)$$

2.4 Optimal barge size

In this section, we derive optimality conditions for the optimal barge size chosen by a representative barge operator, and present a closed-form solution of the optimal barge size under certain assumptions.

In the optimal barge-size discussion, barge-size capacities q_i and the cost function C need to be specified as function of the barge size. Barge size $\bar{q}$ is defined as the maximum value of the capacity function (in tonnes), which means $\bar{q} = max\{q_i\,, i = 1,2,..n\} = q_n$.[14] Capacities are denoted by $q_i(\bar{q})$ and the cost function by $C(\bar{q})$. Given this notation, expected utility as formulated in (4) becomes:

$$E[U(R)] = T\,E\left[\ln\left(\frac{p_t q_t}{C}\right)\right] = T\,E[\ln p_t + \ln q_t - \ln C(\bar{q})]$$
$$= T\,(E[\ln p_t] + E[\ln q_i(\bar{q})] - \ln C(\bar{q})).$$

As barge operators are price-takers, and no barge operator can influence the price individually, the first-order condition (FOC) for expected utility maximization with respect to $\bar{q}$ is:

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[13] For intermediate steps, see Appendix 2.A.

[14] We assume that barges are designed such that there is no 'redundant' capacity, which means that all $\bar{q}$ tonnes per barge can physically be transported at the highest water level.

$$\frac{\partial E[U(R)]}{\partial \bar{q}} = T\left(E\left[\frac{q'(\bar{q})}{q(\bar{q})}\right] - \frac{C'(\bar{q})}{C(\bar{q})}\right) = 0,$$

or in a more compact form:

$$E\left[\frac{q'(\bar{q})}{q(\bar{q})}\right] = \frac{C'(\bar{q})}{C(\bar{q})}.$$

This expression may be interpreted as a '(relative) marginal benefit equals (relative) marginal cost' condition.

The second-order condition (SOC) for expected utility maximization with respect to $\bar{q}$ gives:

$$\frac{\partial^2 E[U(R)]}{\partial \bar{q}^2} = T\left(\sum_{i=1}^{m} \pi_i \left(\frac{q_i''(\bar{q})}{q_i(\bar{q})} - \left(\frac{q_i'(\bar{q})}{q_i(\bar{q})}\right)^2\right) - \frac{C''(\bar{q})}{C(\bar{q})} + \left(\frac{C'(\bar{q})}{C(\bar{q})}\right)^2\right) < 0,$$

or in a more compact form:

$$E\left[\frac{q''(\bar{q})}{q(\bar{q})} - \left(\frac{f'(\bar{q})}{f(\bar{q})}\right)^2\right] < \frac{C''(\bar{q})}{C(\bar{q})} - \left(\frac{C'(\bar{q})}{C(\bar{q})}\right)^2.$$

We provide a binary example ($m = 2$), where we have capacity $q_H(\bar{q}) = \bar{q}$ for high water levels H, and capacity $q_L(\bar{q}) < \bar{q}$ for high water levels L, and where π_H and π_L are the associated probabilities.

The FOC for the binary example is given by:

$$\pi_L \frac{q_L'(\bar{q})}{q_L(\bar{q})} + (1 - \pi_L)\frac{1}{\bar{q}} = \frac{C'(\bar{q})}{C(\bar{q})}.$$

And the SOC is:

$$\pi_L\left(\frac{q_L''(\bar{q})}{q_L(\bar{q})} - \left(\frac{q_L'(\bar{q})}{q_L(\bar{q})}\right)^2\right) - (1 - \pi_L)\frac{1}{\bar{q}^2} < \frac{C''(\bar{q})}{C(\bar{q})} - \left(\frac{C'(\bar{q})}{C(\bar{q})}\right)^2.$$

As one may expect, the first-order and second-order conditions restrict the choice of the functional forms of $C(\bar{q})$ and $q_L(\bar{q})$, as well as their parameter values. We choose an example with the following functional forms that have empirical support, (see Section 2.6 for numerical examples): $C(\bar{q}) = \kappa_0 + \kappa_1 \bar{q}^{\kappa_2}$ and $q_L(\bar{q}) = \phi_0 \bar{q}^{\phi_1}$ with $\kappa_0, \kappa_1, \kappa_2, \phi_0, \phi_1 > 0$. If the SOC holds, this yields a unique global optimal barge size[15]:

$$\bar{q} = \left(\frac{\kappa_0(1 - \pi_L + \pi_L \phi_1)}{\kappa_1(\kappa_2 - 1 + \pi_L - \pi_L \phi_1)}\right)^{1/\kappa_2}.$$

Employing comparative statics, we find that:

$$\frac{\partial \bar{q}}{\partial \pi_L} = \frac{1}{\kappa_2}\left(\frac{1 - \pi_L + \pi_L \phi_1}{\kappa_1(\kappa_2 - 1 + \pi_L - \pi_L \phi_1)}\right)^{\frac{1}{\kappa_2}} \kappa_1^{\left(2 - \frac{1}{\kappa_2}\right)} (\phi_1 - 1) \frac{\kappa_2 + 2(-1 + \pi_L - \pi_L \phi_1)}{\left(\kappa_1(\kappa_2 - 1 + \pi_L - \pi_L \phi_1)\right)^2},$$

which means that a higher probability of low water levels (or, otherwise stated, more extreme climate change) leads to the choice of smaller barge if the capacity function is concave ($\phi_1 < 1$). If the capacity function is indeed concave ($\phi_1 < 1$), the comparative statics with respect to the convexity parameter of the capacity becomes:

$$\frac{\partial \bar{q}}{\partial \phi_1} = \frac{1}{\kappa_2}\left(\frac{1 - \pi_L + \pi_L \phi_1}{\kappa_1(\kappa_2 - 1 + \pi_L - \pi_L \phi_1)}\right)^{\frac{1}{\kappa_2}} \kappa_0^{\left(\frac{1}{\kappa_2} - 1\right)} \kappa_1 \, \pi_L \frac{\kappa_2}{\left(\kappa_1(\kappa_2 - 1 + \pi_L - \pi_L \phi_1)\right)^2}.$$

Thus, a more convex capacity function leads to the choice of larger ships. For the convexity parameter of the cost function, it is immediately clear that $\frac{\partial \bar{q}}{\partial \kappa_2} < 0$. This means that more expensive capacity leads to the choice for smaller barges. We observe that the optimal barge size does not depend on the elasticity of demand. An explanation for this is that barge operators individually cannot influence the market freight price when they choose their barge size. Therefore, the elasticity parameter does not enter the first order condition.

2.5 Optimal infrastructure investments by government

Another instrument, this time available to the government, is the investment in inland waterway infrastructure. Inland waterways may be adjusted to cope better with water-level uncertainty and climate change. Usually this means dredging the river or building barrages

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[15] For the intermediate steps and the SOC, see Appendix 2.B.

across the river, which both have an increasing effect on water levels and therefore capacities. Infrastructure investments are modelled such that capacities increase as an effect of a monetary investment. Therefore, apart from empirical considerations, we do not need to specify the type of infrastructure project.

Technically, we model an investment in an infrastructure project as increased capacities $\tilde{q}_i(\bar{q})$ such that $\tilde{q}_i(\bar{q}) > q_i(\bar{q})$ for $i = 1, \dots, m$. The cost of investment in infrastructure at the beginning of a period (year) is denoted by $I = I\left(\{\tilde{q}_i(\bar{q})\}_{i=1,..,m}\right)$. Optimal investments are derived from maximizing the change in expected welfare[16], where a level of zero for the investment is used as the reference case:

$$\Delta E[W] = \frac{D^{T+1} - D}{D - 1}\left(E[CS] - E[CS_0]\right) - I$$

$$= \frac{D^{T+1} - D}{D - 1}\left(\frac{N_B^{\left(\frac{1}{\varepsilon}+1\right)} E\left[\tilde{q}_i^{\left(\frac{1}{\varepsilon}+1\right)}\right] - N_{B0}^{\left(\frac{1}{\varepsilon}+1\right)} E_0\left[q_i^{\left(\frac{1}{\varepsilon}+1\right)}\right]}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}\right) - I.$$

We also need to substitute the equilibrium value of N_B, as from a social planner's perspective the number of firms in a market is endogenous. This yields:

$$\Delta E[W] = \frac{D^{T+1} - D}{D - 1}\left(\frac{\alpha\,(1 + r^f)^{\varepsilon+1}\, C(\bar{q})^{\varepsilon+1}\, E\left[\tilde{q}_i^{\left(\frac{1}{\varepsilon}+1\right)}\right]}{\left(\frac{1}{\varepsilon}+1\right)\left(\prod_{i=1}^{m} \tilde{q}_i^{\pi_i}\right)^{\left(2+\varepsilon+\frac{1}{\varepsilon}\right)}} - \frac{N_{B0}^{\left(\frac{1}{\varepsilon}+1\right)} E_0\left[q_i^{\left(\frac{1}{\varepsilon}+1\right)}\right]}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}\right) - I$$

This is the criterion which is maximized in the numerical welfare analysis in Section 2.6. In two cases, only investments in infrastructure are considered, and $\Delta E[W]$ is maximized over I. In order to maximize over I, further assumption are made on $\tilde{q}_i(\cdot)$ in all presented cases. In two other cases, both infrastructure investments and capacity choice are considered. $\Delta E[W]$ is then maximized over I, and $E[U(R)]$ is maximized over $\bar{q}$. The expression for $E[U(R)]$ for the cases where both optimal barge size and optimal investment in infrastructure are chosen becomes:

$$E[U(R)] = T\,\left(E[\ln p] + E\left[\ln\left(\tilde{q}_i(\bar{q})\right)\right] - \ln C(\bar{q})\right).$$

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[16] Delta expected welfare is taken in order to avoid problems with infinite expected welfare for some elasticities.

In the entire numerical analysis, optimization occurs through finding a solution to the first-order condition, and evaluating the expression of the second order condition.

2.6 Numerical welfare analysis

In this section, we provide the numerical results of the theoretical analysis of the previous Sections 2.2 to 2.5. The change in (expected) welfare is used as a criterion to evaluate the attractiveness to society of an investment strategy, when the choice of barge size is based on expected utility. Given a reference situation, we present seven additional cases (making a total of eight cases) where we study how barge-size adjustment and infrastructure investment both affect welfare, under a climate change scenario. We choose dredging as a potential example of infrastructure investment. We keep the analysis as realistic as possible, given the current knowledge of the cost of infrastructure improvements, and choose values for input parameters based on empirical studies. We provide a sensitivity analysis with respect to the scale parameter of cost function of infrastructure investments. We also study the sensitivity of the results to the elasticity of demand for transport. The water-level distribution is taken as binary, with a low water-level state and a high water-level state (although it is continuous, as shown in the empirical estimation of the effective load capacity later on).

Our assumption of the elasticity of demand is based on the study by Jonkeren (2009, pp. 32), so we take a value of -0.5. The scale parameter α is calibrated to the value of $2.5 * 10^7$ in order to obtain a number of barges that reflect the observed number of barges in the Rhine market, which is around 9700 (for an overview of the composition of the Rhine fleet, see CCNR and European Commission, 2007). The weekly risk-free interest rate per week, r^f, is taken as 0.1 per cent (corresponding to a value of approximately 5.3 per cent per year). The decision horizon for a barge operator to exit the market once it has entered the market is taken as one year, so $T = 52$ weeks. This assumption can be considered as a minimum period for holding an investment in this market from a liquidity perspective.

We assume that the *effective* capacity depends on water level w. A regression equation is estimated from trip data on the Rhine market (Vaart!Vrachtindicator, 2003-2007) in order to obtain an expression for effective capacity. In this regression we set water level at 260 cm for the case where $w > 260$ cm, as the effective capacity is unaffected for water levels above that threshold. After estimation, the regression becomes:[17]

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[17] For more detailed regession output, see Appendix 2.D.

$$\ln \text{loadfactor} = -0.0134826\, w - 0.5850203\ \ln \bar{q} + 0.0027283\, w \ln \bar{q} + bX \qquad (2.7)$$

In this equation X denotes the other control variables such as distance, travel time, month of the year and cargo type. Effective capacity can be derived from (2.7), given the assumption that loadfactor is proportional to effective capacity. Therefore, when comparing relative differences in loadfactor, loadfactor may be substituted by $\frac{q(w)}{\bar{q}}$, where $q(w)$ denotes effective capacity. By using $q(260) = \bar{q}$, one obtains:

$$\ln\left(\frac{q(260)}{\bar{q}}\right) - \ln\left(\frac{q(w)}{\bar{q}}\right) = 0.0134826\,(260 - w) - 0.0027283\,(260 - w)\ln \bar{q},$$

or equivalently:

$$q(w) = e^{0.0134826\,(260-w)}\bar{q}^{1-0.0027283(260-w)}. \qquad (2.8)$$

As the exponent of $\bar{q}$ will be smaller than 1 in (2.8), we use the minimum-operator to avoid $q(w) > \bar{q}$ for small $\bar{q}$. This gives our preferred specification of the effective capacity function:

$$q(w) = \min\left(\bar{q}, e^{0.0134826\,(260-w)}\bar{q}^{1-0.0027283(260-w)}\right).$$

In the remainder, we continue with a binary water-level/capacity-distribution. In our reference case, the capacity of barges at a high water level q_H $(= \bar{q})$ is set equal to 1500 tonnes, which may be considered a representative (median) barge in terms of capacity (see CCNR and European Commission, 2007). The cost per week for the barge operator as a function of $\bar{q}$ takes the form of $C(\bar{q}) = 8000e^{0.0002\bar{q}} - 5770$. These figures are taken as an approximation to values reported by NEA (2008).

In the analysis, we assume the length of the trip to be equal to 400 km, which is based on the Vaart!Vrachtindicator (2003-2006), and is representative as an average for trips between the Port of Rotterdam and popular destinations in Germany. Concerning the binary water-level distribution we make the following assumptions. We assume that the water levels at Emmerich, which is a place on the Rhine close to the German-Dutch border, are representative for the entire trip-length. As a cut-off value which distinguishes low water levels from high water-level distributions we take 190 cm. Furthermore, we assume that the year 2005 is representative for a year before climate change, and that the extreme dry year 2003 is representative for a year after climate change. From water-level data from iidesk.nl we obtain that, before climate change, the low-water probability is roughly represented by $\pi_L = 1/3$, and for high water levels it is $\pi_H = 2/3$. After climate change, we assume this is $\pi_L = 2/3$ and $\pi_H = 1/3$.

By using Rijkswaterstaat data[18], we obtain an investment cost function for dredging on the Waal (the main part of Rhine in the Netherlands) We assume there are no economies/diseconomies of scale, so this investment cost function can be extrapolated to the entire trip length of 400 km. The investment cost function is approximated by:

$$I = \Delta waterlevel * 1.2 * 1.01^{(\Delta waterlevel - 20)}, \qquad (2.9)$$

where I is the annualized investment cost in millions of euros, and $\Delta waterlevel$ is the cm increase in the water level due to dredging.

This set of input values gives rise to an equilibrium outcome, which is presented in Tables 2.1, 2.2 and 2.3. Note that in these tables $E[p]$ is the expected price per tonne, and $E[Rev]$ is the expected *weekly* total revenue for the barge operators. Furthermore, $\Delta E[W]$, $E[Rev]$ and I are given in thousands of euros. In Table 2.1 the outcome *before* climate change is presented:

Table 2.1: Optimal barge size and infrastructure investment *before* climate change.

Case	Barge-size Adjustment	Infrastructure Investment	*ΔE[W] (x1000) per year*	N_B	p_L	p_H	*E[p]*	*E[Rev] (x1000) per week*	q_L *(tonnes)*	q_H *(tonnes)*	*cm dredging*	*I (x1000) per year*
I			-	9,670	8.36	2.97	4.77	52,829	894	1,500	-	-
II	☑		23,354	5,894	9.09	2.51	4.70	51,500	1,407	2,680	-	-
III		☑	8,347	9,448	6.64	3.11	4.29	50,867	1,027	1,500	21.5	26,134
IV	☑	☑	44,883	5,381	5.96	2.72	3.80	47,814	1,903	2,819	32.0	43,276

In Case II, where we study barge-size adjustments alone, it can be seen that market forces would imply an increase in the current median barge size from 1,500 to about 2,700 tonnes. This is in line with the reports from the market that there is a tendency to increase barge size. For example, Rabobank Capaciteitsmonitor (2007) reports that the average capacity in the

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[18] We thank Siemen Prins from Rijkswaterstaat for his help in providing cost data.

Dutch inland navigation fleet increased from 1,500 to 1,622 tonnes between the years 2000 and 2005. Also Buck Consultants (2008) and CBS (2010)[19] report increases in barge size. This shift seems to be consistent with welfare-economic trade-offs (the gain in welfare is about €23.4 million per year). The reason of this gap between the actual size of barges and the optimal barge size may be attributed to, among others things, a lag effect that barges have in practice a long-lasting lifetime. In Case III, where we look at infrastructure investments (alone), we see that the optimal annual investment is €26.1 million, corresponding to a dredging of 21.5 cm, which results in a net expected welfare gain of €8.3 million annually. This implies a benefit-cost ratio of about 1.32 ($\approx (26.1 + 8.3)/26.1$) (note that this result holds before any change in climate conditions). Combining the two adaptation strategies, there is a welfare gain of €44.9 million, which is, it is important to note, considerably more than the gain of the two strategies separately. The mechanism underlying this 'super-additivity'-effect is that it is attractive to hold even larger barges in the new infrastructure environment, which yields an additional welfare gain. In addition, it should be noted that when barge size increases, less barges become necessary in the market (a drop from about 9,700 in case I to 5,900 in Case II and 5,400 in Case IV). The results for the situation *after* climate change are given in Table 2.2:

Table 2.2: Optimal barge size and infrastructure investment *after* climate change.

Case	Barge-size Adjustment	Infrastructure Investment	$\Delta E[W]$ (x1000) per year	N_B	p_L	p_H	$E[p]$	$E[Rev]$ (x1000) per week	q_L (tonnes)	q_H (tonnes)	cm dredging	I (x1000) per year
V			-80,297	10,541	7.04	2.50	5.53	57,396	894	1,500	-	-
VI	☑		-66,883	7,374	7.16	2.09	5.47	56,633	1,267	2,344	-	-
VII		☑	-35,995	9,573	4.79	3.03	4.20	50,979	1,193	1,500	44.7	68,514
VIII	☑	☑	3,545	5,445	4.11	2.69	3.64	47,467	2,264	2,801	53.9	90,715

Note: The reference value for welfare is the current situation without climate change, i.e. Case I.

As may be expected climate change has a welfare-decreasing effect. If no measures are taken a welfare loss of €80.3 million per year will occur. When only barge-size adjustments are considered, smaller barges are preferred than in the situation before climate change (2,344 vs. 2,680 tonnes before) as a reaction of barge operators to more frequent low water levels. When additional infrastructure investments take place, a slight decrease in optimal barge size occurs (2,801 vs 2,819 tonnes before). Cases VII and VIII show that a government will have to invest more in infrastructure as a reaction to climate change. When the right measures are

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[19] For the relevant CBS table, see Appendix 2C.

taken in barge size and infrastructure optimization, the situation after climate change (Case VIII) can still be a slight improvement over the current situation (Case I) with an expected welfare gain of $€3.5$ million. The welfare gain (net of a climate change effect of $-€80.3$ million) of both infrastructure investment and barge-size optimization is $€83.8$ million $(3.5 + 80.3)$. This is again more than the sum of the effects of only barge size optimization $€13.4$ million $(-66.9 + 80.3)$ and the effect of infrastructure investment $€44.3$ million $(-36.0 + 80.3)$.

We are also interested in the 'net' effect of climate change after optimization has taken place. This means that we again do welfare analysis where Case IV is taken as the reference situation (in this case, barge size and depth of dredging are $2{,}819$ tonne and 32.0 cm, respectively). The results of a climate change for this situation are given in Table 2.3. Importantly, the 'net' effect of climate change on barge-size choice (Case VI) is that barge sizes are decreased (from $2{,}819$ to $2{,}611$), while there was an increase (from 1500 to $2{,}344$) when starting from the suboptimal situation. The annual welfare loss of climate change (in $\Delta E[W]$ terms) after optimizing barge size is $€54.1$ million and is $€41.4$ million so somewhat lower after additional dredging. The welfare effect of both measures taken together is a loss of $€41.3$ million, and 'super-additivity' no longer holds.

Table 2.3: Optimal barge size and infrastructure investment *after* climate change based on optimal levels before climate change.

Case	Barge-size Adjustment	Infrastructure Investment	*ΔE[W] (x1000) per year*	N_B	p_L	p_H	*E[p]*	*E[Rev] (x1000) per week*	q_L *(tonnes)*	q_H *(tonnes)*	*cm dredging*	*I (x1000) per year*
V			-55,603	5,745	5.23	2.38	4.28	50,977	1,903	2,819	32.0	43,276
VI	☑		-54,137	6,167	5.19	2.41	4.26	50,893	1,780	2,611	32.0	43,276
VII		☑	-41,361	5,410	4.11	2.69	3.64	47,454	2,279	2,819	54.0	90,978
VIII	☑	☑	-41,338	5,445	4.11	2.69	3.64	47,467	2,264	2,801	53.9	90,715

Note: The reference value for welfare is Case IV. The values for the capacity q_H and the investment level I are the optimal values before climate change.

We see that the Case VIII in both Table 2.2 and Table 2.3 yield the same barge size and dredging depths. However in cases VI, the fact that already more has been dredged in the analysis 'after-initial-optimization', appears to motivate having larger barges in Table 2.3. A similar reasoning holds for the Cases VII in both tables.

An important conclusion of Tables 2.1 to 2.3 is that climate change may lead to a substantial welfare decrease in this market (about €80 million per year). However, a considerable part of this decrease is due to that barge size and water management intensity are already at suboptimal levels in the initial situation, so for the current climate conditions. Once barge size and water management are at their optimal levels for the current climate conditions, the negative effects of climate change are about €55 million per year, so substantially smaller than the above-mentioned €80 million. Also, the welfare losses of adjusting barge size and water management intensity to their new optimal levels are then somewhat lower (from €55 to €41 million per year).

Another important conclusion is that for the initial situation, which describes the current barge market, the major welfare optimizing adjustment appears to be by the barge operators, so in the private domain (upward barge-size adjustment). This conclusion is consistent with the stylised fact that the average size of barges has increased substantially over the last decades. Once the system is optimised under current climate conditions, the public sector appears to be the strongest contributor to the minimisation of welfare decrease due to climate change. So, both private and public actors have a role to play in the optimization of adaptation strategies. The balance of the two depends on the initial conditions in the market. The upward adjusting of barge size is a costly process in the short run, but not in the long run when older barges are withdrawn from the market. Therefore the optimal government policy is to let the market slowly adjust barge size and adjust water management intensity levels only gradually. There is no reason for the government to interfere with the private decisions of barge operators regarding barge size.

We performed a sensitivity analysis with respect to two parameters: on the one hand with respect to the scale parameter of the infrastructure investment function, on the other with respect to the scale parameter of the constant elasticity of demand parameter ε. The scale parameter of the investment cost function infrastructure, which was initially set at 1.2, is in the sensitivity analysis set at 0.6 and 2.4 respectively, which represent halving and doubling the investment costs. As may be expected this has a significant impact on the investment made in infrastructure. The number of centimetres dredged is in certain cases more than doubled or halved respectively. This shows that the results are still sensitive with respect to the scale parameter of the cost function. The optimal barge size, under combined dredging and barge-size optimization, seems hardly affected by the change in the cost scale parameter: the incentive to approximately double the barge size remains. For the elasticity parameter ε, the initial value for this parameter was assumed to be -0.5 in the analysis above. In a sensitivity analysis, we have used the values -0.25, -1.0, and -2.0 (with an additional scaling of the constant in the demand function such that the equilibrium number of barges for the cases I remained constant at 9,670). The optimal barge size is again hardly affected under this parameter change: about doubling is seen for all relevant cases. For the cases after climate change, a consistent pattern is observed that the higher the elasticity of demand (in absolute sense), the higher the optimal level of investment in infrastructure. From the sensitivity analysis, it can be concluded that the optimal barge size is rather insensitive to the specification of the investment cost function and the elasticity of demand for transport, but that the optimal invest in infrastructure is sensitive.[20]

2.7 Conclusion

In this chapter we formulated a theoretical model to describe the low water-level uncertainty in the inland navigation market. Climate change is expected to occur, which has implications for this market with regard to water-level uncertainty. A negative effect of climate change on welfare is expected due to the increase in cost per tonne of transport when low water levels occur more frequently. The market actors may take measures to adapt to the new situation of climate change. As an example, we studied barge-size adjustments by barge operators. Under certain simplifying assumptions, we were able to derive the optimal barge size analytically. An increase in the convexity of cost functions, the concavity of the capacity function, and the probabilities of low water levels will lead to the choice of smaller barges. A property of the constant elasticity demand context that we adopted is that the choice of optimal barge size does not depend on the elasticity of demand.

Numerically it was shown that in the current market (both before and after climate change) there are incentives to almost double the barge size. The reason that this still has not occurred may be explained by the long lifetime of barges that are currently in use. Thus, climate change does not provide a reason to stop the current trend towards larger barges. The only effect is that this trend towards larger barges will end at a lower size than would be the case without climate change. The government may also take measures to decrease the harm caused by climate change. In this study we consider an investment in infrastructure by means of dredging. We find a benefit-cost ratio higher than 1 for this for investments both before and after climate change. Thus, both with and without climate change, welfare would increase if government intensifies dredging.

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[20] A full output of this sensitivity analysis is available upon request.

When studying the ‘net’ effect of climate change, which means that we assume that barge-size choice and the investment in infrastructure is optimal before climate change, we observe that the barge size decreases about 8 per cent when only barge-size adjustments are considered. The increase in infrastructure investments is still considerable, which is about 70 per cent more than the optimal situation before climate change. This would mean that, after climate change, public adaptation may be more important than private adaptation when the situation is optimal before climate change.

For the combined effect of barge-size adjustment and infrastructure investment, it can be concluded that the benefit in terms of expected welfare is ‘super-additive’ for the situation before climate and also for the situation after climate change when starting from the current situation. This ‘super-additivity’ property can be attributed to the opportunity for barge operators to hold even larger barges in the new environment where low water is less harmful for their capacities. However, for the situation after climate change, when starting from an optimized situation, super-additivity no longer holds.

A sensitivity analysis was performed with respect to the elasticity parameter of the demand function and the scale parameter of the cost function of infrastructure investment. The optimal barge size is rather insensitive in the change of these two parameters. Doubling barge size is observed consistently. However, the amount to invest in infrastructure quite depends on the parameter specification in the cost of investment and the demand function.

A few limitations of the model are the assumptions of one barge size, one type of commodity that is transported, one representative distance, and the occurrence of the same water level everywhere along the river. If necessary, these assumptions could be made more realistic for policy studies. Next, in Chapter 3, the effect of imbalance on freight prices is studied under competition with imperfect information. Also, the differences in climate-implied increases in transport costs are studied between regions with high and low demand for transport.

Appendix 2.A – Change in expected welfare

This appendix gives the intermediate steps for deriving the expanded version of the expression for the change in expected welfare, $\Delta E[W]$, in equation (2.6):

$$\Delta E[W] = E[W] - E[W_0]$$

$$= \frac{D^{T+1}-D}{D-1}\left(E\,[CS] - E_{\,0}\,[CS_0]\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(E\left[\int_0^{N_B q}\left(\left(\frac{x}{\alpha}\right)^{\frac{1}{\varepsilon}} - p\right)dx\right] - E_0\left[\int_0^{N_{B0} q}\left(\left(\frac{x}{\alpha}\right)^{\frac{1}{\varepsilon}} - p_0\right)dx\right]\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(E\left[\int_0^{N_B q}\left(\frac{x}{\alpha}\right)^{\frac{1}{\varepsilon}} dx\right] - E_0\left[\int_0^{N_{B0} q}\left(\frac{x}{\alpha}\right)^{\frac{1}{\varepsilon}} dx\right]\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(E\left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}x^{\left(\frac{1}{\varepsilon}+1\right)}\right]_0^{N_B q} - E_{\,0}\left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}x^{\left(\frac{1}{\varepsilon}+1\right)}\right]_0^{N_{B0} q}\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(E\left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}(N_B q)^{\left(\frac{1}{\varepsilon}+1\right)}\right] - E_{\,0}\left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}(N_{B0} q)^{\left(\frac{1}{\varepsilon}+1\right)}\right]\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}\left(E\left[(N_B q)^{\left(\frac{1}{\varepsilon}+1\right)}\right] - E_0\left[(N_{B0} q)^{\left(\frac{1}{\varepsilon}+1\right)}\right]\right)\right)$$

$$= \frac{D^{T+1}-D}{D-1}\left(\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}\left({N_B}^{\left(\frac{1}{\varepsilon}+1\right)}\,E\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right] - {N_{B0}}^{\left(\frac{1}{\varepsilon}+1\right)}\,E_{\,0}\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right]\right)\right)$$

Appendix 2.B – Intermediate steps for optimal barge size example

This appendix contains the first-order and second-order conditions for deriving the optimal barge size $\bar{q}$.

The first-order condition reads:

$$\pi_L \frac{\phi_0 \phi_1 \bar{q}^{\phi_1 - 1}}{\phi_0 \bar{q}^{\phi_1}} + (1 - \pi_L)\frac{1}{\bar{q}} = \frac{\kappa_2 \kappa_1 \bar{q}^{\kappa_2 - 1}}{\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}}$$

$$\frac{\pi_L \phi_1 + (1 - \pi_L)}{\bar{q}} = \frac{\kappa_2 \kappa_1 \bar{q}^{\kappa_2 - 1}}{\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}}$$

$$\pi_L \phi_1 + (1 - \pi_L) = \frac{\kappa_2 \kappa_1 \bar{q}^{\kappa_2}}{\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}}$$

$$(1 - \pi_L + \pi_L \phi_1)(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) = \kappa_2 \kappa_1 \bar{q}^{\kappa_2}$$

$$\kappa_0 (1 - \pi_L + \pi_L \phi_1) = \kappa_1 (\kappa_2 - 1 + \pi_L - \pi_L \phi_1) \bar{q}^{\kappa_2}$$

$$\bar{q} = \left(\frac{\kappa_0 (1 - \pi_L + \pi_L \phi_1)}{\kappa_1 (\kappa_2 - 1 + \pi_L - \pi_L \phi_1)} \right)^{1/\kappa_2}.$$

The second-order condition reads:

$$\frac{\partial}{\partial \bar{q}} \left(\frac{\pi_L \phi_1 + (1 - \pi_L)}{\bar{q}} \right) < \frac{\partial}{\partial \bar{q}} \left(\frac{\kappa_2 \kappa_1 \bar{q}^{\kappa_2 - 1}}{\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}} \right)$$

$$-\frac{\pi_L \phi_1 + (1 - \pi_L)}{\bar{q}^2} < \frac{(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2 - 2} - (\kappa_2 \kappa_1 \bar{q}^{\kappa_2 - 1})^2}{(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2})^2}$$

$$-\big(\pi_L \phi_1 + (1 - \pi_L)\big)(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2})^2 < (\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2} - (\kappa_2 \kappa_1 \bar{q}^{\kappa_2})^2$$

$$\begin{aligned} &-\big(\pi_L \phi_1 + (1 - \pi_L)\big)(\kappa_0{}^2 + 2(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) + \kappa_1{}^2 \bar{q}^{2\kappa_2}) \\ &\qquad < (\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2} - (\kappa_2 \kappa_1 \bar{q}^{\kappa_2})^2 \end{aligned}$$

$$\begin{aligned} &-\big(\pi_L \phi_1 + (1 - \pi_L)\big)(\kappa_0{}^2 + 2(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) + \kappa_1{}^2 \bar{q}^{2\kappa_2}) \\ &\qquad < \kappa_0 \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2} + \kappa_2 (\kappa_2 - 1)(\kappa_1 \bar{q}^{\kappa_2})^2 - (\kappa_2 \kappa_1 \bar{q}^{\kappa_2})^2 \end{aligned}$$

$$-\big(\pi_L \phi_1 + (1 - \pi_L)\big)(\kappa_0{}^2 + 2(\kappa_0 + \kappa_1 \bar{q}^{\kappa_2}) + \kappa_1{}^2 \bar{q}^{2\kappa_2}) < \kappa_0 \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2} - \kappa_2 (\kappa_1 \bar{q}^{\kappa_2})^2$$

$$\begin{aligned} &-\big(\pi_L \phi_1 + (1 - \pi_L)\big)(\kappa_0{}^2 + 2\kappa_0) - \big(\pi_L \phi_1 + (1 - \pi_L)\big) 2\kappa_1 \bar{q}^{\kappa_2} \\ &\qquad - \big(\pi_L \phi_1 + (1 - \pi_L)\big) \kappa_1{}^2 \bar{q}^{2\kappa_2} < \kappa_0 \kappa_2 (\kappa_2 - 1) \kappa_1 \bar{q}^{\kappa_2} - \kappa_2 \kappa_1{}^2 \bar{q}^{2\kappa_2} \end{aligned}$$

$$\left(\left(\pi_L\phi_1 + (1-\pi_L)\right) - \kappa_2\right)\kappa_1{}^2\bar{q}^{2\kappa_2} + \left(\kappa_0\kappa_2(\kappa_2 - 1) + 2\left(\pi_L\phi_1 + (1-\pi_L)\right)\right)\kappa_1\bar{q}^{\kappa_2} + \left(\pi_L\phi_1 + (1-\pi_L)\right)(\kappa_0{}^2 + 2\kappa_0) > 0\,.$$

This is a quadratic expression in terms of $\bar{q}^{\kappa_2}$.

Appendix 2.C – Table showing Dutch inland navigation fleet split up by tonnage

Table A2C: Number of Active Barges under Dutch Flag for different Tonnage Classes

Period	650 – 1000 tonne	1000 – 1500 tonne	1500 – 2000 tonne	2000 – 3000 tonne	> 3000 tonne
1997	1798	1124	429	596	145
1998	1191	1075	407	580	142
1999	1192	1104	411	608	151
2000	1288	1065	406	625	147
2001	1067	1078	442	696	171
2002	1045	1051	456	729	178

Source: CBS(2010)

Note: More recent data were not available from CBS.

Appendix 2.D – More detailed regression output for the effective capacity estimation

This appendix gives more detail for the effective capacity estimation in equation (2.7). The logarithm of the loadfactor is regressed on the waterlevel, the logarithm of the shipsize, their interaction, and a few other variables that are reported below. For the waterlevel variable, the logarithm of the shipsize and their interaction, the coefficient estimates, t-values and the 95 per cent confidence intervals are given. The complete regression output can be obtained from the author upon request.

Table A2D: More detailed output for loadfactor/effective-capacity estimation

Logloadfact	Coef.	T	95% Conf. Interval	
Wlev	-0.0135	-10.58	-0.0160	-0.0110
Logshipsize	-0.5850	-23.28	-0.6343	-0.5358
Wlev*Logshipsize	0.0027	15.82	0.0024	0.0031
Logfuelprice	Included			
Logdistance	Included			
Logtraveltime	Included			
Time-trend	Included			
Constant	Included			
Month-dummies	Included			
Cargotype-dummies	Included			
Streamdirection-dummies	Included			
R^2	0.6341			

CHAPTER 3

A MATCHING MODEL FOR THE BACKHAUL PROBLEM[21]

3.1 Introduction

Freight prices play a fundamental role in trade and therefore determine regional and international transport activities (see, e.g., Krugman, 1991). Hence, a deeper understanding of freight prices is important for our understanding of freight transport. A fundamental issue is then whether freight prices have a one-to-one relationship with costs or that freight prices are endogenous with respect to transport demand. In an increasing number of theoretical models, the importance of this issue has been recognised. For example, Anderson and van Wincoop (2004) stress the need to deal with this issue in studies on trade.

There are a number of reasons why freight prices may be endogenous with respect to transport activity. Transport markets may be oligopolistic or density economies may arise (e.g., Behrens et al., 2006; Behrens et al., 2009). Another reason as already discussed 100 years ago (Pigou, 1913) is that a large share of the transport costs are *joint* (because carriers return to the location of origin) whereas the demand for transport is direction specific, which is frequently referred to as *the backhaul problem.*

The ‘backhaul problem’ is a well-known phenomenon in transport economics, both in freight and passenger transport studies. It refers to the situation where the volume of transported goods or persons is not in balance between two (or more) locations, which means that transport flows are mainly in one (or more) dominant direction(s). Carriers may then be faced with the difficulty of finding freight or passengers (backhaul) for their return trip. The importance of the backhaul problem was also noted by Samuelson (1954) in his seminal paper in which iceberg transport costs were introduced: "Realistically, ...there are joint costs of a round trip, so [the transport costs for east and west transport] will tend to move in opposite directions, depending upon the strengths of demands for east and west transport."

Imbalance in freight transport flows is extremely common (see e.g. Wilson, 1987). In the current study we aim to study the effect of imbalance on price formation, so one must know the degree of imbalance at the level of the individual carrier, which is difficult to

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[21] This chapter is based on Demirel et al. (2010) ‘A Matching Model for the Backhaul Problem’, *Transportation Research: Part B* 44.4: 549-561.

observe. The imbalance at a more aggregate level has been extensively studied however. In particular, the imbalance in flows at the national level using annual observations has been studied by a large number of studies in the trade economics literature and has been shown to be substantial (see e.g. Lee et al., 2006). Most likely, the imbalance is much more pronounced for transport flows between smaller regions and shorter periods of observation (due to time-variation in demand). At the level of carriers, imbalance may even be more pronounced, because carriers are frequently specialised in a certain type of freight which generates additional imbalance. For example, transport carriers which are specialised in the transport of edible oils are generally not allowed to transport other kinds of (nonedible) freight.[22] Imbalance in a context with location shift of firms and agglomeration, and endogenous freight prices is studied by Behrens et al. (2009). However no distinction is made between fronthaul and backhaul prices. In a recent study Takahashi (2010) studies imbalance in a new economic geography setting. Takahashi concludes that differences in freight prices are the result of differences in region size. Larger regions pay a higher freight price. Differences in freight price have the effect that regions become more equal in size.

Theoretical contributions to the backhaul literature typically assume imperfect competition in the transport market or the presence of regional agglomeration. For example, the study by Rietveld and Roson (2002) assumes a transport monopolist, whereas Behrens et al. (2006) assumes a limited number of transport suppliers. Behrens and Picard (2008) as well as Behrens et al. (2009) assume the presence of regional agglomeration. These models have two important characteristics in common: they do not apply to the case of perfect competition and they assume perfect information about supply and demand. In contrast, we are particular interested in competitive transport markets because in many countries, the truck as well as the inland shipping market are characterized by a high level of competition. In these markets there are a large number of suppliers so that the market power due to the size of the supplier can be assumed away. In these markets, there is also free entry and low capital costs which enhances competition. For example in the inland navigation market in Western Europe thousands of carriers are active, of which most are sole-proprietorships.

To understand these markets, it is common to rely on the standard competitive model that is used in textbooks (see Boyer , 1998, but also Felton, 1981). This model is indeed useful to explain behavior for these transport markets, but a major restriction of the analysis

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[22] At first sight it may seem that in the passenger market the backhaul problem is absent, as nearly all passengers return to their location of origin. However, there is a large time variation in demand which induces low load factors and therefore a backhaul problem in the public transport as well as in the taxi market.

of the standard competitive model is that it is assumed that information about demand and supply is perfect, which we believe is a restrictive assumption and which also generates the prediction that given imbalance in transport flows, backhaul prices are zero, because of excess supply in the low demand region, which is inconsistent with empirical observation, as will be explained in detail in the next section.

Our study on backhaul pricing is not only relevant to increase our understanding of freight markets, it also sheds light on policy questions, such as how to share the burden of infrastructure improvement in a transnational context. A common practice is that each country pays for the infrastructure costs on its own territory. However, in the case of backhaul problems the benefits of the improvement are distributed in a rather uneven way: one country will receive a much larger share of the benefits than the other one. Knowledge on how the benefits are spread between the two locations (countries) may help to arrive at a proper division of infrastructure costs. A case with high political relevance concerns the distribution of costs between Belgium and The Netherlands on sharing the costs of dredging in the West-Scheldt river, which is located in Dutch territory, but where the Belgian port of Antwerp is the main beneficiary. In this case it has been decided that Belgium will pay for the dredging, even though the river is situated on Dutch territory. Similar discussions, but more implicit, take place between other pairs of countries along the Rhine or Danube, where water management costs to improve the navigability have to be shared between countries and where benefits are unevenly spread due to the backhaul problem.

In the Section 3.2 we discuss backhaul issues assuming a competitive market with perfect information, as is standard in textbooks, and we emphasise the importance of introducing imperfect information. We introduce in Section 3.3 a two-location transport framework which incorporates a matching model to study the backhaul problem. In Section 3.4 we analyse the backhaul problem numerically, with input values chosen from the inland navigation market on the Rhine river in Western-Europe. In particular, we investigate the effect of (anticipated) changes in transport cost on freight prices, in the context of imbalance. An increase in transport cost may for example be anticipated in Europe due to climate change, as low water levels will decrease the speed of freight transport, (see Jonkeren et al., 2007). Section 3.5 concludes.

3.2 Relationship with the literature

To understand the issues relevant to the backhaul literature, it is sufficient to focus on transport between two locations (one location with a high demand for transport and one with a low demand). Theories based on perfect competition with perfect information predict that above a minimum degree of imbalance in demand, the quantity transported from location L, with low demand for transport, is less than location H, with high demand for transport, and the price for transport from the low demand location to the high demand location, the so-called backhaul price, will drop to zero.[23] The latter result is intuitive because carriers are indifferent between returning with or without backhaul. This means that the cost of transport from one location to the other is fully borne by the high demand location's customers.[24] This cost is equal to the round trip cost of transport. The type of equilibrium where the quantities transported are not the same in both directions will be called throughout this chapter the *Imbalanced Equilibrium*.

Another equilibrium may arise, which we will call throughout this chapter the *Balanced Equilibrium*. The quantities transported then are exactly the same in both directions. According to the competitive model with perfect information, in this equilibrium the carriers' value of returning *with* backhaul exceeds the value of returning without backhaul and *all* carriers return with backhaul. Fronthaul prices will be higher than the backhaul price due to the difference in demand, but the backhaul price will be positive.

A priori, it is not clear whether the Balanced or the Imbalanced Equilibrium generally emerges. In case that the demand for transport is very elastic, the Balanced Equilibrium seems the most natural outcome, whereas if the demand for Imbalanced Equilibrium is very inelastic, the Imbalanced Equilibrium will be more common. Studies usually point out that the demand for transport is rather insensitive to the freight price (for a review on the inland shipping market see Jonkeren et al., 2007), which is consistent with the view that transport flows are imbalanced. Nevertheless, this does not imply that the Balanced Equilibrium does not occur. For example, Jonkeren et al. (2008) examine transport flows in Western-European inland shipping market and point out that certain submarkets seem quite balanced.

A summary of both types of equilibria for the competitive model with perfect information is given in Table 3.1. Subscript i denotes the market from where transport starts and can be equal to H, the high demand location, or, L, the low demand location. Q_i represents quantity transported from location i and p_i represents the price of transport from location i. In this setting, there is no third equilibrium where $Q_H > Q_L$, so some of the

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[23] This result is the classical result as featured in transport economics textbooks such as Boyer (1998).

[24] For convenience, transport-demanding customers are called customers in the text.

carriers return empty from location L, and, at the same time, $p_H \geq p_L > 0$. Thus, when transport flows are imbalanced, the competitive model rules out the possibility of a positive price in the low demand location. We will however argue that in a setting with imperfect information, backhaul prices will be positive even when transport flows are imbalanced.

Table 3.1: Summary of the two Equilibria for the competitive model with perfect information in a market with a high (H) and a low (L) demand location.

	Quantities Transported	Prices	Interpretation
Balanced Equilibrium	$Q_H = Q_L$	$p_H \geq p_L > 0$	
Imbalanced Equilibrium	$Q_H > Q_L$	$p_H \geq \boldsymbol{p_L} = \mathbf{0}$	Backhaul Problem

In the inland navigation market, Jonkeren et al. (2007) show that backhaul prices (from Germany to the Netherlands) are 76 per cent of the fronthaul prices although the quantity transported from the fronthaul location (the Netherlands) exceeds the quantity transported from the backhaul location (Germany) by at least 50 per cent (Statistics Netherlands, 2007).[25] Nevertheless, backhaul prices are far from close to zero. The same is observed for the trucking industry in the U.S.A., (see Felton, 1981).

It is also not difficult to give a wide range of anecdotal examples for the taxi market that describe the backhaul problem that depart from the predictions of the competitive model. In the Netherlands, cab drivers and customers are allowed to bargain about the price (up to a maximum), but in our experience, cab drivers never offer trips at even close to zero prices, even if the taxi will go anyway in the direction the customer wishes to go.[26]

The competitive model with perfect information assumes that customers and carriers possess complete information about each other's (future) location in the market. Customers and carriers find each other immediately. This implies the absence of market friction and of search time for carriers as well as for customers. In many competitive transport markets,

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[25] Plausibly, as argued above, the imbalance at the level of the carriers is substantially higher due to restrictions on the type of freight and variation in demand over time etc.

[26] One may also examine freight prices, which are publicly available, for numerical evidence. For example, in the maritime sector, the freight prices for 1 TEU container of plastic bags, from Shanghai to San Francisco is $\$ 2{,}065$, whereas the backhaul price is $\$ 1{,}111$. So the backhaul price is roughly 50 per cent less than the fronthaul price, but it is far from zero. These numbers are taken from www.freight-calculator.com in November, 2007. Note that in this example, insurance, additional fuel and handling costs are close to zero, so we may interpret the freight prices as prices net of insurance, additional fuel and handling costs. As is well known, the imbalance between merchandise goods flows between China and the U.S. is large (in value terms, the flow from China is 4 times that of the return flow (see WTO, 2005). Nevertheless the backhaul price for the return trip from the U.S. to China is considerable. However Sjostrom (2004) argues that the maritime market is not competitive due to collusion. Therefore the maritime market may not be a good example.

search time for customers is an obvious cost component, not only in the taxi market where taxis either cruise or passively wait for customers (see Arnott, 1996), but also in the inland shipping market (see Meelker, 2006). One might add exogenous search times in the standard competitive model in order to arrive at positive backhaul prices, but this does not do justice to the observation that search times are endogenous (see Arnott, 1996). In the matching model of a perfect competitive market with imperfect information that we will introduce in Section 3.3, we show that the endogenously determined carrier's expected search time is a possible cause for positive backhaul prices.[27] The model developed is also consistent with another stylised fact for the inland shipping as well as the taxi market. It has well been documented that many carriers regularly wait for new customers (see e.g. Meelker (2006) for the inland shipping market). In the current chapter we also aim to determine the waiting time endogenously, which is left unexplained in competitive models with perfect information. To model imperfect information we make use of a matching model.

Matching models are nowadays popular to analyse markets where agents are searching for each other and face a certain difficulty to find each other and form a match. This kind of models are now standard in the labour market economics literature (see e.g. Pissarides, 2000), but are also used in housing economics (see e.g. Wheaton, 1990). Examples of matching models applied to the taxi market, can be found in Lagos (1996) and Arnott (1996). The matching model is also well applicable in many freight transport markets, as carriers and customers search for each other and have difficulty to find each other. As argued above, this difficulty is due to a combination of spatial and time variation in demand and supply.

3.3 The matching model

3.3.1 The matching function

Suppose that a fixed number of identical risk-neutral customers with a demand for transport are located in locations H and L. We define the numbers of customers located at each side by N_i where $i = H, L$. We allow for a difference in demand between location H and location L. Hence, the number of customers in one location exceeds the number of customers in the other

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[27] Other reasons for positive backhaul prices may be found in additional fuel costs for transport with freight and waiting time due to loading up and unloading. These costs could be added exogenously to both the competitive and the matching model. However, we argue that these are not the only causes of positive backhaul prices and cannot explain the examples in the main text.

location. We choose (arbitrarily) location H to be the location with high demand for transport, and L to be the location with low demand for transport, so $N_H \geq N_L > 0$.[28] For convenience, other exogenous parameters are assumed to be identical for both locations.

Each customer aims to have one good transported by identical risk-neutral carriers to the opposite side. We assume that a customer withdraws from the market after it has found a carrier that is willing to move the good to the other side and is immediately replaced by a new customer, so the number of customers remains constant over time.[29] A carrier may at most move one good, so it is either full or empty.

We assume that customers and carriers have to search for each other due to imperfect information about each other. It is assumed that given search, customers and carriers contact each other according to a well-defined contact function. Carriers and customers are only able to contact each other when they are in the same location L or H.[30] The contact function in location i specifies then the number of contacts taking place in location i during a time period as a function of the number of searching carriers and customers in that location.

Given a contact, the customer and the carrier bargain about the freight price. If they agree on a price, which we later on show to occur with probability one, the customer and carrier are matched. Hence, the matching function is identical to the contact function. When a carrier and a customer are matched, the customer pays the carrier the agreed freight price, the cargo is loaded up and the carrier is obliged to move the good towards the other location.

In the current chapter, we focus on the steady state. We assume that moving is costly, as it takes time. At every moment in time, there are C_M carriers on their way moving *between* locations with or without freight. We denote C_{Si} as the number of searching carriers *at* location i. The total number of carriers in the market C is then equal to $C_M + C_{SH} + C_{SL}$.

In steady state the number of searching customers is constant in both endpoints. This implies that inflow must be equal to outflow in both endpoints. As the speed and distance is the same in both directions for carriers, in the steady state the number of carriers moving in both directions must be equal, so $C_M/2$ carriers move in every direction.

We define $u_i = C_{Si}/C$ as the number of carriers that search in location i relative to the total number of carriers and $v_i = N_i/C$ as the number of customers relative to the total

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[28] The case that $N_L = 0$ can be received upon request from the authors.

[29] This is an easy way of modelling freight demand without having to worry about the exact production process of the goods moved.

[30] We restrict the search technology in this way to avoid mathematical complexities, see e.g. Pissarides (1994). Even though this assumption about the contact function might be restrictive for some transport markets, it is unlikely to affect our main conclusions.

number of carriers.[31] Therefore $0 < u_i < 1$ and $0 < v_i < \infty$. We introduce the variable $\theta_i = v_i/u_i$, which can be interpreted as a measure of market tightness in i. It can be easily seen that θ_i equals N_i/C_{Si}, the number of customers divided by the number of searching carriers in location i.

The (continuous) contact function, denoted as m, defines the number of contacts between searching carriers C_{Si} and the number of customers, N_i, per (infinitely small) period. This function can therefore be written as $m(C_{Si}, N_i)$ and is assumed to be increasing in both arguments. The function is assumed to have a constant returns to scale property, such that $m(\omega\, C_{Si}, \omega\, N_i) = \omega\, m(C_{Si}, N_i)$, where $\omega > 0$.

We define q_i as the customers contact rate, so the rate at which a customer contacts a searching carrier in i. It follows that:

$$q_i = \frac{m_i}{N_i} = \frac{m(u_i C,\ v_i C)}{v_i C} = m\left(\frac{u_i}{v_i},\ 1\right) = m\left(\frac{1}{\theta_i},\ 1\right).$$

The above equation implies that q_i is a negative function of θ_i, whereas it can be shown that $\theta_i q_i$ is a positive function of θ_i (see e.g. Pissarides, 2000). Given θ_i and q_i, the carrier's contact rate at which a searching carrier contacts a customer is determined and defined by $\theta_i q_i$. Further, note that the assumptions imply that $\theta_i q_i$ and q_i are negatively related. Furthermore, we impose the standard restrictions on the limits of the contact function that if $q_i \to 0$ then $\theta_i q_i \to \infty$, and if $q_i \to \infty$ then $\theta_i q_i \to 0$. We emphasize that the contact rates, q_i and $\theta_i q_i$, are both endogenously determined.

3.3.2 Bellman equations

Carriers are in two possible states: they are either *searching at* a certain location i or *moving between* two locations (with or without freight). For further modeling purposes, a monetary asset value is assigned to be in one of these two states. We define S_i as the asset value of *searching* in i, and M_i as the asset value of moving from location i to location j. It is convenient to define M_i at the moment of departing from location i.[32] Note that M_i may be positive or negative. In the latter case, it is more convenient to interpret M_i as the monetary value of the *obligation* to move from location i to location j.

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[31] Note that 'u' may be interpreted as *unemployed* carriers, and 'v' may be interpreted as the number of customers with a *vacancy*.

[32] Note that the value of moving depends on where the carrier is *between* H and L. In the current model, we allow for this complication, but we need only to define the asset value *at the moment of departing from* H and L.

To derive the asset value of searching S_i, we define sc as the carriers' instantaneous search costs per unit of time, and p_i as the price received to move a good from location i to the opposite side. The discount rate is denoted as r per unit of time. The following Bellman equation defines then the value of S_i:

$$rS_i = -sc + \theta_i q_i (p_i + M_i - S_i). \qquad (3.1)$$

The interpretation of (3.1) is straightforward (see, similarly, Mortensen and Pissarides, 1999). The left-hand-side is the return of searching rS_i. The right-hand-side is equal to the cost of searching, $-sc$, plus the expected gain of finding a customer and moving the good to the other side, which is equal to $\theta_i q_i (p_i + M_i - S_i)$. So the expected gain is equal to the product of $\theta_i q_i$, the rate at which a carrier finds a customer, and $p_i + M_i - S_i$, which is the surplus a carrier gains from a match with the customer. The surplus of the match is equal to the received freight price p_i to the other location plus the asset value of moving M_i, minus the asset value of searching S_i.

The carriers' cost of moving the good is assumed to be independent of whether or not the carrier moves freight and is proportional to the time it takes to move the good. We define mc as the cost of moving per unit of time. The duration of the trip is stochastically determined. We assume that the average duration of a *round* trip is distributed with a mean equal to $1/\lambda$. So λ can be interpreted as the average speed at which a carrier moves between locations. As we have assumed that customers and carriers are risk neutral, all decisions made by carriers will *not* depend on other properties of the distribution than its mean. Hence, for convenience, we will assume that the duration of a round trip is *exponentially* distributed. In this case, the duration of a single trip is exponentially distributed with mean equal to $1/(2\lambda)$. Consequently, 2λ can also be interpreted as the rate of arriving at the other location.

Given these assumptions, the following equation defines the asset value of M_i:

$$rM_i = -mc + 2\lambda\left(max\left(S_j, M_j\right) - M_i\right), \qquad for\, j \neq i. \quad (3.2)$$

Equation (3.2) defines the return on the asset of moving, rM_i. It consists of the immediate cost of moving, $-mc$, plus the expected gain of arriving at the other location. This gain is equal to the rate of arriving at the other location, 2λ, multiplied with the net value of arriving at the other location j, defined by $max\left(S_j, M_j\right) - M_i$, where $j \neq i$. Note that this net value depends on the maximum value of two types of strategies in the other location (searching or moving) because carriers may choose then between *two strategies*: *searching for freight* or *moving without freight to the other location*.[33]

We will impose now one additional condition on the exogenous parameters. We will assume that $sc > r\, mc\, /(r + 2\lambda)$. This assumption is reasonable as r/λ is very small in practice and sc and mc are of the same order of magnitude.[34] This assumption essentially states that the carriers' search costs are not negligible, so imperfect information is an issue for carriers.

When a customer searches for a carrier to move its good, the customer attaches an asset value V_i to being this state, (which can also be interpreted as the value of being in this kind of market). When matching occurs, the customer receives immediately price J for the good, and pays the freight price p_i.[35] There is a per period cost of search κ to find a carrier.[36] The following Bellman equation defines then V_i:

$$rV_i = -\kappa + q_i\,(J - V_i - p_i). \qquad (3.3)$$

The customers' return on searching rV_i is thus equal to the search cost, $-\kappa$, plus the expected gain of finding a carrier $q_i(J - V_i - p_i)$. This expected gain is the rate q_i multiplied by the surplus $J - V_i - p_i$. This surplus is equal to the revenue J for selling the product minus the paid freight price p, and minus the loss of asset V_i, as the customer leaves the market. Solving for V_i gives $V_i = (q_i(J - p_i) - \kappa)/(r + q_i)$.

We assume free entry of carriers at no cost.[37] The number of carriers in the market, C, is therefore endogenously determined. To be able to study the backhaul problem, we let carriers make only round trips.[38] We assume, without loss of generality, that carriers may only enter and leave the market in the same location.[39] We assume that this is location H. Furthermore, it can be proven that our assumption that $N_H \geq N_L$ implies that $S_H \geq S_L$. See

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[33] In equilibrium, it can never be optimal for a carrier to search first and move to the other side after a while without freight. As market circumstances do not change in our model, moving to the other side without freight may only occur immediately after arriving.

[34] For example, for the numerical example on inland navigation later on, it seems reasonable to assume that r is 0.05 and λ is 50, so r/λ is equal to 0.001.

[35] Note that one may also assume that the customer receives J the moment that the good arrives at the other side. As travel durations are exogenous, this gives the same results.

[36] This cost may be interpreted as the combined cost of search and storage.

[37] This is done in order to model perfect competition. It is also a natural long-run assumption in the absence of sunk costs.

[38] The assumption of round trips is essential to the backhaul problem studied, see Rietveld and Roson (2002) and Boyer (1998), otherwise carriers would not incur round trip costs.

[39] This assumption is not restrictive, because entering/leaving the market is a long-run decision, based on the asset-value, so it is rather arbitrary whether the carrier enters or leaves the market in location H or L.

Appendix 3.A for a proof.[40] This means that entry and exit of carriers at location H will occur until $S_H = 0$ and $S_L \leq 0$.

We will impose now a restriction such that the market exists. We suppose that $J + \kappa/r$ exceeds $mc/(r+\lambda)$. This condition is intuitive. It simply states that the moving cost must be less than the benefits of having the good moved (which equals J plus the cost of search forever).

When the transport market exists (so goods are moved), a necessary implication is that either in location H *or* L the value of searching *strictly exceeds* the value of moving to the other side without freight (for a proof see Appendix 3.B). Hence, the possibility of moves without freight in both directions is excluded. By the free-entry condition $S_H = 0$ and $S_L \leq 0$, and using (3.2) it follows that $S_H > M_H$. One of the following two equilibria will then occur:[41]

the Imbalanced Equilibrium: $S_H > M_H$ and $S_L = M_L$
the Balanced Equilibrium: $S_H > M_H$ and $S_L > M_L$.

Both equilibria may arise. For example, in the extreme case that $N_H = N_L$, it appears that the Balanced Equilibrium will occur.[42] When $N_H > N_L$, one may have either the Balanced or Imbalanced Equilibrium. Intuitively, when N_H is close to N_L, the Balanced Equilibrium will occur, and when N_H is much greater than N_L, then the Imbalanced equilibrium will arise. As emphasized in the introduction, we are in particular interested in the Imbalanced Equilibrium.

Note that in both equilibria, S_H exceeds M_H, so all carriers in H search for freight (and never return empty to L). This means that the fraction of carriers that arrive in H and search for freight, denoted by z_H, is equal to one ($z_H = 1$). In the Imbalanced Equilibrium, carriers in L are indifferent between searching for freight or returning empty to H. Therefore a strictly positive fraction, denoted as $1 - z_L$ of carriers, will return empty from L to H. The variable z_L represents the fraction of carriers that arrive in L and search in L for freight. In the Balanced Equilibrium, $z_L = 1$ and $S_L > M_L$. In the Imbalanced Equilibrium, $0 < z_L < 1$ and $S_L = M_L$. Hence the following condition holds:

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[40] This proof relies on a number of additional assumptions (e.g. steady state, price formation) that are made explicit later on.

[41] Note that we have assumed that $N_L > 0$ (see 2.1). In the case that $N_L = 0$, then $S_L < M_L$ and an equilibrium with only one-way transport will arise. Note also that in the Imbalanced Equilibrium, the opposite situation where $S_H = M_H$ and $S_L > M_L$ cannot arise.

[42] This is easy to see, as due to symmetry, market outcomes in L must be the same as in H.

$$(z_L - 1)\,(S_L - M_L) = 0. \qquad (3.4)$$

We emphasize that it is the Imbalanced Equilibrium which is of main empirical interest, as in this equilibrium carriers can be said to have a ‘backhaul problem’.

3.3.3 Price determination in the long run

Given equations (3.1) to (3.4), and the free-entry assumption which implies that $S_H = 0$, we obtain, as shown in Appendix 3.C, the following two price equations:

$$p_H = \frac{sc}{\theta_H q_H} + \frac{mc}{r+2\lambda} - \frac{2\lambda}{r+2\lambda} S_L, \qquad (3.5)$$

$$p_L = \frac{sc}{\theta_L q_L} + \frac{mc}{r+2\lambda} + \frac{\theta_L q_L + r}{\theta_L q_L} S_L. \qquad (3.6)$$

Note that $sc/\theta_i q_i$ can be interpreted as expected search costs. Consequently, freight prices in both locations are equal to the sum of the expected search cost, the discounted one-way cost of moving the good and a term which is, when the discount rate r is small, approximately equal to $-S_L$ in the high demand location and equal to S_L in the low demand location. Recall that $S_L \leq 0$. Consequently, freight prices in the high demand location p_H exceed the prices in the low demand location p_L. Note that the exact value of S_L depends on the type of equilibrium. As in the Imbalanced Equilibrium some carriers choose to move empty from L to H, and some do wait and search for freight, carriers must be indifferent between the two, and since $S_H = 0$, $S_L = M_L = -mc/(r+2\lambda)$, whereas in the Balanced Equilibrium $S_L = M_L = -mc/(r+2\lambda)$ because all carriers prefer moving full instead of empty.

Interpretation of the above equations is facilitated by assuming that r/λ approaches zero. Note that r and λ are both strictly positive, so this assumption essentially implies that λ is much larger than r. Given this assumption, $p_L + p_H = \frac{sc}{\theta_L q_L} + \frac{sc}{\theta_H q_H} + \frac{mc}{\lambda}$. So the sum of the prices in H and L is equal to the sum of the round trip costs and the *carriers’* search costs.[43] Then, (3.5) and (3.6) imply that:

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[43] Clearly, when the interest rate approaches zero, carriers have no intrinsic preference for the present time relative to the future. So for each round trip the sum of the freight prices depends only on the sum of the costs, and not on specific components of costs.

$$p_H \leq \frac{sc}{\theta_H q_H} + \frac{mc}{\lambda} \qquad \text{and} \qquad p_L \geq \frac{sc}{\theta_L q_L} \tag{3.7}$$

where equality holds in the Imbalanced Equilibrium. Hence, in the Imbalanced Equilibrium, the price in the low demand location, the backhaul price, is a compensation for a carrier's *expected* search costs. Only when $\theta_L q_L$ approaches infinity, so the expected search time in the low demand location approaches zero, then $p_L = 0$. However, in Section 3.5, we will show that $\theta_L q_L$is finite, leading to Theorem 1, that says that backhaul prices p_L will always be strictly positive.

3.3.4 Steady-state equilibrium stocks and flows

In steady state, the outflow of carriers from a location equals the inflow of carriers into that location. Hence, at i, it must hold that $\theta_i q_i u_i = z_i \lambda \left(1 - u_i - u_j\right),\ for\ \ i \neq j$. We solve now for the number of searching carriers in both locations, $u_i\ (i = L, H)$, so:

$$u_i = \frac{\lambda\, z_i}{\theta_i q_i + \lambda \left(z_i + z_j \dfrac{\theta_i q_i}{\theta_j q_j}\right)} \qquad for\ \ j \neq i, \tag{3.8}$$

where $z_H = 1$ and $0 < z_L \leq 1$.

Hence, the number of searching carriers in i depends on the speed λ, and $\theta_i q_i$, which is the inverse of carriers' average search time in location i, the fraction of carriers that return with freight in i as well as j, z_i and z_j respectively, as well as the search time in i relative to the search time j. In the case that $\theta_i q_i$ approaches infinity (expected search time in i is zero), then u_i approaches zero. This is the situation assumed in the competitive model with perfect information.

3.3.5 Bargaining and conditions for positive backhaul prices

Given a contact, the carrier and the customer are assumed to negotiate a freight price p_i according to a Nash-bargaining rule (see Binmore et al. (1986))[44]. It is assumed that:

$$p_i = arg\ max\ (M_i - S_i + p_i)^{\beta} (J - V_i - p_i)^{1-\beta}, \tag{3.9}$$

where β measures the bargaining power of the carriers, and $1 - \beta$ measures the bargaining power of the customer ($0 < \beta < 1$). The first-order condition with respect to p_i is then

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[44] This bargaining rule has become standard in the labour market and housing market literature, see e.g. Wheaton (1990).

$$\beta(J - V_i - p_i) = (1-\beta)(M_i - S_i + p_i). \qquad (3.10)$$

Equations (3.1) and (3.3) imply that $J - V_i - p_i > 0$ and $M_i - S_i + p_i > 0$. Since customers and carriers are identical, it follows that every contact will result, after bargaining, in a match.

For the Imbalanced Equilibrium, we derive now the backhaul price from the low demand location, p_L. In the Imbalanced Equilibrium, $M_L = S_L$ holds. Using (3.3) and (3.10):

$$\beta\left(J - \frac{q_L(J - p_L) - \kappa}{r + q_L} - p_L\right) = (1-\beta)p_L \qquad (3.11)$$

Solving for p_L:

$$p_L = \frac{\beta(rJ + \kappa)}{r + (1-\beta)q_L} \qquad (3.12)$$

We are now able to formulate Theorem 3.1, which holds for both the Balanced and Imbalanced Equilibrium.

Theorem 3.1

In a matching model for a two-location market with frictions when there is a positive backhaul flow, the backhaul price p_L *will be strictly positive.*

For the Balanced Equilibrium, this result can be given without further proof, as in this Equilibrium $S_L > M_L$ holds, which implies that search in the low demand location, L, has a higher value than returning empty. This must be induced by a positive compensation for the waiting costs, which they receive as the strictly positive backhaul price ($p_L > 0$). For the Imbalanced Equilibrium, the proof of Theorem 3.1 is given in Appendix 3.D.

Similar to the competitive model with perfect information, we may now construct Table 3.2, which summarizes the main result of our matching model. It presents the quantities transported and the prices under the two equilibria for the matching model, where information is imperfect. The quantities transported follow from the definition of the two equilibria. For a formal proof that $p_H \geq p_L$ in both type of equilibria, see Appendix 3.D.

Table 3.2: Summary of the two types of equilibrium for the two-location matching model.

	Quantities Transported	Prices
Balanced Equilibrium	$Q_H = Q_L$	$p_H \geq p_L > 0$
Imbalanced Equilibrium	$Q_H > Q_L$	$p_H \geq \boldsymbol{p_L} > 0$

Throughout the chapter we have assumed a constant returns to scale matching function. This is essential for the intuitive results obtained above. Examples of the maybe non-intuitive result where $p_L > p_H > 0$ can be given for the Imbalanced Equilibrium when a nonconstant returns to scale matching function is assumed. We provide a numerical example in Appendix 3.E. Given the increasing returns to scale assumption of the matching function, the search times in the low demand location may exceed those in the high demand location such that the search costs in L exceed those of H, and so p_L may exceed p_H.

3.4 Numerical analysis

3.4.1 Calibration of the model

In order to perform a numerical analysis, we assume a functional form for the matching function m. We use a Cobb-Douglas function $m(x, y) = \phi\, x^{\alpha}\, y^{1-\alpha}$. Note that ϕ is a scale parameter of friction. This implies that

$$q_i = m\left(\frac{1}{\theta_i}, 1\right) = \phi\, \theta_i^{-\alpha} \qquad (3.13)$$

It has been established above that the prices depend on the expected search cost of carriers. In our model, these costs depend, among others, on the degree of search friction in the market, represented by ϕ, the value of the good J, the imbalance in demand between the two locations, represented by the number of customers N_H and N_L and on the speed λ. Numerical values for the exogenous parameters sc, mc, λ, κ, r and J have been chosen for the market of inland navigation carriers which predominantly move freight between the Netherlands and Germany on the Rhine River (see Jonkeren et al. (2007) and Table 3.3 for details).

The time period is taken as one year. The values of ϕ and α, which are difficult to observe, are obtained by calibrating the model using information on search times of customers and carriers both in H and L. ϕ is then set to 80 and α is set to 0.5. We will label the outcome of this model as the reference case.

Using the model of Section 3.3, the equilibrium outcome is given in Table 3.4 with a description given for every variable. As $S_L = M_L$, it can be seen that the Imbalanced Equilibrium arises.[45]

Table 3.3: Exogenous parameters

Parameter	*Value*	*Description*
sc	€150,000	Annual carriers' search cost
mc	€250,000	Annual carriers' cost of moving
λ	50	Annual trip speed measured in round trips per year. We assume a return trip duration of ca. 1 week
κ	€25,000	Annual customers' search cost
r	0.05	Annual interest rate
N_H	400	Number of customers located in H
N_L	100	Number of customers located in L
J	€100,000	Received price by a customer for the good that is moved
β	0.5	Bargaining power parameter
α	0.5	Parameter of Cobb-Douglas matching function
ϕ	80	Friction parameter

In line with the focus of this chapter, we see that the backhaul price p_L is positive. It is also substantial, as p_L is 14 per cent of p_H, even though 75 per cent of carriers return empty to H ($z_L = 0.25$). Positive backhaul prices are a consequence of positive search time, which is 2.04 days in L.

We have also examined a case where the friction parameter ϕ approaches infinity, so friction becomes essentially negligible and the competitive model with perfect information emerges. In line with the above model, backhaul prices drop to zero, and the fronthaul price equals the round trip costs.

In the next subsection, we present a case where we study a decrease in speed λ and compare this with the reference case.

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[45] In our model it appears that the Balanced Equilibrium only arises if N_H is extremely close to N_L.

3.4.2 Delays in transport

Due to climate change it is expected that the Rhine river will be blocked more often due to too high water levels in winter whereas capacity of transport will be reduced due to too low water levels in summer.[46] Both lead to a decrease in the speed of transport. This phenomenon has received considerable attention in the media, also when the impacts of climate change on the future of the transport sector were discussed. In the model developed above, the effects of a reduction in speed can be analysed by a decrease in λ. We decrease λ from 50 ('Normal Speed') to 40 ('Low Speed'), so speed falls by 20 per cent. It appears that the type of equilibrium (Imbalanced Equilibrium) does not change. The equilibrium outcome can be found in Table 3.5.

The results of a lower speed, captured by λ, implies, of course, a substantially longer expected moving time per trip and a higher move cost. It appears that both customers' and carriers' search times and number of matches are hardly affected however, so the increase in moving cost is borne entirely by customers in H, which pay higher freight prices. So, customers in the high demand location H will be negatively affected (V_H will decrease), while no such thing happens for customers in the low demand location. Note that p_L is hardly affected.

This has important implications for the West-European inland navigation market, which covers a large share of the overall freight market due to the presence of a number of well known rivers, such as the Rhine. In this market, the majority of goods are moved from the Netherlands (in particular, the sea harbor in Rotterdam) to industrial areas in Germany, whereas much less goods are moved from Germany to the Netherlands. Our results show that German firms importing goods from the Netherlands will be confronted with higher prices, whereas Dutch firms importing goods from Germany will hardly be affected. Hence, the welfare losses of changes in anticipated water levels will be borne almost entirely by the German firms importing goods from the Netherlands. This strongly suggests that, in this context, predominantly German firms will benefits of new infrastructure to improve navigation of the River Rhine.

The intuition for the result in the above example that a region with high demand for transport has to pay relatively more under climate change, can be given as follows. In the imbalanced equilibrium, which is more plausible empirically than the balanced equilibrium,

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[46] Jonkeren et al., (2007) study welfare losses for Western-Europe caused by the increased periods with low water-levels on a part of the Rhine river in recent years. They estimate a welfare loss of € 91 million for the year 2003.

all costs implied by navigating, whether full or empty, are carried by the region with high demand for transport (e.g. Germany). When costs of transport increase as a result of climate change, these costs will, as long as the equilibrium remains imbalanced, again be carried by regions with high demand for transport (German regions). Regions with a high demand for transport will therefore benefit relatively more from adaptation measures, like infrastructure investments, that reduce the effects of climate change.

Table 3.4: Equilibrium outcome for the reference case of the matching model

Variable	*Value*	*Description*
p_H	€ 5,830	Price from H to L
p_L	€ 837	Price from L to H
z_L	0.251	Fraction of arriving carriers that search in L
C	383.7	Total number of carriers
Carriers' search time in H	2.030 days	365.25 days / $\theta_H q_H$
Carriers' search time in L	2.040 days	365.25 days / $\theta_L q_L$
Customers' search time in H	10.27 days	365.25 days / q_H
Customers' search time in L	10.22 days	365.25 days / q_L
Number of matches per year in H (Q_H)	14,231	$\phi C_{SH}^{\alpha} N_H^{(1-\alpha)}$
Number of matches per year in L (Q_L)	3,574	$\phi C_{SL}^{\alpha} N_L^{(1-\alpha)}$
Single-trip moving time	3.653 days	365.25 days / (2λ)
Single-trip moving cost	€ 2,499	$mc/(r+\lambda)$
Carriers' search cost in H	€ 834	$sc/\ \theta_H q_H$
Carriers' search cost in L	€ 837	$sc/\ \theta_L q_L$
S_H	€ 0	Asset value of searching for a carrier in H
M_H	−€ 4,996	Asset value of moving for a carrier in H
S_L	−€ 2,499	Asset value of searching for a carrier in L
M_L	−€ 2,499	Asset value of moving for a carrier in L
V_H	€ 93,336	Asset value of searching for a customer in H
V_L	€ 98,326	Asset value of searching for a customer in L
q_H	35.6	Rate of finding a carrier for a customer in H
q_L	35.7	Rate of finding a carrier for a customer in L
θ_H	5.06	Market tightness
θ_L	5.01	Market tightness
u_H	0.206	Fraction of total carriers that search in H
u_L	0.052	Fraction of total carriers that search in L
v_H	1.04	Ratio of customers in H to total carriers

v_L	0.261	Ratio of customers in L to total carriers
C_{SH}	79.1	Number of carriers that search in H
C_{SL}	20.0	Number of carriers that search in L
C_M	284.6	Number of carriers that move

Table 3.5: Effects of variations in the round trip rate λ

Variable	*”Normal Speed”*	*” Low Speed”*
λ (exogenous)	50	40
p_H	€ 5,830	€ 7077
p_L	€ 837	€ 837
z_L	0.251	0.251
C	383.7	454.3
Carriers’ search time in H	2.030 days	2.028 days
Carriers’ search time in L	2.040 days	2.040 days
Customers’ search time in H	10.27 days	10.28 days
Customers’ search time in L	10.22 days	10.22 days
Number of matches per year in H	14,231	14,217
Number of matches per year in L	3,574	3,575
Single-trip moving time	3.653 days	4.566 days
Single-trip moving cost	€ 2,499	€ 3,123
Carriers’ search cost in H	€ 834	€ 833
Carriers’ search cost in L	€ 837	€ 837

3.5 Conclusion

A deeper understanding of freight transport requires an insight how freight prices emerge. A key element of freight transport is that the demand for transport is direction specific, which creates a ‘backhaul problem’. In this chapter we modeled the backhaul problem by means of a matching model in a two-location transport framework. We were motivated by observations that competitive models with perfect information do not adequately explain positive backhaul prices. In particular, according to the competitive model, backhaul freight prices drop to zero when the quantities transported between locations differ, so a proportion of the carriers return without freight from low demand locations. Imperfect information, which implies search, and therefore search and waiting costs may explain this phenomenon. It would however be ad-hoc to incorporate search costs exogenously in the competitive model with perfect information. Therefore we develop a model where search times and therefore search costs are determined endogenously. We demonstrate how search times vary with essential exogenous parameters, such as transport cost.

We presented a two-location transport model which allows us to study backhaul pricing under imperfect information. Similar to the competitive model with perfect information, it turned out that we have to distinguish between two types of equilibrium: the Balanced Equilibrium, so carriers transport freight in both directions and, the Imbalanced Equilibrium, so a positive fraction of carriers move without freight from the low demand location. The Imbalanced Equilibrium is the more interesting one from an empirical perspective. Indeed, given a wide range of numerical parameters, we end up in the Imbalanced Equilibrium.

In the Imbalanced Equilibrium, the round trip transport cost is fully borne by the customers in the high demand location. However, positive backhaul prices result due to carriers’ compensation for expected search time. Hence, we have addressed the above mentioned limitation of the competitive model with perfect information.

To offer more numerical insight in the presented model, we presented a numerical example. The chosen parameter set was taken such that it represents certain segments of the inland navigation market on the Rhine river in Western Europe. Furthermore, we studied, numerically, the effect of reduction in travel speed due to extreme water levels, e.g. as a result of climate change, leading to higher trip durations. This is especially relevant in the context of the inland navigation market between the Netherlands and Germany. Most goods in this market are transported from the Netherlands to Germany. An interesting finding was that the German firms importing goods from the Netherlands will predominantly pay for the increased costs of transport, whereas the Dutch firms importing goods from Germany will hardly pay for the increased costs. This strongly suggests that the benefits of improved infrastructure in order to prevent delays in transport will mainly benefit German firms.

We end with a few recommendations for further research. First it might be an improvement for this type of model to allow carriers to search for contact with customers while they are moving. Second, a more realistic production process for transport demanding customers could be modeled. Next, in Chapter 4, an empirical study of imbalance and freight prices is presented.

Appendix 3.A – Proof that if $N_H \geq N_L$ then $S_H \geq S_L$

In order to prove that given $N_H \geq N_L$ then $S_H \geq S_L$, we distinguish between the Balanced and the Imbalanced Equilibrium. For the Balanced Equilibrium, barges search at both location H and L, that is $z_H = z_L = 1$, and for the Imbalanced Equilibrium it appears that $S_L = M_L$, which means $z_H = 1$ and $z_L \leq 1$.

Showing that $S_H \geq S_L$ for the Imbalanced Equilibrium is straightforward. Note that in the Imbalanced Equilibrium one has that $S_L = M_L$ in the low demand region ($N_L < N_H$). Hence, using (3.1), (3.2), (3.3) and (3.10), one gets $S_L = -\frac{mc}{r+2\lambda} + \frac{2\lambda}{r+2\lambda} S_H$ and $S_L = -\frac{sc}{r} + \frac{\theta_L q_L \beta(rJ+\kappa)}{r(r+(1-\beta)q_L)}$, which implies that $S_H \geq S_L$ if $\frac{\theta_L q_L \beta(rJ+\kappa)}{r+(1-\beta)q_L} + mc > 0$. As the latter condition holds we can conclude that $N_H \geq N_L$implies $S_H \geq S_L$ for the Imbalanced Equilibrium.

Now we will give the proof for the Balanced Equilibrium. From the definitions of $\theta_i = v_i/u_i$, $u_i = C_{Si}/C$ and $v_i = N_i/C$, for $i = H, L$, and the observation that $N_H/v_H = N_L/v_L$ it follows that:

$$\frac{N_H}{\theta_{Hu_H}} = \frac{N_L}{\theta_{Lu_L}} \qquad (3A.1)$$

From the steady state conditions in Section 3.3.4 we have $\theta_i q_i u_i = z_i \lambda (1 - u_i - u_j), \mathit{for}\ \ i \neq j$. For the Balanced Equilibrium this becomes

$$\theta_H q_H u_H = \theta_L q_L u_L \qquad (3A.2)$$

Combining $(3A.1)$ and $(3A.2)$ for the Balanced Equilibrium we get $N_H q_H = N_L q_L$ which means that if $N_H \geq N_L$ then $q_L \geq q_{H,}$. Note that $\frac{\partial \theta_i q_i}{\partial q_i} < 0$ and $q_L \geq q_H$ imply that $\theta_H q_H \geq \theta_L q_L$ and $q_L \theta_H q_H \geq q_H \theta_L q_L$.

Combining equations (3.1), (3.2), (3.3) and (3.10), one gets $S_H - S_L = \frac{N}{D}$, where $N = \beta(r + 2\lambda)\big(r(\theta_H q_H - \theta_L q_L) + (1-\beta)(q_L \theta_H q_H - q_H \theta_L q_L)\big)\left((r + 2\lambda)\left(J + \frac{\kappa}{r}\right) + sc - mc\right)$ and $D = r\beta^2(r + 4\lambda)\theta_H q_H \theta_L q_L + (r + 2\lambda)^2(r^2 + (1-\beta)(q_H + q_L) + (1-\beta)^2 q_H q_L + \beta(1-\beta)(q_L \theta_H q_H + q_H \theta_L q_L) + r\beta(\theta_H q_H + \theta_L q_L))$. To prove that $S_H - S_L$ is nonnegative we observe that the denominator D is always positive. The numerator N is always nonnegative. This is established by showing that both $(r+2\lambda)\left(J+\frac{\kappa}{r}\right)+sc-mc$\and $r(\theta_H q_H-\theta_L q_L)+(1-\beta)(q_L\theta_H q_H-q_H\theta_L q_L)$ are nonnegative. The former is always nonnegative as we earlier imposed existence of the transport market by imposing $J+\frac{\kappa}{r}>\frac{mc}{r+2\lambda}$. The latter is nonnegative since $\theta_H q_H>\theta_L q_L$ and $q_L\theta_H q_H>q_H\theta_L q_L$ in the Balanced Equilibrium. Therefore for the Balanced Equilibrium $N_H\geq N_L$ implies $S_H\geq S_L$.

Appendix 3.B – Restrictions on asset values

We will prove that *either* $S_H > M_H$ *or* $S_L > M_L$ (but not both, so it is not true that $S_H \leq M_H$ *and* $S_L \leq M_L$.). This can be proven by contradiction. Suppose first that $S_H \leq M_H$ *and* $S_L \leq M_L$. Note that $S_H = 0$, which implies that $M_H \geq 0$. Equation (2) implies then that for $i = H, L$:

$$rM_i = -mc + 2\lambda (M_j - M_i), \qquad j \neq i, \qquad \text{(3B.1)}$$

which implies that $M_H = M_L = -mc/r < 0$. This is inconsistent with $M_H \geq 0$.
Hence, we have established that *either* $S_H > M_H$ *or* $S_L > M_L$.

Appendix 3.C – Derivation of Equations (3.5) and (3.6)

Independent of whether the type of equilibrium is Balanced or Imbalanced, $S_H > M_H$, $S_L \geq M_L$ and $S_H = 0$. The Bellman equations (3.1) and (3.2) for $i = L, H$ can then be written as:

$$0 = -sc + \theta_H q_H (M_H + p_H) \qquad \text{(3C.1)}$$

$$r M_H = -mc + 2\lambda (S_L - M_H) \qquad \text{(3C.2)}$$

$$r S_L = -sc + \theta_L q_L (M_L - S_L + p_L) \qquad \text{(3C.3)}$$

$$r M_L = -mc + 2\lambda (- M_L) \qquad \text{(3C.4)}$$

These four equations imply that:

$$p_H = \frac{sc}{\theta_H q_H} + \frac{mc}{r+2\lambda} - \frac{2\lambda}{r+2\lambda} S_L \qquad \text{(3C.5)}$$

$$p_L = \frac{sc}{\theta_L q_L} + \frac{mc}{r+2\lambda} + \frac{\theta_L q_L + r}{\theta_L q_L} S_L \qquad \text{(3C.6).}$$

Equations (3C.5) and (3C.6) correspond with equations (3.5) and (3.6) in the text respectively.

Appendix 3.D – Proof of Theorem 3.1 and that $p_H \geq p_L$

We first prove that $p_H \geq p_L$ for the Imbalanced Equilibrium. In this equilibrium we have $S_L = M_L = -\frac{mc}{r+2\lambda}$. Therefore (3.5) and (3.6) may be written as:

$$p_H = \frac{sc}{\theta_H q_H} + \frac{mc}{r+2\lambda}\left(1 + \frac{2\lambda}{r+2\lambda}\right) \qquad \text{(3D.1)}$$

$$p_L = \frac{sc - \frac{r\,mc}{r+2\lambda}}{\theta_L q_L} \qquad \text{(3D.2)}$$

Recall that our assumptions imply that the denominator of the right hand side of (3D.2) is positive. Thus (3D.1) and (3D.2) imply that p_i is decreasing in $\theta_i q_i$ ($i = H, L$) and $p_H > p_L$ for $\theta_H q_H = \theta_L q_L$. One may consider these two equations as the (inverse) 'demand' functions for $i = H, L$, which both describe how prices depend on the carriers' contact rate. We can also construct two corresponding upward-sloping 'supply' functions. From (3.15), we have:

$$p_L = \frac{\beta(rJ + \kappa)}{r + (1-\beta)q_L} \qquad \text{(3D.3)}$$

and from (3.3) combined with (3.10) we get

$$p_H = \frac{\beta(rJ+\kappa) + (S_H - M_H)(1-\beta)(r+q_H)}{r+(1-\beta)q_H} \qquad \text{(3D.4)}$$

We showed earlier that $\frac{\partial \theta_i q_i}{\partial q_i} < 0$. Therefore p_L is increasing in $\theta_L q_L$. It is also clear from (3D.3) and (3D.4) that $p_H \geq p_L$ for $q_H = q_L$ because $S_H > S_L$. Note that a value of q_i

corresponds uniquely with one value of $\theta_i q_i$. Given the result that $p_H > p_L$, in the downward sloping demand functions, and that $p_H \geq p_L$, the upward sloping supply functions, the equilibrium price p_H, at the intersection of (3D.1) and (3D.4), will be at least as high as equilibrium price p_L, at the intersection of (3D.2) and (3D.3). Therefore $p_H \geq p_L$ in the Imbalanced Equilibrium.

We can now prove Theorem 1 for the Imbalanced Equilibrium in the following way. Note that using (3D.2) we know that $p_L \to 0$ if $\theta_L q_L \to \infty$, whereas $p_L \to \infty$ if $\theta_L q_L \to 0$. Furthermore from (3D.3) we know that $p_L \to 0$ if $q_L \to \infty$ or $\theta_L q_L \to 0$, and that $p_L \to \beta(J + \kappa / r)$, if $q_L \to 0$ or $\theta_L q_L \to \infty$. This means that there must be an intersection between (3D.2) and (3D.3) for a positive (p_L, $\theta_L q_L$) combination. As p_H defined by (3D.1) has similar limit properties as p_L defined by (3D.2) and p_H defined by (3D.4) exceeds p_L defined by (3D.3) in (p_i, $\theta_i q_i$) space, one can conclude that there also exists an intersection between (3D.1) and (3D.4) for a strictly positive (p_H, $\theta_H q_H$) combination. Hence, we have proved Theorem 3.1.

Second, we prove that $p_H \geq p_L$ for the Balanced Equilibrium. From (3.5) and (3.6) we have

$$p_H = \frac{sc}{\theta_H q_H} + \frac{mc}{r + 2\lambda} - \frac{2\lambda}{r + 2\lambda} S_L, \tag{3D.5}$$

$$p_L = \frac{sc}{\theta_L q_L} + \frac{mc}{r + 2\lambda} + \frac{\theta_L q_L + r}{\theta_L q_L} S_L. \tag{3D.6}$$

Given the result that $S_H \geq S_L$ and $S_H = 0$ we have $S_L < 0$. Therefore $p_H > p_L$ for the same value of $\theta_i q_i$. These equations can again be considered as (inverse) ‘demand’ functions (although we do not say anything about monotonicity). The ‘supply’ curves can be obtained in the following way as above. From (3.3) and (3.10) we obtain:

$$p_L = \frac{\beta(rJ + \kappa) + (S_L - M_L)(1-\beta)(r + q_L)}{r + (1-\beta)q_L} \tag{3D.7}$$

$$p_H = \frac{\beta(rJ + \kappa) + (S_H - M_H)(1-\beta)(r + q_H)}{r + (1-\beta)q_H} \tag{3D.8}$$

We now establish that $p_H \geq p_L$ for the same value of q_i. From (3.2) we have $rM_H = — mc + 2\lambda (S_L — M_H)$, which gives

$$M_H = -\frac{mc}{r+2\lambda} + \frac{2\lambda}{r+2\lambda} S_L .$$

This makes $S_L - M_L = \frac{mc}{r+2\lambda} + S_L$ and, due to $S_H = 0$, $S_H - M_H = \frac{mc}{r+2\lambda} - \frac{2\lambda}{r+2\lambda} S_L$. Since $S_L < 0$ we have $S_H - M_H > S_L - M_L$. Therefore $p_H \geq p_L$ for the same value of q_i.

As every value of q_i implies a unique value for $\theta_i q_i$, $p_H \geq p_L$ holds also for the same value of $\theta_i q_i$. We again have that $p_H \geq p_L$ for both the ‘demand’ and the ‘supply’ functions. Therefore the equilibrium price p_H, at the intersection of (3D.5) and (3D.8), will be higher than the equilibrium price p_L, at the intersection of (3D.6) and (3D.7). Therefore $p_H \geq p_L$ holds also for the Balanced Equilibrium.

Appendix 3.E – Example where $p_L > p_H$ given increasing returns to scale

In this appendix we present an example where $p_L > p_H$ for the case of an *increasing* returns to scale matching function under the presence of an Imbalanced Equilibrium (note that throughout this chapter we assume constant returns to scale). We take the same values for the exogenous parameters as in Table 3.3, except $\lambda = 3000$ instead of $\lambda = 50$ and set the Cobb-Douglas parameters of the matching function equal to 0.6 (increasing returns to scale) instead of 0.5 (constant returns to scale). This is an example where speed is extremely high, or equivalently the transport distance is low relative to the search time. In our numerical example, it means that a single trip takes only 1.5 hours, so the cost of a roundtrip plays a less important role than the search time for a customer. The outcome is an Imbalanced Equilibrium for which some of the most interesting variables can be found in Table 3E.1. The increasing returns to scale property of the matching function is the most probable reason for the search time to be so different between *H* and *L* which, in combination with low roundtrip costs, leads to $p_L > p_H$. When we would assume constant returns to scale, however, $p_H > p_L$ would be obtained.

Table 3E.1: Equilibrium outcome for an example where $p_L > p_H$; increasing returns to scale matching function

Matching Function $m(x,y)=\phi x^{\gamma} y^{\delta}$	*Constant Returns to Scale* $\gamma=\delta=0.5$	*Increasing Returns to Scale* $\gamma=\delta=0.6$
Speed	λ*=50*	λ*=3000*
p_H	€ 5,785	€ 380
p_L	€ 1,044	€ 392
z_L	0.190	0.189
C	399.9	113.3
Carriers' search time in *H*	1.92 days	0.72 days
Carriers' search time in *L*	2.54 days	0.95 days
Customers' search time in *H*	9.71 days	3.62 days
Customers' search time in *L*	12.75 days	4.78 days
Single-trip moving time	3.653 days	0.061days
Single-trip moving cost	€ 2,499	€ 42
Carriers' search cost in *H*	€ 789	€ 297
Carriers' search cost in *L*	€ 1,044	€ 392

CHAPTER 4

ENDOGENOUS FREIGHT PRICES AND TRADE IMBALANCES[47]

4.1 Introduction

In this chapter we study the effect of imbalance on freight prices by means of empirical evidence. Similar to Chapter 2, low water levels reduce capacities, and are taken up as an explanatory variable in the estimation of freight prices. This chapter adds an empirical dimension to the theoretical layout on imbalance and freight prices in Chapter 3.

Transport costs play a fundamental role in the determination of the location of regional economic activities (see, e.g., Krugman, 1991, 1998; Ottaviano and Puga, 1998; Neary, 2001). A characteristic assumption in these studies is that transport costs are exogenous. However, recently, a number of studies have emphasized that transport costs are *endogenous*. In particular, we refer to the recent studies by Behrens and co-authors (Behrens and Gaigné, 2006; Behrens et al., 2006; Behrens et al., 2009). For example, Behrens et al. (2006) introduced the presence of density economies into a new economic geography model by assuming that unit shipping costs decrease with the aggregate volume of trade. Endogeneity of transport costs is clearly also important for studies on international trade. For example, Anderson and van Wincoop (2004) stress the need to deal with this issue in studies on trade. Note that, although transport costs, i.e. the physical costs of a shipment, are only a share of trade costs, (Duranton and Storper, 2008), transport costs are generally thought to be the most important trade cost *within* countries and one of the most important components of trade costs *between* countries. This certainly applies to trade within the EU where artificial trade barriers are absent or limited. According to Sánchez et al. (2003) and Limão and Venables (2001), artificial trade barriers are reduced to low levels as a result of trade liberalization. Therefore, it is plausible that the relative importance of transport costs in total trade costs has increased in recent decades.

There are a number of reasons why transport costs are endogenous (for recent studies which discuss this issue, see Duranton and Storper, 2008, and Anderson, 2008). One reason is

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[47] Chapter 4 is based on Jonkeren et al. (2010) Endogenous Transport Prices and Trade Imbalances, Journal of Economic Geography, forthcoming.

that the unit shipping costs decrease with the volume of trade due to the presence of density economies (e.g. Behrens et al., 2006). Another reason is that industry location is endogenous (see, Behrens et al., 2009). The current article addresses another aspect i.e., that the endogeneity of transport costs results from an imbalance in terms of trade volumes between two regions (Behrens and Picard, 2008; Boyer, 1998). This causes the freight price in one direction to exceed the price in the opposite direction when *a positive proportion of carriers are required to return without paid cargo*.[48] One of the implications of the imbalance is that, ceteris paribus, unit shipping costs increase with trade. It is therefore theoretically ambiguous what the net effect is of a change in the traded volume on trade costs as it depends on what type of effect dominates, density economies or imbalance. In one market, the net effect may be negative while for other markets it may be positive.

The effect of imbalance on freight prices may potentially be very large. For example, the freight price for a 1 TEU (twenty-foot equivalent unit) container of plastic bags from Shanghai to San Francisco is currently $ 2,065, whereas its backhaul price is $ 1,111. So the backhaul price is roughly 50 per cent less than the fronthaul price (this kind of information is publicly available on freight price websites such as www.freight-calculator.com). Likely, the main explanation for this observation is that the merchandise goods flow from China to the U.S. is much larger than the other way around (in value terms, the flow from China is 4 times that of the return flow).

In the current study, we focus on price formation in a spatial inland waterway transport network for predominantly dry bulk cargo. This market is highly competitive with thousands of small carriers (see Table 4.1), the majority of those carriers being one-ship enterprises. In addition, the carriers offer a relatively homogenous product (transport of different types of bulk cargo) and shippers may easily switch from one inland waterway carrier to another. In the inland waterway sector, imbalances in transport flows are frequently observed. Imbalances are caused by regional differences in demand for transport. For example, in Europe, most seaports, such as Rotterdam (in the Netherlands) and Antwerp (in Belgium), receive more cargo (iron ore, coal, etc.) from overseas locations than they dispatch to these locations. This implies that more cargo is transported from the seaport regions to the hinterland regions than in the opposite direction, which causes an imbalance in inland shipping trade flows.

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[48] For an early discussion of this phenomenon, usually called the “backhaul problem”, see Pigou (1913).

Table 4.1: Number of registered barges per Rhine-country per segment on 31/12/2006

	Netherlands	Germany	France	Belgium	Switzerland	Luxemburg	Total
Dry cargo	3828	1803	1316	1272	20	13	8252
Tanker	767	422	77	223	37	18	1544
Total fleet	4595	2225	1393	1495	57	31	9786

Source: CCNR and European Commission, 2007.

This is not the first empirical study to focus on freight prices. There is an extensive literature, mainly focusing on maritime transport, in which the determinants of freight prices are analysed, but imbalances in transport flows are usually ignored. We are aware of four studies in which the effect of an imbalance in transport flows on maritime shipping prices has been examined empirically (Blonigen and Wilson, 2008; Wilmsmeier et al., 2006; Márquez-Ramos et al., 2005; Clark et al., 2004). However, in these studies, imbalance is assumed to be exogenous, which is at odds with theory (note that Clark et al. (2004) and Márquez-Ramos et al. (2005) allow for density economies by including aggregate trade volume as an explanatory variable and treat trade volume as an endogenous variable).

We estimate the marginal effect of an imbalance in transport flows on the unit freight price of trips in the inland waterway transport market in North West Europe. We mention some major differences between the current study and the four freight price studies mentioned above. First, these studies use information on imbalances of bilateral routes, while we also take into account characteristics of the network using a spatially-weighted regional imbalance measure, in line with other economic applications of spatial problems (see, for example, Boarnet, 1994a, 1994b; Rice et al. 2006). Spatial weighting implies that we take the imbalances in other (particularly adjacent) regions into account when determining the imbalance for a specific region. Second, to our knowledge, we are the first to consider imbalance as an endogenous variable, using the presence of sea-ports as instruments. Third, we empirically capture density economies in a different, and arguably more fundamental, way than Clark et al. (2004) and Márquez-Ramos et al. (2005). Using a broad definition of density economies such as used by Brueckner et al. (1992), density economies arise because a higher traffic density on a route allows the carrier to use larger vessels and to operate this equipment more intensively (at higher load factors). In addition, higher traffic densities on a route allow for a more intensive and efficient use of the port facilities that serve that route implying lower time costs per unit handled. As we have a very rich data set, we are able to capture density economies by means of three trip-specific control variables: vessel size, load factor and travel time. The travel time of a trip includes the time of loading, transporting, and unloading the cargo.[49] Fourth, our study concerns inland waterway transport, which comes close to the ‘ideal’ standard perfect competitive market, while previous studies focus on the maritime transport sector, where market power of carriers is potentially an important issue as argued by some studies (Sjostrom, 2004).

The importance of inland waterway transport as part of the overall transport sector for the regional economy is determined by geographical constraints. Only in those regions where the natural infrastructure offers sufficient opportunities does inland waterway transport play a significant role in inland transport. Examples of such regions include parts of Europe (the rivers Rhine, Danube, and their tributaries), the US (the Great Lakes area and the Mississippi river) and China (the Yangtze and the Pearl River).

The river Rhine is the most important trade river in Europe as it connects large economically important areas within and between the Netherlands and Germany. The Netherlands and Germany are neighbouring countries and trade between these countries is intensive. In 2005, Germany was the most important export country for the Netherlands, and the Netherlands was the fifth export country for Germany.

The river Rhine has its source in Switzerland in the Alps and runs through the Ruhr area, one of the most industrialized areas in Germany, to Rotterdam, in the Netherlands, one of the world’s major seaports, where it flows into the North Sea. In the Rhine corridor, inland waterway transport competes heavily with road and rail transport. In general, inland waterway transport is cheaper (per tonne-kilometer), but slower than the other modes. In 2005, 58 percent of all bilateral inland trade, measured in tonnes, from the Netherlands to Germany, was transported by inland waterways. In the opposite direction, inland waterway transport accounted for 41 percent (CBS, 2008; TLN, 2007).[50] Hence, trade costs between the Netherlands and Germany strongly depend on inland waterway freight prices. So, an understanding of price formation in the inland waterway transport market is fundamental to understand the endogeneity of trade costs between the Netherlands and Germany. Next, Section 4.2 describes the data and formulates the empirical model. Section 4.3 presents the results, and, finally Section 4.4 makes some concluding remarks.

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[49] Large ports (which usually have more efficient handling facilities), may induce relatively short (un)loading times, leading to shorter travel times. On the other hand, higher volumes may imply density diseconomies in case of congestion.

[50] In 2005 in total, 127 million tonnes were transported from the Netherlands to Germany, and 73 million tonnes the other way around implying an imbalance ratio of 0.57. For inland waterway transport this ratio is 0.41. For the survey data used in the current article, we find a ratio of 0.49, indicating that our data is quite representative.

4.2 Methodology and data

4.2.1 Methodology

Our aim is to estimate the effect of an imbalance in transport flows on the freight price. In a multi-region network, one may measure imbalance for a trip between two regions at the level of the *route* (for example, for each route one can calculate the ratio of the cargo flow in one direction and the cargo flow in the other direction) or at the level of the *region* (for example, for each region one can calculate the ratio of the export and import cargo flows). In this chapter, we will measure imbalance at both levels.

At the *route level*, imbalance is measured bilaterally, so on every route the imbalance is measured by the ratio of the cargo flow in one direction and the cargo flow in the opposite direction. Hence:

$$M_{ij} = T_{ij}/T_{ji}, \tag{4.1}$$

where M_{ij} is the *route imbalance* for a trip from region i to region j; T_{ij} is the number of trips *with cargo* from i to j and T_{ji} is the number of trips *with cargo* from j to i. In our application, we will use the logarithm of M_{ij}.

In a multi-region network, carriers may not move back and forth between two regions but will make more complicated journeys as they cruise through the network for shipments (we have examined this for a randomly-selected sample of carriers in our data; it appears that only 1 out of 50 carriers immediately travels back to the region of origin). Measuring imbalance at the level of *routes* will then not adequately capture the effect of an imbalance in transport flows on freight prices. It is straightforward to give relevant examples.

An illuminating example is when carriers transport goods from A to B, but a positive proportion of these carriers move from B to C (possibly without cargo), and then transport cargo from C to A. In this example, the freight price from A to B depends not only on the demand for transport from A to B, and from B to A, but also on the demand characteristics of the B to C and C to A routes.[51] Measuring imbalance at the level of routes implies that only the demand for transport from A to B, as well as the demand for transport from B to A, is

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[51] Another example is to presume that there exists demand for transport from region B to C (but not from C to A). The freight price from A to B then depends not only positively on the demand for transport from A to B and negatively on the demand for transport from B to A, but also negatively on the demand for transport from region B to C.

incorporated in the measure in order to explain the freight price for the A to B trip. It follows that an empirical analysis of the effect of an imbalance in transport flows on freight prices in multi-region networks which only includes measures of route imbalance is likely to underestimate the importance of the effect of an imbalance in transport flows on freight prices, because the route imbalance does not adequately capture imbalance at the network level. In other words, if the difference between the route imbalance and the theoretically appropriate imbalance variable is random error, then the estimated effect is biased towards zero, see Verbeek, 2000, p. 120. This implies that it is important to measure imbalance taking network characteristics into account.

In a multi-region network, there does not exist one generally accepted imbalance measure, as this measure requires complete information about the demand functions of all routes, which is not available. We will improve on the route imbalance variable by introducing a measure that takes into account how close regions are located to each other. This measure will be called the region imbalance variable – as opposed to the route imbalance concept - and is defined as the ratio of the export and import cargo flows in a region. To take the geographical relationship between regions into account, we construct a spatially-weighted region imbalance variable, I_i, which is defined as follows:

$$I_i = \frac{\sum_j w_{ij} O_j}{\sum_j w_{ij} D_j} , \qquad (4.2)$$

where O_j is the number of trips *with cargo* departing from region j; D_j is the number of trips *with cargo* arriving in region j; and w_{ij} is a weighting factor.[52] The principle of weighting is used in many spatial applications (see Boarnet, 1994a, 1994b; Rice et al. 2006). One may define w_{ij} in several ways. For example, if $w_{ii} = 1$ and $w_{ij} = 0$ for $i \neq j$ then regions other than i do not play a role in the determination of the imbalance in region i, so in this case $I_i = O_i/D_i$. In our empirical specification, we define w_{ij} as follows:

$$w_{ij} = \frac{F(d_{ij})}{\sum_j F(d_{ij})}, \quad \text{so that} \quad \sum_j w_{ij} = 1 \text{ for all } i. \qquad (4.3)$$

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[52] An alternative way of measurement of I_i is to measure O_j and D_j in terms of the amount of cargo (in tonnes) instead of the number of trips with cargo. Because the correlation between the region imbalance variable measured in number of trips with cargo and the same variable measured in tonnes is close to one (0.98), it appears that the results are insensitive in this respect.

We will use $F(d_{ij}) = e^{-\gamma d_{ij}}$, so F can be interpreted as an exponential-decay factor, d_{ij} is the distance between regions *i* and *j* and γ is a decay parameter.[53] One difficulty is how to obtain a value for γ. In our application, we will not arbitrarily fix γ as is often done in empirical studies. Instead, the parameter γ will be estimated using information about the distance navigated *without* cargo by inland waterway carriers before starting a new trip with cargo. The weight w_{ij} may thus be interpreted as an inverse indicator of economic distance: the shorter the distance between two regions, the higher the probability that trips without cargo will be made to collect cargo from a neighbouring region. We will now give an – admittedly simple - example for which holds that the weighted region imbalance variable, I_i, is more appropriate than the route imbalance variable. We will suppose there are only three regions, A, B and C.

Suppose there is demand for transport between regions A and B as well as between A and C, but not between B and C. Suppose further that the distance between regions B and C is negligible and the distances between A and B and A and C are so large, that carriers would hardly make an empty trip from B to A (or C tot A) to pick-up cargo.[54] Because regions B and C are close to each other, we have essentially a two-region network so the appropriate measure of imbalance for regions B and C is the ratio of the sum of the departing cargo from B and C to the sum of the arriving cargo in B and C (Boyer, 1998). Using the weights for regions A, B and C, the region imbalance indicator I_i as defined in (4.2) exactly measures the imbalance in the correct way whereas the route imbalance variable M_{ij} as defined in (4.1) does not (as it ignores that B and C are essentially one region). We emphasize that this does not prove that the region imbalance measure is superior to the route imbalance measure for all possible network configurations but in the present configuration it certainly is.

In networks with more than two regions, freight prices are expected to depend positively on the imbalance in the region of *origin*, as well as negatively on the imbalance in the region of *destination*. So, we will use *two* indicators of region imbalance (only in a two-region network, there is no distinction between measuring at the level of the region or at the level of the route). We aim to estimate the effect of the imbalance in the “origin region”, denoted as I_i and the imbalance in the “destination region”, denoted as I_j on the freight price.

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[53] The use of the distance-decay principle is widespread in network modelling. For example, Hojman and Szeidl (2008) introduce a model of network formation in which benefits from connections decay with distance.

[54] In this case the weights are determined as follows: $w_{BB} = w_{CC} = w_{BC} = w_{CB} = 0.5$, $w_{AB} = w_{BA} = w_{AC} = w_{CA} = 0$ and $w_{AA} = 1$.

Later on, we will show in the empirical application that these two imbalance variables have about opposite effects. Therefore, we will use a more parsimonious measure of the imbalance for the pair of regions i and j, I_{ij}, which we will call the "region imbalance difference", and which is defined by the ratio of the imbalance in the origin region and the imbalance in the destination region:

$$I_{ij} = I_i / I_j \tag{4.4}$$

The use of I_{ij} in the price equation implies that the effects of I_i and I_{ij} are assumed to be identical and that the effect of I_j is inversely proportional to that of I_i.

4.2.2 Data

We employ a data set, the Vaart!Vrachtindicator, which contains detailed information about trips made by inland waterway carriers in North West Europe (more information can be found on the website www.vaart.nl, as well as in Jonkeren et al., 2007). The carriers report information (via the Internet) about their trips, such as the freight price, region and date of (un)loading, capacity of the ship, number of tonnes transported, type of cargo, etc. We distinguish between trips from and towards 15 regions, using a classification as reported by the carriers (see Figure 4.1). Information on the region imbalance values for the 15 regions can be found in Appendix 4.A.

The data set contains information on inland waterway transport trips that occur in the spot market where the freight price is negotiated per trip. In our application we use the logarithm of the price per tonne. Inland waterway transport enterprises that operate in the long-term market (and work under contract) are not included in the data set. The data cover therefore only a limited part of the whole inland waterway transport market, but, descriptives of our imbalance variable calculated for the Netherlands and Germany are consistent with publicly available data. This suggests that the sample is representative in terms of imbalance variables.

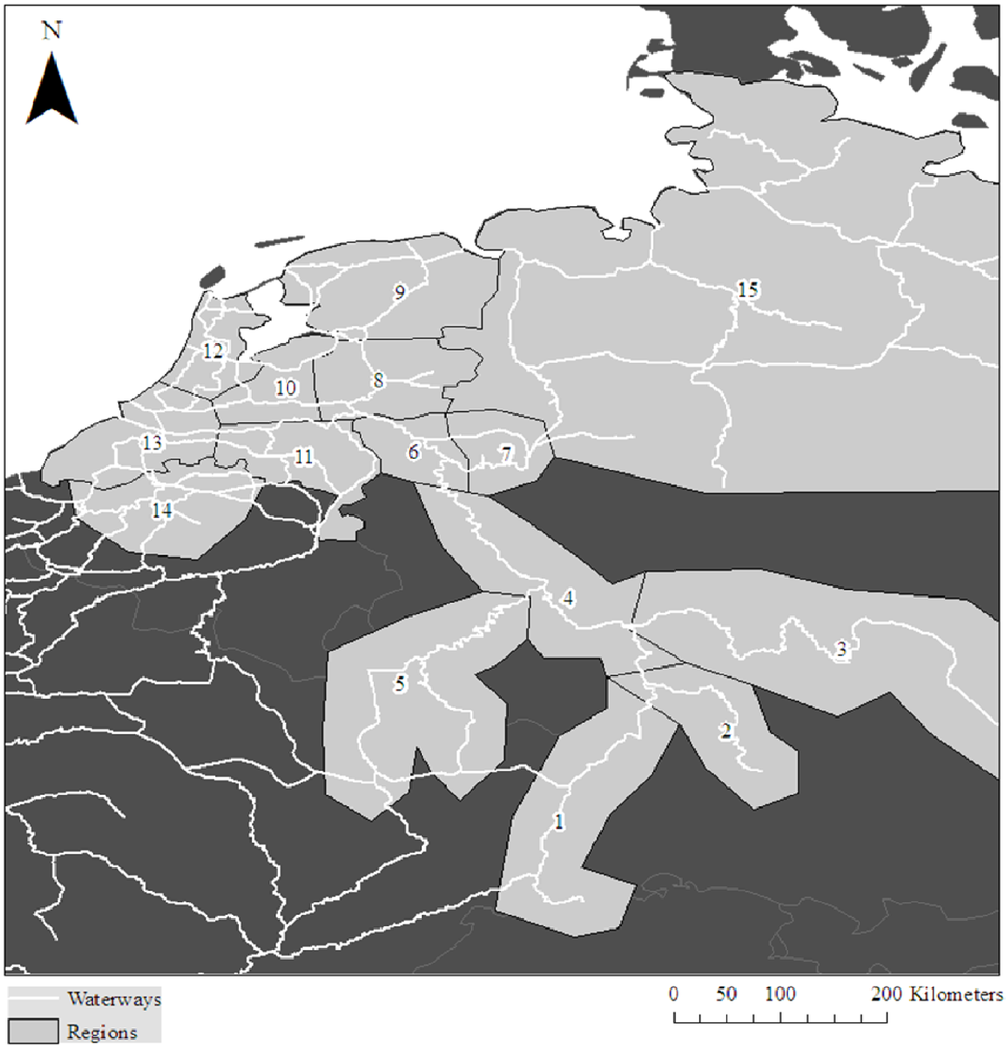

Figure 4.1: Regions in the inland waterway transport market in North West Europe
Note: 1 Upper Rhine, 2 Neckar, 3 Main/ Danube, 4 Middle Rhine, 5 Moselle/ Saar, 6 Ruhr, 7 West German Canals, 8 Netherlands East, 9 Netherlands North, 10 Netherlands Centre, 11 Netherlands South, 12 Amsterdam Port Area, 13 Rotterdam Port Area, 14 Antwerp Port Area, 15 North German Canals.

The database contains 21,865 observations of inland waterway trips in North West Europe, reported between January 2003 and January 2007. For about 6,000 trips information on the stream direction, which we will use as control variable, is difficult to determine. Therefore, these trips are excluded from the analysis. Appendix 4.B offers the same descriptives as in Table 4.2, but now including the mentioned 6,000 trips. With these extra trips we are able to distinguish between 20 regions instead of 15 regions. The descriptives in Appendix 4.B and the analysis based on 20 regions (which generates similar results and can be received upon request) show that our sample is not selective. Observations with missing information, a few extreme outliers, and observations that concern container transport were also excluded. We exclude observations referring to container transport because the price for container transport is expressed as the freight price per container instead of the freight price per tonne. Further, we excluded a limited number of observations for which the measurement of the route imbalance is unreliable as M_{ij} may contain substantial measurement error if the number of trips between two regions is small.[55] Ultimately, 10,794 observations (of which 10,324 trips concern transport of dry bulk and 470 trips refer to wet bulk) are used for multivariate analysis.

Table 4.2: Descriptives of key variables of transports flows and trip data

Variable	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
M_{ij} (route imbalance)	0.27	100.00	7.32	14.92
log(M_{ij})	-1.32	4.61	1.14	1.23
I_{ij} (region imbalance difference)	0.45	2.76	1.64	0.71
log(I_{ij})	-0.81	1.02	0.37	0.56
I_i (region imbalance, origin)	0.74	1.81	1.44	0.39
log(I_i)	-0.30	0.59	0.32	0.31
I_j (region imbalance, destination)	0.66	1.81	1.00	0.34
log(I_j)	-0.42	0.59	-0.05	0.30
Price per tonne (in €)	1.45	54.55	8.13	5.37
Travel time (in days)	1.00	30.00	5.25	2.27
Distance trip (in km)	97.00	4000.00	569	271
Distance navigated without cargo (in km)	0.00	908.00	95.15	97.03

Source: The Vaart!Vrachtindicator (2003 – 2007).

The descriptives of key variables used in the analysis are shown in Table 4.2. The average trip (including loading and unloading time) takes about five days. The average freight price per tonne transported is € 8.13.

To calculate the region imbalance variable, we need information about the decay parameter γ. This parameter has been estimated on basis of the carriers' distribution of distances navigated without cargo before starting a trip (see Appendix 4.C). To estimate γ in this way is useful because after a carrier has been unloaded, carriers frequently travel *without cargo* to another region from where the next trip with cargo starts. In one out of three trips, carriers navigate more than 100 kilometres without cargo before starting a new trip. In one out of nine trips, carriers navigate even more than 200 kilometres without cargo. The average distance navigated without cargo is about 95 kilometres, which is substantial compared with

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[55] For the selected sample, the number of trips between two regions exceeds 96 for all routes, so this is not an issue in the current application.

the average distance navigated with cargo which is 569 kilometres (see Table 4.2). The estimated value of the parameter γ related to the exponential distribution of distances without cargo equals 0.011 (see Appendix 4.C).

As an illustration of the effects we aim to capture, it may be useful to focus on freight prices in one specific region. Freight prices for trips originating from the Rotterdam port area are 32 percent higher than prices for trips arriving here, whereas the (weighted) number of trips with cargo departing from the port of Rotterdam is about two times higher than the (weighted) number of trips with cargo arriving in the port of Rotterdam (see Appendix 4.A). Although only suggestive, it seems that the effect of imbalance on freight prices may be substantial.

Our main focus is now to examine the effect of the route and region imbalance difference - M_{ij} and I_{ij} - on freight prices.[56] In addition to the two imbalance measures mentioned above, we include a large number of control variables in the price equation to be estimated:

$$\log\left(Y_{rijt}\right) = \beta_1 \log\left(M_{ij}\right) + \beta_2 \log\left(I_{ij}\right) + \beta_3 X_{rijt} + \varepsilon_{rijt} \qquad (4.5)$$

where Y_{rijt} denotes the freight price per tonne for trip *r* from region *i* to region j at time *t*, M_{ij} is the route imbalance for a trip between regions *i* and j, I_{ij} is the region imbalance difference for a trip between regions i and j, X_{rijt} refers to observed explanatory variables of the trip, ε_{rijt} denotes unobserved random error and β's are coefficients to be estimated.

The control variables in X_{rijt} include: a time trend, travel time[57] and distance, both in logarithms; ship size (categorized by 5 dummy variables); 47 bulk cargo dummies (e.g. coal, gravel, fertilizer, wheat, corn, soya), the fuel price in logarithm and the load factor, defined as the ratio of the tonnes transported and the capacity of the inland vessel, also in logarithm. Furthermore, we include water level as an explanatory variable by means of 9 dummies. As shown by Jonkeren et al. (2007), water levels have strong effects on prices, as low water levels impose restrictions on the load factors of inland waterway vessels. Water level is measured at Kaub (a town in Germany at the East bank of the river Rhine) because Kaub is the critical bottleneck in terms of the load factor for trips that take place in the river Rhine

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[56] To identify the effect of an imbalance in transport flows on freight prices, we do *not* exploit any time-variation in regional imbalances, because much of the time-variation observed in the imbalance variables is due to measurement error, which induces a strong measurement error bias.

[57] For 76 percent of the observations we have the trip-specific travel time. For the other observations this variable is not reported, so we use the region-to-region specific average travel time. This introduces some measurement error in this variable.

basin. As not all trips pass Kaub, we make a distinction between the effect of the water level for trips that pass Kaub and that for trips that do not pass Kaub. The costs of navigation may depend on the navigation direction as downstream navigation requires less fuel than upstream navigation. We distinguish between five different navigation directions. Finally, we include a dummy variable for each month (11 dummies) to control for unobserved monthly changes in supply and demand factors. A discussion of the results of our analysis will be presented in Section 4.3.

4.3 Results

4.3.1 The effect of imbalance on the freight price

Equation (4.5) has been estimated using ordinary least squares, as well as using instrumental variables. As the imbalance variables are aggregate measures, we allow for clustering on the basis of the region of destination. This prevents the standard errors to be biased downward (Moulton, 1990).[58] Clustering on the basis of region of origin or on the basis of routes generates almost identical results. However, clustering on the basis of the region of destination is the more conservative procedure, in the sense that the standard errors are larger, so we opt to report this way of clustering.

OLS estimates of the effect of imbalance may be biased due to endogeneity of the imbalance variable because freight prices and flows are simultaneously determined. Hence, shippers in regions with a, for them, favourable imbalance (i.e. in regions where supply of carriers is relatively large) will increase their demand for inland waterway transport capacity because the freight price for trips that depart from that region is low. In the case of inland waterway transport, the endogeneity of imbalance may be argued to be important, as the inland waterway transport sector competes with the rail and road sectors for the same cargo. On the other hand, one may think that endogeneity is not an issue, as, especially in case of transport over long distances, the cost advantage of using inland waterway transport instead of alternative transport modes is substantial. Furthermore, as the inland waterway transport costs are only a small part of the overall production costs of the goods, it may be thought that demand for transport is quite inelastic with respect to the unit freight price. We are aware of a number of recent studies which demonstrate that demand for inland waterway transport in

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[58] Not allowing for clustering results in standard errors which are about four times smaller for the aggregate variables.

Europe is inelastic. For example, Jonkeren et al. (2007) report that the demand elasticity is about -0.5.

We use an instrumental variable approach to address the endogeneity of the imbalance variables. Our instruments are two sea port dummies which measure whether a trip starts or ends in a sea port. These instruments can be argued to be exogenous with respect to the unit freight price, because the freight price is unlikely to affect the presence of sea ports. Hence, the exclusion restriction is that the presence of sea ports has no direct effect on freight prices, conditional on transport flows.

The port dummies are not only exogenous, one may expect that they are also strong predictors of the region imbalance difference. In Europe, seaports such as Rotterdam and Antwerp import more bulk cargo from overseas locations than they export to these locations, because industries in the hinterland of those seaports use large quantities of bulk cargo as inputs in their production processes and deliver manufactured goods as output. This implies that more bulk cargo is transported from the seaports to the hinterland regions than in the opposite direction.

The strength of the instruments has been examined by regressing the logarithm of the region imbalance difference on the control variables X_{rijt} and the two sea port dummies. It turns out that the instrumental variables are highly significant, with a F-value of more than 100. In addition, when we exclude the route imbalance in the specification of the model (consistent with our results), such that the number of instruments exceeds the number of endogenous regressors, then a standard overidentification test shows that the two instruments are jointly valid (so they are internally consistent with each other).[59]

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[59] Note that this test is rather weak in the sense that both instruments represent similar variables. Still, one may interpret the test as a misspecification test.

Table 4.3: Estimation results for the freight price in the inland waterway transport market

	OLS		IV	
Explanatory Variables	***Coefficient***	***Std. Error***	***Coefficient***	***Std. Error***
Constant	-3.342	0.248	-3.295	0.271
Region imbalance difference, log(I_{ij})	0.116	0.038	0.296	0.085
Route imbalance, log(M_{ij})	-0.013	0.006	0.008	0.013
Log(travel time)	0.086	0.013	0.079	0.012
Log(distance)	0.689	0.037	0.695	0.037
Time trend/1000	0.278	0.036	0.276	0.037
Log(fuelprice)	0.027	0.061	0.031	0.061
Log(loadfactor)	-0.421	0.048	-0.428	0.048
Vessel size				
0 – 1000 tonnes	0.313	0.016	0.319	0.015
1000 – 1500 tonnes	0.208	0.015	0.213	0.015
1500 – 2000 tonnes	0.127	0.017	0.130	0.017
2000 – 2500 tonnes	0.080	0.013	0.083	0.013
> 2500 tonnes	Reference		Reference	
Navigation direction				
Upstream	0.202	0.053	0.006	0.074
Up-and-downstream	0.229	0.038	0.087	0.066
Partly upstream	0.149	0.063	-0.035	0.080
Partly downstream	0.051	0.036	-0.003	0.036
Downstream	Reference		Reference	
Water level, trips via Kaub				
< 180	0.433	0.032	0.424	0.032
181 – 190	0.325	0.042	0.317	0.043
191 – 200	0.275	0.024	0.272	0.023
201 – 210	0.249	0.030	0.245	0.030
211 – 220	0.163	0.027	0.156	0.025
221 – 230	0.133	0.026	0.129	0.025
231 – 240	0.111	0.020	0.108	0.019
241 – 250	0.066	0.017	0.066	0.017
251 – 260	0.029	0.009	0.030	0.009
≥ 261	Reference		Reference	
Water level, trips not via Kaub				
< 180	0.326	0.057	0.327	0.061
181 – 190	0.283	0.049	0.283	0.053
191 – 200	0.179	0.042	0.179	0.047
201 – 210	0.158	0.044	0.162	0.048
211 – 220	0.103	0.042	0.103	0.045
221 – 230	0.042	0.037	0.043	0.043
231 – 240	0.043	0.035	0.045	0.040
241 – 250	0.020	0.039	0.025	0.043
251 – 260	0.008	0.033	0.011	0.040
≥ 261	-0.019	0.032	-0.015	0.040
Month dummies				
January	Reference		Reference	

February	-0.066	0.011	-0.068	0.012
March	-0.133	0.016	-0.133	0.016
April	-0.098	0.015	-0.100	0.016
May	-0.085	0.017	-0.087	0.018
June	-0.082	0.023	-0.084	0.024
July	-0.068	0.025	-0.069	0.026
August	-0.132	0.026	-0.133	0.027
September	-0.045	0.025	-0.047	0.025
October	0.024	0.027	0.023	0.027
November	0.078	0.023	0.079	0.024
December	0.159	0.020	0.159	0.020
Cargo dummies, 46	Included		Included	
R^2	0.8669		0.8644	

The dependent variable is the logarithm of the price per tonne. The results are based on data from the Vaart!Vrachtindicator (2003 – 2007).

Using IV, the estimated region imbalance elasticity is 0.296 (s.e. 0.085), substantially higher than the elasticity of the OLS estimation 0.116 (s.e. 0.038). The results are shown in Table 4.3. A Hausman t-statistic ($t = 2.36$) implies that we reject the null hypothesis of exogeneity at the 95 percent confidence level, indicating that the OLS estimates of the region imbalance difference elasticity are inconsistent (see Wooldridge, 2002, p.120). If we focus on the route imbalance effect, we see that its impact on the freight price is rather limited in size and statistically insignificant given the IV approach (employing OLS, the effect has even the 'wrong' sign, also indicating that IV is the superior approach). This finding is consistent with the observation that only a few carriers travel back and forth between regions.

Recall that I_{ij} is defined as I_i/I_j, and we use the logarithm of this variable. Our main result is therefore that the elasticity of I_{ij} with respect to the freight price is equal to 0.296. To understand the size of the effect, it is useful to consider a one standard deviation increase in the imbalance in the origin region, I_i, which is 0.39 (see Table 4.2). Assuming that I_i increases by one standard deviation (from its mean which is equal to 1.44), then the freight price for trips that depart from this region will be 7.0 percent higher. This has been calculated by $((1.44 + 0.39)/1.44)^{0.296} - 1 = 0.07$. As the freight price includes the costs of navigation plus the time costs of loading and unloading (the handling costs of loading and unloading are paid for by the shipper), the calculated increase in freight price applies to the 'full' freight price. A similar calculation for an increase in I_j generates almost the same result but with the opposite sign: $((1.00 + 0.34)/1.00)^{-0.296}-1 = -0.08$.

It is also interesting to study the joint effects of the imbalance in the origin region (I_i) and the destination region (I_j) focusing on opposite trips between the Rotterdam port area (where a large seaport is located) and the Neckar area. In the latter area, the (weighted) number of trips with cargo leaving the Neckar area is 34 percent lower than those arriving whereas the (weighted) number of trips with cargo leaving the Rotterdam port area is 81 percent higher than those arriving. Comparing the two trips, the freight price of the trip from the Rotterdam port area to the Neckar area is 70 per cent higher than the trip in the opposite direction due to the differences in imbalance in the origin region and the destination region.[60]

We will now briefly discuss the results for the control variables. It appears that the travel time elasticity is about 0.08, and the distance elasticity is about 0.69. The sum of these elasticities is less than 1, suggesting economies of scale in terms of the length of the trip. The load factor elasticity is estimated to be about -0.42, implying lower prices per tonne at higher load factors. Further, we find that the price decreases as the vessel size increases, indicating economies of vessel size. Stream direction does not appear to have an effect on prices given the IV estimates, consistent with the idea that prices reflect round-trip cost of transport between regions, so the one-way cost of transport do not affect prices conditional on round-trip cost.

We find that low water levels increase the transport costs for water levels lower than 260 cm, in line with Jonkeren et al. (2007). The effect is stronger for trips that pass Kaub than for trips that do not pass Kaub. The December dummy implies the existence of relatively high freight prices in the month December confirming a phenomenon which is well known in this sector (many inland waterway transport enterprises do not work at the end of the year for holiday reasons and they put their inland ship in maintenance. As a result, supply falls and freight prices rise). The barge-fuel price effect is not statistically significant even at the 10 percent level. Note that we control for a time trend, and that, during the period analysed, fuel prices strongly correlate with this time trend, so the fuel price effect is difficult to identify.

4.3.2 Sensitivity analyses

In this section, we test for the robustness of the reported effect of the region imbalance difference variable. To be more specific, we examine the sensitivity of the results with respect to the assumption that the effect of the logarithm of the imbalance variable for the origin region is equal in value (but with opposite signs) to the effect of the logarithm of the imbalance variable for the destination region (4.3.2.1), controls for cargo type (4.3.2.2), the number of kilometers navigated without cargo before a trip with cargo starts (4.3.2.3) and the value of the decay parameter γ used to estimate the weights (4.3.2.4).

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[60] $(((0.656 + 1.15)/ 0.656)^{0.296} – 1) + (((1.81 – 1.15)/ 1.81)^{-0.296} – 1) = 0.70$

4.3.2.1 Measuring imbalance: distinguishing between origin and destination regions

The region imbalance difference is measured as the ratio of the origin-and destination-region imbalances. However, it could be argued that this specification is too restrictive, so we allow here for a separate impact of the origin-and destination imbalance variables on the freight price. We find that the effect of the origin imbalance variable, $\log(I_i)$, is 0.332 (s.e. 0.109), and the destination imbalance variable, $\log(I_j)$, -0.229 (s.e. 0.082). In line with theory, the effect of the origin imbalance variable is positive, whereas the effect is negative for the destination imbalance variable. Furthermore, it appears that the sum of the coefficients is not statistically different from zero (the sum equals 0.103 with a standard error equal to 0.082) justifying the use of $\log(I_{ij})$ in the empirical analysis. The standard error of the sum of the coefficients is calculated using standard covariance rules.

4.3.2.2 Controls for cargo type

In the previous section, we have shown that our measure of the region imbalance difference has a strong positive effect on the freight price. We have controlled for cargo type, as it may be argued that the cargo transported affects the unit costs via the density (mass per volume) of the cargo. So, the cargo type is a relevant control variable, as there is correlation between region imbalance and cargo type (imbalance is region-specific but also the production of certain goods and raw materials is region-specific). However, one may argue that the effect of the type of good transported on the freight price, and therefore the region imbalance effect, is biased because the type of good transported may be endogenous. For example, because of a decrease in freight prices, it may become profitable to transport certain goods that otherwise would not have been profitable to transport (e.g. bricks). A counterargument would be that demand for inland waterway transport is price inelastic as discussed above, so it is not very likely that the cargo type is strongly endogenous with respect to the freight price.

In a sensitivity analysis we have therefore excluded the 47 dummy controls for cargo type. The region imbalance difference effect is then equal to 0.274 (s.e. 0.089) (note that, in this analysis, the region imbalance difference parameter may also be biased because of omitted-variable bias). Hence, our results are robust with respect to controlling for cargo type, indicating that this is a minor issue in the market analysed. Note that this issue is likely to be more relevant in the maritime transport market. For example, most of the goods shipped from the Netherlands to China appear to consist of used paper, which is transported at bottom freight prices.

4.3.2.3 Controlling for the distance navigated without cargo before starting a trip

We have argued above that due to differences in imbalance between regions, it will be frequently beneficial for carriers to navigate without cargo to a region with a more favorable imbalance. Therefore, trips that start from regions with an imbalance that is favorable for the carriers are likely to be preceded by a relatively long distance navigated without cargo. This conjecture is confirmed by a weak negative correlation between the natural logarithm of the distance navigated without cargo variable and the natural logarithm of the region imbalance difference variable. In a perfectly competitive transport market, the distance navigated without cargo before starting a paid trip should not have any effect when controlling for imbalance factors[61], but, in a market with imperfections (e.g. search costs), the bargaining position of carriers may depend on this distance, and therefore affect the bargained freight price. It appears that controlling for distance navigated without cargo in the regression hardly affects the region imbalance difference coefficient (which is equal to 0.231 with an s.e. equal to 0.084). We find that the effect of distance navigated without cargo on the freight price is small with an elasticity of only 0.01.

4.3.2.4 Different values for the decay parameter

Recall that the value of the decay parameter γ has been estimated assuming an exponential distribution of the variable which measures the distance navigated without cargo. γ is therefore equal to the inverse of the average distance navigated without cargo before starting a trip, which is slightly more than 95 kilometres. We have examined the robustness of our results by assuming that the distance navigated without cargo is 70 or 110 kilometres, implying a γ of 1/70 and 1/110 respectively. This range of γ seems reasonable because very small values for γ imply that navigating without cargo is costless, whereas very large values for γ imply that navigating without cargo is prohibitively expensive. Both implications are unrealistic and inconsistent with the data. Thus, extreme values for γ are not realistic. We find that the results and, in particular, the effect of the imbalance in the origin region on the freight price remains essentially unaltered for these other values for γ. An increase of one standard deviation in the ratio of the export and import cargo flows in the origin region (I_i) now results in an increase of 6.3 percent (if $\gamma = 1/70$) and 7.7 percent (if $\gamma = 1/110$) of the freight price.

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[61] A shipper will choose the barge-operator that offers the lowest price, so a barge-operator cannot ask a higher price if it has to navigate empty to the place of loading for a particular trip.

4.4 Conclusion

In the extensive literature on (regional and international) trade and regional activity, it is common to assume that transport costs are exogenous, but recently a new literature has emerged which argues that these transport costs are endogenous. For example, Behrens et al. (2006) make the assumption that unit freight prices negatively depend on trade volume using density economies arguments. In this chapter, we also argue that transport costs are endogenous, but use an entirely different argument. Our argument is that transport costs depend on imbalances in trade flows because carriers have to return to high demand regions without paid cargo. This implies that, ceteris paribus, unit freight prices positively depend on trade.

Here, we have studied this effect empirically using an ongoing survey for carriers in the inland waterway transport spot market in North West Europe, which covers mainly the Netherlands and Germany. Between these two countries, about 50 percent of all physical trade is transported by inland waterways, so the price formation in the inland waterway transport market is fundamental to our understanding of the cost of trade between these two countries. The survey provides not only information about freight prices for each trip, but also detailed micro-information about a large number of control variables.

One important difference between the current study and existing empirical maritime transport studies is that the latter studies measure density economies by means of the size of the flow on routes (volume) and do not take into account the potential endogeneity of the imbalance variable, whereas in our empirical application, we control for density economies by means of several variables (vessel size, load factor and travel time), and emphasize that transport costs are endogenous with respect to the imbalance in export and import cargo flows in regions (the ‘region imbalance’). Although standard transport economic theory on pricing of transport services within a two-region setting motivates our study, we have argued that in the case of a multi-region network where carriers cruise for shipments, a measure of trade imbalances at the level of the route may be less appropriate than a measure of imbalances at the level of the region. In our empirical application we employ both measures.

Our first finding is that regional imbalances play a much more prominent role than route imbalances in the determination of freight prices in the market analyzed. Our main finding is that a one standard deviation increase in the ratio of the export and import cargo flows in the region of origin increases the price for inland waterway transport from this region by about 7 percent. A range of sensitivity analyses show that this effect is robust.

It is difficult to compare this result with those of other empirical studies because of differences in measurement of imbalance and because endogeneity of imbalance is not taken into account.[62]

The inland waterway transport market we have studied covers 'exporting' regions (regions from which more trips with cargo depart than arrive) along the North Sea coast, and 'importing' regions in the hinterland. The exporting regions include the seaports of Amsterdam, Rotterdam and Antwerp. Most bulk cargo enters Europe from sea via these ports and is then transported further to the hinterland making use of inland waterway transport. The hinterland regions do not export bulk goods on a large scale (they tend to export manufactured goods and services) to the sea-port regions. Hence, the *physical* transport flow, and therefore the number of inland waterway transport trips with cargo between seaports and hinterland is very unbalanced. One of the main consequences is that unit prices for transport from the seaports to the hinterland are substantially higher than the other way round.

Our results also have important implications for studies on international trade as reviewed by Anderson and van Wincoop (2004). Our study makes a strong case that freight prices from the Netherlands to Germany are substantially higher than the other way around *because* the Netherlands transports much more to Germany than the other way around. We can only speculate to what extent our results also hold for trade between other countries, but it is plausible that our results also hold more generally. Next, the dissertation ends with Chapter 5, where the conclusion is formulated.

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[62] Nevertheless we mention a few reported effects. Clark et al. (2004) find that a 100 per cent point decrease in imbalance (defined as US exports – US import divided by bilateral trade) increases transport costs by about 6 per cent. Wilmsmeier et al. (2006) report that an increase of the ratio of the volume of imports of country *i* from country *j* over the volume of exports from county *i* to country *j* by one point will lead to an increase in the freight costs by 0.05 per cent. For details on the exact interpretation of the coefficients we refer to the mentioned studies (also see Blonigen and Wilson, 2008).

Appendix 4.A – Imbalance by region, I_i

Table A.4.A: The imbalance I_i and the logarithm of the imbalance by region

Region	I_i	log(I_i)	nr. in map
Rotterdam port area (NL)	1.811	0.594	13
Amsterdam port area (NL)	1.649	0.500	12
Netherlands, South (NL)	1.626	0.486	11
Antwerp port area (B)	1.409	0.343	14
Netherlands, Centre (NL)	1.154	0.143	10
Netherlands, North (NL)	1.060	0.058	9
Upper Rhine area (D, F, CH)	1.002	0.002	1
Main and Danube (D, A, H)	0.960	-0.041	3
North German Canals (D)	0.923	-0.08	15
Ruhr area (D)	0.829	-0.187	6
Netherlands, East (NL)	0.811	-0.21	8
Middle Rhine area (D)	0.808	-0.213	4
West German Canals (D)	0.746	-0.293	7
Moselle and Saar area (D, F)	0.742	-0.299	5
Neckar area (D)	0.656	-0.422	2

Note: NL = the Netherlands; B = Belgium; D = Germany; F = France; CH = Switzerland; A = Austria; H = Hungary.

Appendix 4.B – Descriptives of key variables of transports flows and trip data

Table A.4.B: Descriptives of key variables of transports flows and trip data based on 16,584 observations (including trips for which the navigation direction is difficult to determine).

Variable	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
M_{ij} (route imbalance)	0.01	100.00	7.16	14.91
log(M_{ij})	-4.61	4.61	0.94	1.40
I_{ij} (region imbalance difference)	0.36	2.76	1.42	0.69
log(I_{ij})	-1.02	1.02	0.21	0.55
I_i (region imbalance, origin)	0.66	1.81	1.30	0.42
log(I_i)	-0.42	0.59	0.21	0.34
I_j (region imbalance, destination)	0.66	1.81	1.05	0.35
log(I_j)	-0.42	0.59	-0.003	0.30
Price per tonne (in €)	0.85	54.55	7.53	5.05
Travel time (in days)	1.00	31.00	5.03	2.39
Distance trip (in km)	12.00	4000.00	520.27	284.00
Distance navigated without cargo (in km)	0.00	908.00	89.91	93.57

Source: The Vaart!Vrachtindicator (2003 – 2007).

Appendix 4.C – Distribution of distance navigated without cargo before starting a paid trip

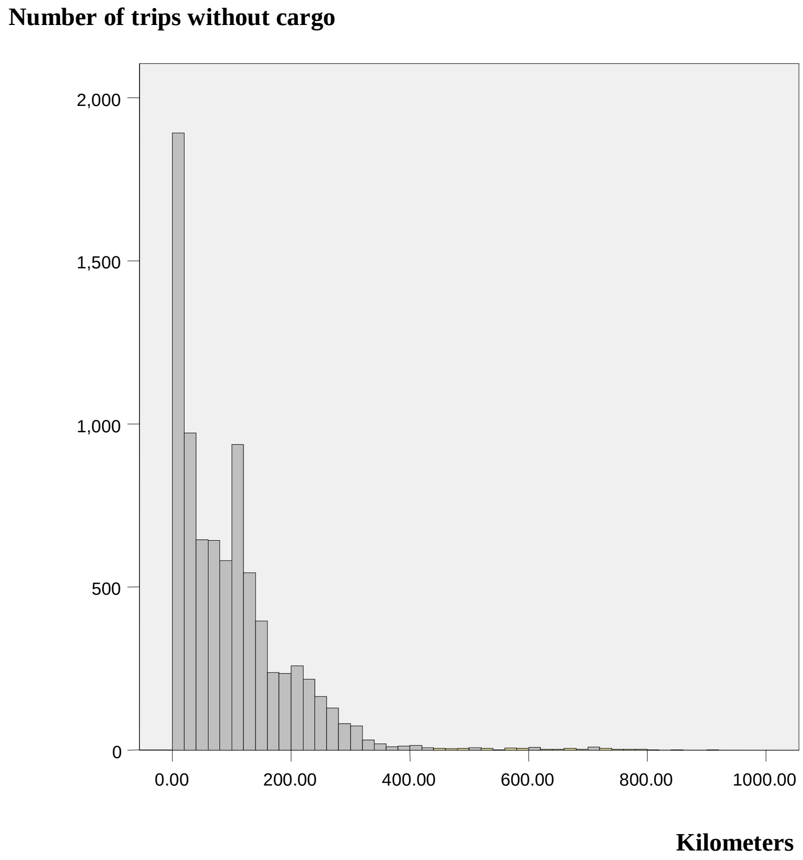

Figure A.4.C: Distribution of distance navigated without cargo before starting a paid trip.

Note that the variable “distance without cargo” is missing for observations in the period up to June 2004 as it was not included in the first 18 months of the survey. Therefore, the number of observations for this variable is 8,177.

CHAPTER 5

CONCLUSION

5.1 Summary

Climate change is expected to influence many aspects of life in the future. Besides the increased occurrence of natural disasters like floods, droughts, and hurricanes, economic activity is expected to be affected more gradually. Climate change is often associated with changes in weather patterns, and more likely increased costs, and increased uncertainty. Transport, agriculture, and tourism are commonly mentioned sectors that are directly affected by climate change. In this dissertation the focus is on the influence of climate change on transport by inland navigation. In the Rhine area in North-Western Europe climate change is expected to cause more extreme and volatile water levels. Extremely low water levels result in capacity decreases, and extremely high water levels in navigation halts. Both capacity decreases and navigation halts imply increases in costs and the occurrence of economic welfare losses.

Measures against climate change may be categorized into mitigation and adaptation measures. Mitigation is associated with the prevention of climate change or softening the change in climate. Transport, considered as a polluter, enters the discussion of climate often through mitigation when the reduction of the emission of greenhouse gases is discussed. Adaptation in the climate change context means the adaptation of the various economic actors to the new environment after climate change. In this dissertation the focus is on adaptation strategies for the inland navigation sector. Adaptation measures (or strategies) can be categorized into public and private measures. Economic welfare analysis is useful to evaluate the efficiency of these types of adaptation measures. In Chapter 2, for example, infrastructure adjustment, which is a public adaptation measure, and barge-size choice, which is a private measure, are both evaluated within the same welfare economic analysis.

Another aspect that is stressed in this dissertation is the influence of imbalances in transport flows between regions on adaptation to climate change. In freight transport, imbalance in goods flows between regions is a commonly observed phenomenon, known as the backhaul problem. Imbalances in demand for transport between regions result in differences in freight prices between regions. In regions where demand for transport is higher, freight prices will also be higher. Climate change is expected to increase the costs of transport, and the direction-dependent freight prices will change accordingly. This will imply different impacts or costs for different regions or countries. Measures, like infrastructure adjustments, that require joint investment will then give benefits that differ by countries. This means that it is important to study imbalance to achieve a fair split of costs according to benefits in this type of adaptation.

The remainder of this conclusion proceeds as follows. In Section 5.2, we summarize the results and provide the answers on the research questions. In Section 5.3 we formulate the implications for adaptation to climate change in this sector. We end the dissertation with Section 5.4, where recommendations for follow-up research are made.

5.2 Results and answers to the research questions

This dissertation addressed the following two research questions:

1. What is the optimal barge-size adjustment for barge operators to cope with climate change, and what are the implications of climate change for investments in inland waterway infrastructure by the public sector?

2. What is the impact of climate change on freight prices in the inland navigation market in the presence of direction dependent freight imbalances?

In order to address the first research question, in Chapter 2 we formulated a theoretical model which described the low water-level uncertainty in the inland navigation market. With this model we are able to derive the optimal barge size, as an example of private adaptation, and the optimal investment in infrastructure, as an example of public adaptation. Given certain simplifying assumptions, we derived the optimal barge size analytically. An increase in the convexity of cost functions, the concavity of the capacity function, and the probabilities of low water levels is then shown to imply the choice for smaller barges.

In the current market however, it is shown by means of numerical analysis that there are incentives to almost double the current barge size. This suggests that the current market is *not* in its steady state, which could be explained by the long lifetime of barges that are currently in use. Thus, climate change does not provide a reason to stop the current trend towards larger barges. However, if we assume that the barge size is optimal before climate change, the model predicts that there will be a slight tendency to decrease the barge size when climate change occurs. The latter result is rather intuitive. Due to climate change, low-water levels, and consequently lower capacities, will occur more often. Barge operators then respond by reducing a part of the capacity which is used less often.

The government may also take public adaptation measures to decrease the potential harm caused by climate change. In this study we have focused on investments in infrastructure, such as dredging, and found a benefit-cost ratio higher than 1 (before and after climate changes). Thus, this suggests that welfare would increase if the government increases investments in infrastructure.

When studying the ‘net’ effect of climate change, which means that we assume that barge-size choice and the investment in infrastructure is optimal before climate change, we observe that the barge sizes may decrease slightly when only barge-size adjustments are considered. However, the increases in infrastructure investments are still considerable. This would mean that, after climate change, public adaptation may be a more important instrument than private adaptation when the situation is optimal before climate change. Combined barge-size adjustment and infrastructure investment yields a gain in expected welfare that is more than the sum of the gain in expected welfare when the two measures are taken separately. This ‘super-additivity’-property can be attributed to the opportunity for barge operators to hold even larger barges in the new environment where low water is less harmful for their capacities. However, for the situation after climate change, when starting from an optimized situation, super-additivity no longer holds.

A sensitivity analysis with respect to the elasticity of the demand and the cost function of infrastructure investment shows that the optimal barge-size choice is rather invariant and remains at the double of the current representative size. The amount to invest in infrastructure, however, rather depends on the level of the cost of investment and of the elasticity of the demand function.

The central theme in Chapters 3 and 4 was the impact of climate change on freight prices under imbalance. This addressed the second research question. Chapter 3 followed a theoretical approach to answer this question. A matching model was applied innovatively to the traditional ‘backhaul’ literature, which is the classical term for the literature of imbalances in transport demand. This added the aspect of imperfect information to the search process. Imperfect information was shown to explain the existence of positive backhaul prices in the presence of imbalanced flows, which have been reported to be zero in the classical literature.

In a two-location transport model, two types of equilibrium were distinguished: the balanced equilibrium, where carriers have a load factor of 1 in both directions and, the imbalanced equilibrium, where the load factor from the low demand region is zero for a part of the carriers. For a wide range of numerical parameters the resulting equilibrium was imbalanced, which is also the more interesting one from an empirical perspective. In the imbalanced equilibrium, the round trip transport cost is fully borne by the customers in the high demand location. However, positive backhaul prices result due to carriers' compensation for expected search time.

A numerical example was presented where the chosen parameter set was taken such that certain segments of the inland navigation market between the Netherland and Germany are represented. Furthermore, we studied, numerically, the effect of reduction in travel speed due to extreme water levels, e.g. as a result of climate change, leading to higher trip durations. The high demand flow in this market is the flow from the Netherlands to Germany. German customers importing goods from the Netherlands were shown to predominantly pay for the increased costs of transport, whereas the Dutch customers (demanding transport from Germany) will hardly pay for the increase in costs. This strongly suggests that Germany will benefit relatively more from investments in infrastructure in order to prevent delays in transport.

In order to generalize the result in the above example where a region with high demand for transport is relatively worse off under climate change, the following intuition was given. In the imbalanced equilibrium, (which is more plausible empirically than the balanced case), all costs associated with navigating, whether full or empty, are carried by the region with high demand for transport (for example, Germany). If the costs of transport increase because of climate change, these costs will, as long as the equilibrium remains imbalanced, again be carried by the region with high demand for transport (German regions). Regions with a high demand for transport will therefore benefit relatively more from measures that reduce the effects of climate change.

Chapter 4 provided an empirical estimation of the effects of low water levels on freight prices under the presence of imbalance. In order to do this, we used a data set for barge operators in the inland navigation market in North-Western Europe, which consists mainly of trips with the Netherlands and Germany as origins and destinations. About 50 per cent of all physical trade between these countries is transported by inland navigation.

Our first finding is that regional imbalances play a much more prominent role than route imbalances in the determination of freight prices in the market studied. Our main finding is that a 1 standard deviation increase in the ratio of the export and import cargo flows in the region of origin increases the price for inland waterway transport from this region by about 7 per cent. For a series of sensitivity analyses this effect seemed robust.

Some regions in the studied inland navigation market may be typified as ‘exporting’ regions as more trips with cargo depart than arrive into this region. These are mainly the regions along the North Sea coast, including the sea ports of Amsterdam, Rotterdam and Antwerp. Most bulk cargo enters Europe via these ports by maritime transport, and is then transported further to the hinterland making use of inland waterway transport. ‘Importing’ regions are typified similarly. The regions are located in the hinterland, and do not export bulk goods on a large scale, as they tend to export manufactured goods and services to the seaport regions. This causes an imbalance in the physical transport flows between seaports and hinterland, and therefore the number of inland waterway transport trips with cargo. This results in higher freight prices per tonne from the seaports to their hinterland. This is in line with the findings of Chapter 3, when seaports are taken as the region with high demand for transport.

5.3 Policy implications for adaptation strategies

Our analysis yields conclusions on both private and public adaptation to climate change. We conclude that both types of adaptation may be useful to cope with climate change, and that combinations of both types of adaptation may lead to welfare-improving outcomes.

We used barge-size adjustment as an example of private adaptation, and found that in the market there is an incentive to considerably increase the current barge size, both before and after climate change. As these incentives are strong, there seems to be a less important role for the public sector regarding this adaptation strategy.

As an example of public adaptation we used investments in infrastructure investment. The analysis of investment in infrastructure had two aspects. First, the optimal level to invest in infrastructure was determined. Secondly, an equity aspect was studied. A fair basis was formulated to divide costs between countries for international infrastructure projects. While our model could be used for any type of infrastructure investment, including dredging, canalizing, or reservoir building, the focus in the presented example was on dredging. For values of the input parameters that are chosen to be in line with reality, our calculations show that the benefit-cost ratio for investments such as dredging is likely to be higher than 1, and is therefore beneficial for society.

The equity aspect is addressed by the observation that, in perfectly competitive markets, those regions with the highest reductions in freight price benefit most in terms of welfare. As the main determinant of difference in freight prices between regions we used imbalances in the demand for transport between regions. As is intuitive, freight prices are higher in regions with a high demand for transport.

The results indicate that, as a result of climate change, customers who are located in regions that attract large transport flows will experience an increase in transport cost when compared with customers located in regions attracting low transport flows demand for transport. This would mean that in an international context different regions or countries would benefit differently from investments such as those for infrastructure. More specifically, customers located in regions with high demand for transport will be saved from relatively greater losses due to climate change if investments in infrastructure are made. In an international context, a fair split of the costs of investments should take account of imbalances in demand for transport between regions. Fairness would imply that the larger share of the costs should go to the countries with high demand for transport.

5.4 Recommendations for follow-up research

We start our recommendations for follow-up research with suggestions for possible improvements of the research in this dissertation. This is followed by recommendations for follow-up research for a broader range of topics.

In Chapter 2 we performed a welfare analysis to evaluate the choice of barge size and the amount to invest in infrastructure. The numerical example concentrated on investments in the form of dredging. While this was sufficient for our purposes in order to formulate the model, for different policy advice purposes new numerical examples could be given for investments in canalizing or in the building of reservoirs. The efficiency of the strategies could then be compared. If necessary for more precise policy advice, more realism could be added to the model used to improve predictions about behaviour and adaptation strategies in this market. While relaxing any of the simplifications in the theoretical setting would lead to more realism, here we mention just a few. For example, more realism could be added to the water-level probability distribution. This would reflect capacities in more detail and also would make inference about risks more realistic. The addition of a future market would also lead to a closer reflection of reality. Also other aspects of the contractual agreements between barge operators and their customers could be added.

In Chapter 3 too, more realism could be added into the model in order to report more precisely on the policy measures that governments need to undertake. More realism could take the form of more realistic production processes by customers or be achieved by introducing the possibility for barge operators to search or be searched while navigating. A possibly useful extension might be to integrate the models of Chapter 2 and 3, and report the optimal amount to invest in infrastructure in conditions of imbalance, and the fair division between two or more cooperating countries in an international context.

In Chapter 4 the interaction effect of climate change and imbalance on freight prices could be studied. Another extension could be a check on the transferability of the results, by using data from different time periods and different countries.

Recommendations for follow-up research on ‘different’ topics can be categorized into the modelling of high water levels, on the one hand, and the evaluation of other adaptation strategies against climate change, on the other. The focus in this dissertation has been on low water levels. Low water levels reduce capacities, while high water levels imply navigation halts. In the current climate setting navigation stops hardly occur (at most on a few days per year). In future climate settings, however, high water levels could play a more significant role in this market. The inclusion of high water levels may lead to quite different results since barge operators are likely to become temporarily unavailable on the transport market, and no revenue is generated. Further, welfare analyses could be done to evaluate adaptation strategies, possibly in the presence of imbalance.

More research could be done to evaluate other adaptation strategies. Other adaptations can be categorized into adaptation by barge operators and adaptation by customers. In Chapter 2, barge-size choice was evaluated as an adaptation strategy for barge operators,. The choice of barge size can be seen as a part of more complete ‘fleet-management’-strategies. Adaptation strategies within this fleet-management may be new barge design to increase capacities and choice of fleet composition, which could mean the use of barges of different size and design.

Besides barge operators, the position of customers of barge operators is also affected by climate change. The behaviour of the customer was implicitly present in the demand functions, but has been rather underexposed in this dissertation. For example, customers are affected by climate change through increases in the freight price, and the availability and reliability of transport. A more explicit modelling of customers may lead to new insights into their adaptation behaviour to climate change. In order to do this, an assessment of the current situation of the customer could be made. The utility function of customers representing their preference for the different aspects of transport such as costs and uncertainty could be obtained by a stated preference research study. After incorporating the influence of climate change into such a utility function, adaptation strategies for customers could be evaluated. Change in stock-keeping behaviour and the possible relocation of customers to areas which depend less on inland navigation could be studied. Modal-shift was studied by Jonkeren et al. (2009).

An adaptation strategy that concerns both barge operators and customers would consist of changes in the terms of agreements for transport. These terms include agreements on financial compensation and degrees of transport obligation under extreme low and high water-levels. In addition, the analysis of future contracts might lead to different results. For example, in the future market in the Rhine area, barge operators receive a price surcharge per tonne if there are low water levels as a compensation for their decrease in capacity. The adaptation of such a contract to climate change could make the market more attractive for barge operators, and have welfare-improving effects.

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NEDERLANDSE SAMENVATTING (SUMMARY IN DUTCH)

ECONOMISCHE MODELLEN VOOR DE BINNENVAART IN DE CONTEXT VAN KLIMAATVERANDERING

Samenvatting en onderzoeksresultaten

In de toekomst zal naar verwachting klimaatverandering diverse aspecten van het leven beïnvloeden. Naast een toename in natuurrampen zoals overstromingen, droogtes, en orkanen, zal ook het economische leven structureel beïnvloed worden. Klimaatverandering wordt veelal geassocieerd met een toename in kosten en onzekerheid. Transport, landbouw en toerisme worden vaak genoemd als sectoren die direct door het klimaat worden beïnvloed. In dit proefschrift staat de invloed van het klimaat op het vrachtvervoer met de binnenvaart centraal. Naar verwachting zullen er door klimaatverandering in het Rijnstroomgebied meer extreme en schommelende waterstanden voorkomen. Extreem lage waterstanden impliceren capaciteitsreducties van schepen, en extreem hoge waterstanden kunnen stremming van de binnenvaart betekenen. Zowel capaciteitsreducties als stremmingen van de binnenvaart betekenen een toename van kosten en het optreden van welvaartsverliezen.

Maatregelen in verband met klimaatverandering kunnen verdeeld worden in mitigatie en adaptatie maatregelen. Mitigatie houdt verband met het voorkomen of verzachten van de verandering in het klimaat. Transport, gezien als vervuiler, komt in de klimaat discussie vaak voor als het gaat om mitigatie d.m.v. reducties in de uitstoot van broeikasgassen. Adaptatie in de context van klimaatverandering betekent het aanpassen van de diverse economische actoren aan de nieuwe omgeving na klimaatverandering. In dit proefschrift ligt de focus op adaptatiestrategieën voor de binnenvaartsector. Adaptatie maatregelen (of strategieën) kunnen gecategoriseerd worden in publieke en private maatregelen. Economische welvaartsanalyse is een manier om de efficiëntie van de diverse adaptatie maatregelen te evalueren. In hoofdstuk 2, bijvoorbeeld, worden zowel investeringen in infrastructuur – een publieke maatregel – als keuze van scheepsgrootte – een private maatregel – geëvalueerd binnen dezelfde welvaartanalyse.

Een ander aspect waar de nadruk op ligt in dit proefschrift, is de invloed van onbalans in vervoersstromen tussen regio’s op de adaptatie aan klimaatverandering. In vrachtvervoer is onbalans in goederenstromen tussen regio’s een vaak geobserveerd fenomeen (dit wordt in de literatuur het backhaul-probleem genoemd). Onbalans in de vraag naar transport tussen regio's heeft verschillen in vrachtprijzen (voor transport in tegengestelde richting) als gevolg. In regio's waar de vraag naar transport hoger is zullen ook de vrachtprijzen hoger zijn. Naar verwachting zullen door klimaatverandering de vervoerskosten alsmede de vrachtprijzen, welke richtings-afhankelijk zijn, stijgen. Dit zal verschillen in transportkosten met zich meebrengen voor transport tussen verschillende regio's of landen. Bij maatregelen, zoals aanpassingen in infrastructuur, die gezamenlijke investeringen met zich mee brengen, zullen verschillende landen dan verschillende baten hebben. Dit betekent dat het bestuderen van onbalans in vervoersstromen belangrijk is om tot een eerlijke verdeling van adaptatiekosten te komen.

In hoofdstuk 2 is een theoretisch model geformuleerd om de onzekerheid voor laag water in de binnenvaartmarkt te beschrijven. Met dit model is de optimale scheepsgrootte, als voorbeeld van private adaptatie, en de optimale investering in infrastructuur, als voorbeeld van publieke adaptatie vastgesteld. Gegeven een aantal veronderstellingen, is de optimale scheepsgrootte analytisch afgeleid. Er is aangetoond dat een toename in de convexiteit van de kostenfuncties, de concaviteit van de capaciteitsfuncties en de kansen op laag water leidt tot een keuze van kleinere schepen.

Door middel van een numerieke analyse is aangetoond dat er in de huidige markt prikkels zijn om de huidige scheepsgrootte vrijwel te verdubbelen. Dit suggereert dat de huidige markt niet in zijn lange termijn evenwicht verkeert, hetgeen verklaard zou kunnen worden door de lange levensduur van de huidige binnenvaartschepen. Ook bij klimaatverandering is er geen reden om de trend naar steeds grotere schepen te keren. Alhoewel, wanneer klimaatverandering wordt bekeken vanuit een situatie waarin de scheepsgrootte is geoptimaliseerd alvorens klimaatverandering optreedt, het model een lichte tendens om de scheepsgrootte te verkleinen voorspelt bij het optreden van klimaatverandering. Dit resultaat is vrij intuïtief. Door klimaatverandering en lage waterstanden zullen capaciteitsbeperkingen vaker optreden. Om 'overtollige' capaciteit te vermijden zullen binnenvaartschippers dan kiezen voor kleinere schepen. De overheid zou publieke adaptatie maatregelen kunnen nemen om mogelijke schade door klimaatverandering te beperken. In deze studie lag de focus op investeringen in infrastructuur, zoals baggeren, en werd een baten-kosten verhouding gevonden die groter was dan één (zowel voor als na klimaatverandering). Dit betekent dat investeringen in infrastructuur door de overheid een welvaartstoenemend effect hebben.

Indien we geïnteresseerd zijn in een ‘netto’-effect van klimaatverandering, waarmee we bedoelen dat de keuze van de scheepsgrootte en de hoeveelheid geïnvesteerd in infrastructuur optimaal gekozen zijn alvorens klimaatverandering optreedt, nemen we waar dat de scheepsgrootte enigszins afneemt wanneer alleen aanpassingen in de scheepsgrootte in beschouwing worden genomen. De investeringen in infrastructuur daarentegen nemen nog steeds aanzienlijk toe. Dit zou betekenen dat na klimaatverandering publieke adaptatie belangrijker wordt als instrument dan private adaptatie wanneer de situatie voor klimaatverandering optimaal is.

Het combineren van aanpassingen in de scheepsgrootte en investeringen in infrastructuur leveren een toename in de verwachte welvaart die hoger is dan de som van de toenames wanneer deze bij de maatregelen afzonderlijk worden getroffen. Deze eigenschap waarbij geldt dat ‘de-som-is-meer-dan-de-delen’ kan toegeschreven worden aan de kans die binnenvaartschippers krijgen om nog grotere schepen te gebruiken na de aanpassing in de infrastructuur. Overigens gaat deze eigenschap niet meer op als er wordt gestart vanuit een geoptimaliseerde situatie voor de klimaatverandering.

Een gevoeligheidsanalyse voor de elasticiteit van de vraag naar vervoer en voor de investeringskosten van infrastructuur laat zien dat de optimale keuze voor de scheepsgrootte vrijwel onveranderd blijft, namelijk een verdubbeling van het huidige representatieve schip. De optimale investering in infrastructuur daarentegen, blijkt nogal af te hangen van de keuze van de parameters in de investeringskosten en de vraagfunctie.

Het centrale thema in de hoofdstukken 3 en 4 is de invloed van klimaatverandering op vrachtprijzen onder onbalans in goederenstromen. In hoofdstuk 3, dat een theoretische benadering heeft, is op een innovatieve wijze een matching model toegepast op de traditionele ‘backhaul’ literatuur, hetgeen de klassieke benaming is voor de literatuur over onbalans in de vraag naar vervoer. Ons model voegt het aspect van imperfecte informatie toe aan het zoekproces. Imperfecte informatie kan het optreden van positieve backhaul prijzen verklaren bij ongebalanceerde vervoersstromen, welke gelijk aan nul zijn in de klassieke literatuur.

In een transport model met twee locaties kan een onderscheid gemaakt worden tussen twee typen evenwichten: het gebalanceerde evenwicht waarbij vervoerders een beladingsgraad van één hebben in beide richtingen, en het ongebalanceerde evenwicht waarbij de beladingsgraad vanuit de regio met lage vraag naar transport nul is voor sommige vervoerders. Voor een brede set van inputwaarden is het resulterende evenwicht ongebalanceerd, welke ook vanuit empirisch oogpunt het meest interessant is. In het ongebalanceerde evenwicht worden de vervoerskosten voor een retourtrip gedragen door de verladers in de regio met hoge vraag naar transport. Toch zijn de vrachtprijzen in de richting vanuit de regio met lage vraag positief vanwege de compensatie die vervoerders krijgen voor het wachten.

Er is een numeriek voorbeeld gepresenteerd, waarbij de parameter set representatief is gekozen voor bepaalde segmenten van de binnenvaartmarkt tussen Nederland en Duitsland. Ook is een afname in vaarsnelheid als gevolg van lage waterstanden door bijvoorbeeld klimaatverandering bestudeerd. In dit voorbeeld is de richting vanuit Nederland naar Duitsland de richting met de hoge vraag naar vervoer. Er is aangetoond dat het met name Duitse verladers zijn (die goederen importeerden via Nederland) die betalen voor de toename in vervoerskosten. Voor de Nederlandse verladers die via Duitsland importeerden stegen de vervoerskosten nauwelijks. Dit suggereert dat vooral Duitsland baat zal hebben van adaptatiemaatregelen zoals investeringen in infrastructuur.

Voor het generaliseren van dit laatste resultaat waarbij regio's met een hoge vraag naar transport relatief slechter af zijn door klimaat verandering kan de volgende intuïtie worden gegeven. In het ongebalanceerde evenwicht, dat empirisch meer plausibel is dan het gebalanceerde evenwicht, worden alle kosten (van heen- en terugreizen) die kunnen worden toegeschreven aan het varen, hetzij beladen hetzij onbeladen, gedragen door verladers uit regio's met een hoge vraag naar transport (bijvoorbeeld Duitsland). Als door klimaatverandering de vaarkosten stijgen zal, zolang het evenwicht ongebalanceerd blijft, de toename ook in de nieuwe situatie gedragen worden door regio's met hoge vraag naar transport (Duitse regio's). Regio's met een hoge vraag naar transport hebben er dus relatief meer baat bij maatregelen om de effecten van klimaatverandering te verminderen.

In hoofdstuk 4 is een empirische schatting uitgevoerd van de effecten van laag water op vrachtprijzen gegeven onbalans. Hiertoe is een dataset van Noord-West Europese binnenvaarders gebruikt, dat met name bestond uit trips met Nederland en Duitsland als begin- en eindpunten. Ongeveer 50 procent van alle fysieke handel tussen deze twee landen gebeurt via vervoer met de binnenvaart.

Het resultaat is dat onbalans, wanneer het wordt gemeten op regio niveau, een veel grotere rol speelt bij het bepalen van vrachtprijzen dan wanneer het wordt gemeten op route niveau. Het voornaamste resultaat is dat een toename van één standaarddeviatie in de verhouding tussen de export en import stroom van een herkomstregio leidt tot een toename van 7 procent in de vrachtprijs vanuit deze regio. Dit effect is robuust voor een reeks van gevoeligheidsanalyses.

Sommige regio’s in de bestudeerde binnenvaartmarkt kunnen getypeerd worden als ‘exporterende’ regio’s omdat er meer uitgaande trips dan binnenkomende trips voor deze regio’s zijn. Dit zijn met name de regio’s langs de Noordzee kust, met o.a. de zeehavens van Amsterdam, Rotterdam en Antwerpen. De meeste bulkgoederen komen Europa binnen via deze havens per zeeschip en worden naar het achterland vervoerd met de binnenvaart. ‘Importerende’ regio’s worden op een vergelijkbare manier getypeerd. De regio’s liggen in het achterland, en hun export richting de zeehavens bestaat minder uit bulkgoederen en meer uit gefabriceerde goederen. Dit is de oorzaak voor de onbalans in de fysieke goederenstroom tussen de zeehavens en het achterland, wat zich ook uit in het aantal beladen trips tussen deze regio’s. Dit heeft hogere vrachtprijzen voor trips vanuit zeehavens naar het achterland als gevolg, en ligt op een lijn met de theorie zoals bijvoorbeeld gepresenteerd in hoofdstuk 3.

Beleidsimplicaties voor adaptatie

Onze analyse leidt tot conclusies over zowel private als publieke adaptatie aan klimaatverandering. We concluderen dat beide typen adaptatie levensvatbaar kunnen zijn om de nadelige effecten van klimaatverandering te verminderen, en dat een combinatie van beide typen adaptatiemaatregelen kan leiden tot welvaartsopbrengsten die hoger zijn dan de som van beide maatregelen afzonderlijk.

We hebben aanpassingen in de scheepsgrootte als voorbeeld van private adaptatie genomen, en gevonden dat er in de huidige markt een prikkel is om de scheepsgrootte aanzienlijk te vergroten, zowel voor als na het optreden van klimaatverandering. Omdat deze prikkel zo groot is, lijkt er een minder grote rol weggelegd voor de overheid m.b.t. deze adaptatie strategie.

Als een voorbeeld van publieke adaptatie hebben we investeringen in infrastructuur gebruikt. De analyse van investeringen in infrastructuur heeft twee aspecten. Het eerste aspect is de optimale investering in infrastructuur. Het twee tweede is het verdelingsaspect van investeringskosten. Er is een basis geformuleerd voor het verdelen van kosten tussen landen bij internationale investeringsprojecten. Het gepresenteerde voorbeeld ging over baggeren, alhoewel ons model gebruikt zou kunnen worden bij elk type infrastructuur investering zoals kanaliseren en de bouw van stuwen. Voor realistische inputwaarden werd een baten-kosten ratio groter dan één gevonden voor baggeren. Hiermee zou dit een maatregel zijn waar de samenleving baat bij heeft vanuit welvaartsoogpunt.

Het verdelingsaspect wordt beantwoord vanuit de observatie dat in perfect concurrende markten regio’s met de hoogste reductie in vrachtprijzen de meeste baat hebben in termen van welvaart. In onze analyse is onbalans in de vraag naar transport tussen regio’s gebruikt als de belangrijkste verklarende factor van verschillen in vrachtprijzen tussen regio’s. Zoals intuïtief is, zijn vrachtprijzen hoger voor regio’s met een hoge vraag naar vervoer.

De resultaten laten zien dat verladers die liggen in regio’s waarnaartoe veel wordt vervoerd, relatief een grotere toename in vervoerskosten ondervinden door klimaatverandering dan regio’s waarnaartoe minder wordt vervoerd. Dit zou betekenen dat verschillende regio’s of landen verschillende baten hebben bij investeringen in een internationale context, zoals bijvoorbeeld bij infrastructuur investeringen. Preciezer geformuleerd, verladers met een grote vraag naar transport zullen dankzij investeringen in infrastructuur meer besparen op vervoerskosten veroorzaakt door klimaatverandering. Een eerlijke verdeling van investeringskosten in een internationale context zou rekening moeten houden met de onbalans in de vraag naar vervoer tussen regio’s. Een groter aandeel in de kosten zou moeten gaan naar landen met een grotere vraag naar vervoer.

Aanbevelingen voor vervolgonderzoek

We beginnen de aanbevelingen voor vervolgonderzoek met mogelijke verbeterpunten op het onderzoek in dit proefschrift. Daarna worden de aanbevelingen voor vervolgonderzoek over ‘nieuwere’ onderwerpen opgenoemd.

In hoofdstuk 2 is een welvaartsanalyse uitgevoerd om de keuze van scheepsgrootte en investeringen in infrastructuur te evalueren. Investeringen in het baggeren is gebruikt als numeriek voorbeeld. Hoewel voldoende voor onze doeleinden, zou voor andere beleidsstudies gekeken kunnen worden naar andere numerieke voorbeelden zoals investeringen in kanalisering en het bouwen van stuwen. De efficiëntie van de diverse investeringsmaatregelen kan dan vergeleken worden. Indien noodzakelijk, kan bij preciezer beleidsonderzoek, het gebruikte model realistischer gemaakt worden, waarmee voorspellingen over kosten en gedrag betrouwbaarder zouden worden. We noemen hier enkele simplificerende aannamen in het model die bij nadere specificatie kunnen leiden tot meer realisme. De kansverdeling van de waterstanden zou realistischer gemaakt kunnen worden. Dit zou capaciteiten en risico’s voor binnenvaartschippers in meer detail weergeven.

Een toevoeging van een termijnmarkt kan ook een betere benadering zijn van de werkelijkheid. Ook andere aspecten van contracten tussen verladers en vervoerders zouden kunnen worden toegevoegd.

Ook in hoofdstuk 3, zou het gebruikte model realistischer gemaakt kunnen worden, om preciezere beleidsuitspraken mogelijk te maken. Meer realisme kan bijvoorbeeld toegevoegd worden aan het productieproces of door zoeken tijdens het varen mogelijk te maken. Een mogelijke extensie kan liggen in de integratie van hoofdstuk 2 en 3, waarbij de optimale investering in infrastructuur gegeven onbalans bepaald zou kunnen worden en tevens een eerlijke verdeling van de kosten tussen twee samenwerkende landen in een internationale context.

Aan de analyse in hoofdstuk 4 zou het interactie-effect van lage waterstanden en onbalans kunnen worden toegevoegd. Een andere extensie zou een check voor de generaliseerbaarheid van de resultaten zijn door data te gebruiken van andere periodes en andere landen.

De aanbevelingen die we doen voor vervolgonderzoek op ‘nieuwere’ onderwerpen bestaan uit onderzoek naar de effecten van hoogwater enerzijds, en de evaluatie van andere adaptatiestrategieën anderzijds. De focus lag in dit proefschrift op lage waterstanden. Lage waterstanden verlagen capaciteiten, terwijl hoge waterstanden de stremming van de binnenvaart uit veiligheidsoverwegingen als gevolg kunnen hebben. In de huidige klimaatomstandigheden gebeurt het stopzetten van de binnenvaart zelden (hooguit enkele dagen per jaar). In toekomstige klimaatscenario’s daarentegen kan hoog water een belangrijkere rol gaan spelen. De hoogwaterproblematiek is van een heel andere orde dan de laagwaterproblematiek omdat vervoer met de binnenvaart dan tijdelijk onmogelijk wordt en er mogelijk geen inkomsten voor binnenvaartschippers zijn. Op een soortgelijke wijze als in dit proefschrift zouden welvaartanalyses uitgevoerd kunnen worden om de adaptatiestrategieën te evalueren, mogelijk door onbalans aan te nemen.

Er zou vervolgens ook nader onderzoek gedaan kunnen worden naar andere adaptatiestrategieën. Deze adaptatiestrategieën kunnen worden gecategoriseerd in adaptatie door binnenvaartschippers en door verladers. In hoofdstuk 2, is de keuze van de scheepsgrootte geëvalueerd als een adaptatiestrategie voor binnenvaartschippers. De keuze van de scheepsgrootte kan beschouwd worden als een instrument binnen een set van vloot-management strategieën. Vloot-management strategieën zouden kunnen bestaan uit het aanpassen van scheepsontwerpen om capaciteiten te verhogen, en de keuze van de vlootsamenstelling, wat het gebruik kan betekenen van schepen van verschillende grootte en ontwerp. Ook kunnen binnen deze beslissingen het te vervoeren goederensoort van de schepen als binnenvaartschepen worden toegevoegd als adaptatiestrategie.

Niet alleen de positie van de binnenvaartschippers, maar ook de positie van verladers zal worden beïnvloed door klimaatverandering. Het gedrag van de verlader is binnen onze modellen impliciet in de vraagfuncties aanwezig, maar is verder onderbelicht gebleven in dit proefschrift. Verladers ondervinden de effecten van klimaatverandering bijvoorbeeld door stijgende vervoerskosten, en de beschikbaarheid en betrouwbaarheid van transport. Een explicietere modellering van verladers kan leiden tot nieuwe inzichten in hun adaptatie gedrag aan klimaatverandering. Hiertoe zou eerst een onderzoek gedaan kunnen worden naar het huidige gedrag van verladers. Nutsfuncties van verladers die hun voorkeuren representeren voor verschillende aspecten van transport, zoals kosten en onzekerheid, zouden d.m.v. een stated-preference onderzoek kunnen worden achterhaald. Na de toevoeging van de effecten van klimaatverandering aan een dergelijke nutsfunctie, kunnen adaptatiestrategieën voor verladers worden geëvalueerd, zoals voorraadbeheer en verhuizing naar locaties die minder afhankelijk zijn van de binnenvaart. Modal-shift, de keuze van alternatieve vormen van vervoer, werd eerder bestudeerd door Jonkeren et al. (2009).

Een adaptatiestrategie die betrekking heeft op zowel vervoerders als verladers bestaat uit mogelijke aanpassingen in vervoerscontracten. Deze bevatten de afspraken over financiële compensaties en mate van vervoersverplichting bij extreem lage en hoge waterstanden. Ook de analyse van termijncontracten zou tot nieuwe resultaten kunnen leiden. In de termijnmarkt van het Rijnstroomgebied krijgen binnenvaartschippers bijvoorbeeld een toeslag per vervoerde ton bij laag water als compensatie voor hun afname in capaciteit. Een aanpassing van een dergelijk contract aan klimaatverandering zou de markt aantrekkelijker kunnen maken voor binnenvaartschippers, en tot een welvaartstoename kunnen leiden.

The Tinbergen Institute is the Institute for Economic Research, which was founded in 1987 by the Faculties of Economics and Econometrics of the Erasmus University Rotterdam, University of Amsterdam and VU University Amsterdam. The Institute is named after the late Professor Jan Tinbergen, Dutch Nobel Prize laureate in economics in 1969. The Tinbergen Institute is located in Amsterdam and Rotterdam. The following books recently appeared in the Tinbergen Institute Research Series:

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(page 1)

(page 2)