Production Uncertainty in the Inland Navigation Market: Climate Change, Optimal Barge Size, and Infrastructure Investments

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ABSTRACT

In this paper a model is developed to study an inland waterway market's production uncertainty due to fluctuating water-levels. Aspects that are studied are climate change and adaptation strategies against climate change. As an example of private adaptation the optimal barge-size, and as an example of public adaptation the optimal amount to investment in infrastructure are derived. We find that the trend to increase barge sizes in the Western European market is theoretically justified. We also show that dredging may be a cost-effective strategy for the Netherlands to cope with climate change.

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).[1] 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.[2]

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 paper 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 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

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1 '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'.

2 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.

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.[3]

The choice of barge size may function as an instrument to cope with water-level uncertainty.[4] While one advantage is that a larger barge makes it possible to benefit from 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.

[3] For evidence see a study on future water-level discharges on the Rhine by Te Linde (2007).
[4] In the analysis we keep barge-design constant, which may be a topic for further research.

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[5] function and the demand function, we are able to derive the optimal barge size analytically.

In Section 2 we present the theoretical framework for the inland navigation market under water-level uncertainty. In Section 3 we determine the equilibrium freight prices, the equilibrium number of barges active in the market and expected welfare. In Section 4 we derive the optimal barge size chosen by barge operators in the market. In Section 5 we present an analysis of infrastructure investment. Section 6 then gives the numerical presentation of the work described in Sections 2 to 5, including a sensitivity analysis with respect to climate change. Section 7 concludes.

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, 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.

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

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 $t = 1,2,...,T$.

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:

$$Q_t = N_B q_t = \alpha {p_t}^{\varepsilon}, \qquad \text{where} \qquad \alpha > 0,\ \varepsilon < 0, \tag{1}$$

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

$$p_t = \left(\frac{1}{\alpha} N_B q_t\right)^{\frac{1}{\varepsilon}}. \tag{2}$$

Following conventions in financial economics, it is assumed that the barge operators' objective function depends on returns on investment (rather than profits)[6]. Periodical returns are defined by profits $p_t q_t - C$ relative to expenses C. So we denote the *periodical* return by $r_t = \frac{p_t q_t}{C} - 1$. 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.[7] In this model, economic agents base their

[6] By using returns rather than profits, we are also able to derive analytical results.
[7] For a theoretical introduction, see Mas-Colell et al. (1995).

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)[8]. This utility function is widely used and can be formulated[9] as:

$$U(R) = \ln(1 + R). \qquad (3)$$

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

$$E[U(R)] = T\ \left(\frac{1}{\varepsilon}\ln N_B - \frac{1}{\varepsilon}\ln\alpha - \ln C + \left(1 + \frac{1}{\varepsilon}\right)E[\ln q_t]\right), \qquad (4)$$

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.

3 Equilibrium

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 (4), yields the equilibrium number of barges, N_B:

[8] 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).

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

$$N_B = \alpha\,(1+r^f)^{\varepsilon}\,C^{\varepsilon}e^{-(\varepsilon+1)E[\ln q]} = \alpha\,(1+r^f)^{\varepsilon}\,C^{\varepsilon}e^{-(\varepsilon+1)\sum_{i=1}^{m}\pi_i \ln q_i}$$
$$= \frac{\alpha\,(1+r^f)^{\varepsilon}\,C^{\varepsilon}}{\left(\prod_{i=1}^{m} q_i^{\pi_i}\right)^{(\varepsilon+1)}}. \qquad (5)$$

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) and (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[10]:

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

$$= \frac{D^{T+1}-D}{D-1}\left(\frac{1}{\left(\frac{1}{\varepsilon}+1\right)\alpha^{\left(\frac{1}{\varepsilon}\right)}}\left(N_B{}^{\left(\frac{1}{\varepsilon}+1\right)}\,E\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right] - N_{B0}{}^{\left(\frac{1}{\varepsilon}+1\right)}\,E_0\left[q^{\left(\frac{1}{\varepsilon}+1\right)}\right]\right)\right). \qquad (6)$$

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 $\bar{q} = max\{q_i, i = 1,2,..n\} = q_n$.[11] 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:

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

or in a more compact form:

[10] For intermediate steps, see Appendix A.
[11] 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.

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

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 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[12]:

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

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

Employing comparative statics, we find that:

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

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:

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

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.

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 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 $I = I(\{\tilde{q}_i(\bar{q})\}_{i=1,\dots,m})$. Optimal investments are derived from maximizing the change in expected welfare[13], where a level of zero for the investment is used as the reference case:

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

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

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:

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

This is the criterion which is maximized in the numerical welfare analysis in Section 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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[13] 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.

6 Numerical welfare analysis

In this section, we provide the numerical results of the theoretical analysis of the previous Sections 2 to 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:[14]

$$\ln \text{loadfactor} = -0.0134826\, w - 0.5850203 \ln \bar{q} + 0.0027283\, w \ln \bar{q} + bX \qquad (7)$$

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 (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:

$$q(w) = e^{0.0134826\,(260-w)}\, \bar{q}^{1-0.0027283(260-w)}. \qquad (8)$$

As the exponent of $\bar{q}$ will be smaller than 1 in (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).

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

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[15], 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:

$$I = \Delta waterlevel * 1.2 * 1.01^{(\Delta waterlevel - 20)}, \qquad (9)$$

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 1, 2 and 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 1 the outcome *before* climate change is presented:

[15] We thank Siemen Prins fom Rijkswaterstaat for his help in providing cost data.

Table 1: Optimal barge size and infrastructure investment *before* 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
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 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)[16] 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:

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

Table 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 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 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 3: Optimal barge size and infrastructure investment *after* climate change based on optimal levels before 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			-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 and Table 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 3. A similar reasoning holds for the Cases VII in both tables.

An important conclusion of Tables 1 to 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.[17]

7 Conclusion

In this paper we formulate 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.

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

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.

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.

Appendix 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 (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 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:

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

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

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

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

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

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

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

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

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

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

Table A.C.1: 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 D – More detailed regression output for the effective capacity estimation

This appendix gives more detail for the effective capacity estimation in equation (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 A.D.1: 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			

References

Buck Consultants International, (2008), Een goede toekomst voor het kleine schip - Visie en actieplan, Rotterdam.

CBS, Central Bureau of Statistics, (2010), The Hague, the Netherlands, website http://statline.cbs.nl/statweb.

CCNR, European Commission, (2007), Market observation for inland navigation in Europe, 2007-1, Central Commission for Navigation on the Rhine, Strasbourg.

Feder, G., (1980), Farm Size, Risk Aversion and the Adoption of New Technology under Uncertainty, *Oxford Economic Papers, New Series*, 32 (2), 263-283.

Gravelle, H., Rees, R. (1992) *Microeconomics*, 2nd ed., Longman Publishing, New York.

iidesk.nl, (2003-2005), Database design, building and maintenance organisation, website: http://www.iidesk.com/water.

Jonkeren, O.E., (2009), *Adaptation to Climate Change in Inland Waterway Transport.* Ph.D. Thesis, (Vrije Universiteit, Amsterdam, the Netherlands).

Jonkeren, O.E., Rietveld, P., van Ommeren, J.N., (2007), Climate change and inland waterway transport; welfare effects of low water levels on the river Rhine, *Journal of Transport Economics and Policy* 41 (3), 387-411.

Koetse, M.J., Rietveld P., (2009), The impact of climate change and weather on transport: An overview of empirical findings, *Transportation Research Part D* 14 (2009), 205-221.

Levy, H., Markowitz, H.M., (1979) Approximating Expected Utility by a Function of Mean and Variance, *The American Economic Review* 69 (3), 308-317.

Mas-Colell, A., Whinston, M.D., Green, J.R., (1995), *Microeconomic Theory*, Oxford University Press, Oxford.

NEA, (2008), *Kostenkengetallen binnenvaart 2008*

Pope, R.D., Kramer, R.A., (1979), Production uncertainty and factor demands for the competitive firm, *Southern Economic Journal* 46 (2), 489-501.

Pratt, J. W. (1964) Risk Aversion in the Small and in the Large, *Econometrica* 32 (1/2), 122-136.

Rabobank, (2007), Capaciteitsmonitor 2000-2005, Persbijeenkomst 30 november 2007 Jarl Schoemaker, NEA Capaciteitsmonitor 27 november 2007

Saha, A. (1994), A two-season agricultural household model of output and price uncertainty, *Journal of Development Economics* 45 (2), 245-269.

Solomou, S., Wu, W. (1999), Weather Effects on European Agricultural Output, 1850 – 1913, *European Review of Economic History* (3), 351-373.

Te Linde, (2007), *Effect of climate change on the rivers Rhine and Meuse* (WL | Delft Hydraulics, Prepared for Rijkswaterstaat).

Vaart!Vrachtindicator, (2003-2005), Data from the *Inland waterway transport portal Vaart!,* retrieved at http://www.vaart.nl.

Varian, H.R., (1995), *Micro-economic analysis*, 3rd ed., W.W. Norton & Company, New York.

Von Neumann, J., Morgenstern, O. (1944) *Theory of Games and Economic Behavior*, Princeton, NJ, Princeton University Press.