Investment dynamics for a congested transport network with competition: application to port planning

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ABSTRACT:
Containerization has caused a revolution in design and operation of freight transportation modes and cargo handling facilities. Ports, as important nodes in an extensive network of transport facilities, have to make strategic decisions in the face of a strongly growing market and volatile demand. The investment decision making has to incorporate scale effects, congestion, competition, and a financing and pricing which has to account for an increasing privatization of port operations. Such port planning requires to address the development aspects of the transport network as well as the investment dynamics of the development of the port node(s). A dynamic investment modeling is proposed in this paper which addresses congestion, scale effects, competition and self-financing, and which can be linked (at a later stage) to a specific freight transport model.

KEY WORDS: strategic decision making, investment dynamics, competition, congestion

1. INTRODUCTION

Containerization has caused a revolution in design and operation of freight transportation modes and cargo handling facilities. This caused an integration of ocean and land transportation services making logistic chains more flexible (i.e. less bounded to certain transportation routes). As a result, international freight flows have become more volatile causing a constant pressure on ports to remain competitive.

An increasing privatization of ports puts pressure on cost recovery and on pricing, influencing the attractivity of the port, determining its market share, and in turn the viability of investments. Port investments are further characterized by large economies of scale, and need to be made in the face of a strong growth of the transport market (double over the next 10-15 years). Congestion in ports as well as other links in logistic chains forms an other important factor determining the attractivity of the particular chains.

Planning for a port is thus faced with an increasing number of uncertainties, and needs to consider developments in the transport network (e.g. hinterland connections and congestion) and investments in other ports. The port can be considered a node in a transport network with competition, which faces a dynamic situation concerning the timing and sizing of capacity expansions.

Modeling of this dynamic system is indicated to map out the many interactions. Existing models address the port expansion problem and the freight movement in the network separately. The majority of the port planning models (e.g. Rotterdam) use trend extrapolation and a constant market share. Freight transportation models make an allocation of demand for freight over a network without considering the investment dynamics of the (port) nodes.

The present paper proposes a modeling approach which integrates the development of the port node with the competition over the network. Section 2 schematizes the transportation problem and the dynamic investment problem of the port node. This is illustrated for the ports of Rotterdam and Antwerp which will be used in the application. Sections 3 and 4 describe the proposed modeling and some sensitivity analyses. Section 5 summarizes observations and conclusions on the modeling and discusses further expansions.

2. PROBLEMS ANALYSIS AND PLANNING APPROACH

2.1 Transport network

Several European ports are involved in a strong competition to serve the European hinterland. The competition focuses in particular on the industrial heart of Europe (the Ruhr basin area, Southern Germany and the area of the Alps). Major container routes in the world are indicated in Figure 1. More specifically Figure 2 illustrates the European situation.

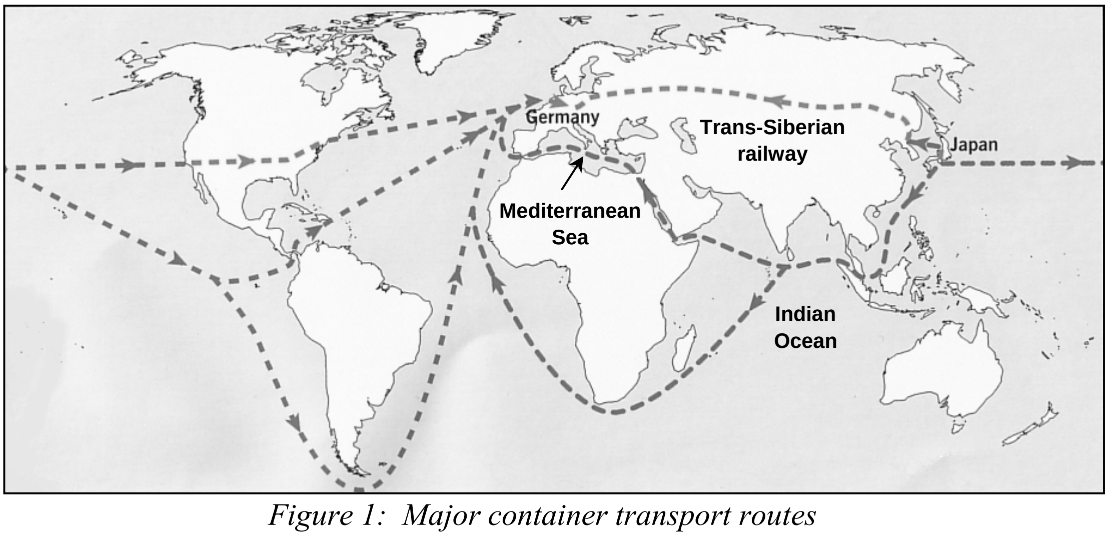

Figure 1: Major container transport routes

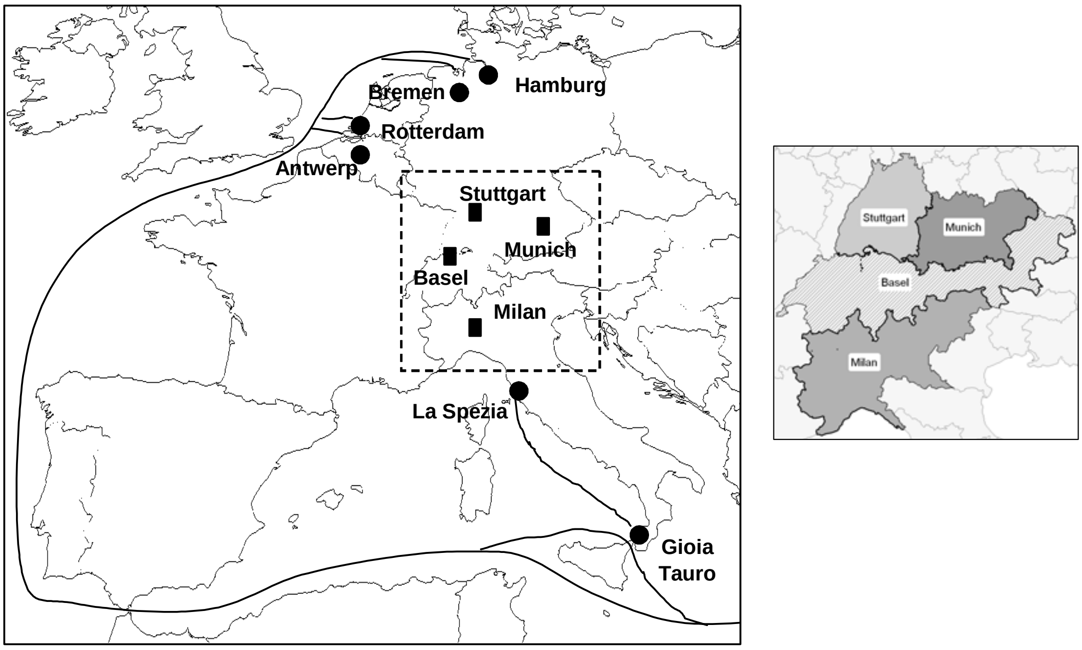

Figure 2 : Competition for the European hinterland

The Port of Rotterdam serves a hinterland that includes the industrial heart of Europe. Its main competitors for this hinterland are the North Sea ports Hamburg and Bremen in North-Germany, and, particularly, Antwerp in Belgium

Ports have responded to the growing competition with large investments. Since 1970, Rotterdam is improving its position in transport-logistic chains for container flows. Expansion of hinterland connections such as the construction of a rail connection between Maasvlakte 1 and Germany (the so-called Betuwe line; investment cost €4.7 billion) is considered an important asset for Rotterdam.

In the 1990s, a large-scale port development program (the so-called Rotterdam Mainport Development Project) has been initiated to support both port competiveness and regional economic development. A major part of this program is a second seaward expansion of the port (the Maasvlakte 2 project) with 1,000 hectares; sixty percent is reserved for container activities. The need for port expansion strongly depends on efficiency improvements that can be realized by the container terminals.

A fast development of the South-European ports, such as those in Italy, might become an additional threat for Rotterdam, particularly if their hinterland connections are developed as well. The rising demand for the Trans-Siberian railway is another potential threat for Rotterdam. This railway connection bypasses the maritime trajectory via, for instance, the Indian Ocean and the Mediterranean Sea and may serve as a faster alternative for container shipments between Asia and Europe.

Figure 3 presents a more abstract schematization of the transport network. Essentially a set of origins and destinations are differentiated which can be reached via alternative routes containing a maritime- and land trajectory and an associated port. Transporters decide on alternative logistical chains to connect a particular origin and destination on the basis of the attractiveness of the alternative chains (see section 2.2).

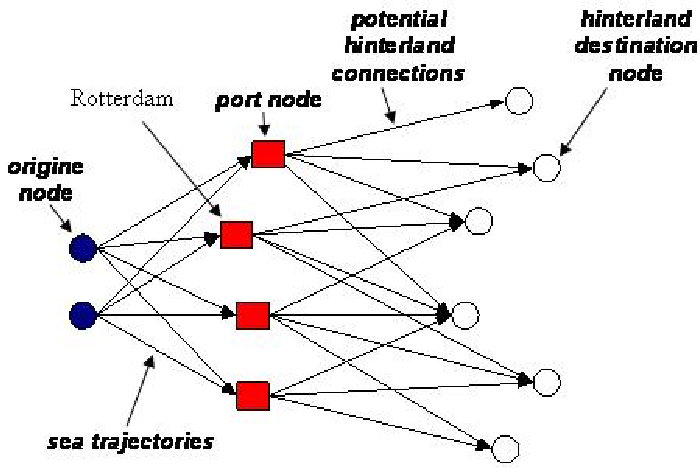

Figure 3: Schematization of the maritime-land freight transport network

2.2 Route choice

The choice for a particular route will be based on the performance of the total chain and includes factors such as out of pocket costs, congestion, reliability and scope possibilities. Out of pocket costs together with the value of time lost in congestion can be considered as a main factor.

The choice problem of the shipping companies can be modelled with a discrete choice model. The shipping companies choose the logistic chain and the associated port based on the utility for each chain. A main variable in this utility is the generalized transport cost for the different logistical chains.
Following this approach the utility for the shipping companies to choose logistical chain (port) i can be written as

$$U_i = \beta_i X_k + \varepsilon_i$$

with X_k : transport cost
ε_i : error term representing measurement errors and choice attributes not modelled

(the model can also be more detailed by specifying a separate utility function for each company; more data on the individual choice of the companies is then needed).

The probability for choosing a certain chain (port) can then be expressed as:

$$p_i = \frac{\exp(U_i)}{\sum_{i=1}^{n} \exp(U_i)}$$

Data to estimate such model can consist of revealed choices by the companies in the past or/and stated preference data collected using a survey. Data on revealed choices is very hard to get; the discrete choice model used in the present study has been based on stated preference (CPB, 2004).

Basically for each origin-destination pair such choice problem can be formulated. The demand through a particular port is then the sum of the flows of the logistic chains using the port.

2.3 Investment timing & sizing

General

The ongoing competition between the North Sea ports has triggered a spiral of investments both in port handling capacity as well as hinterland connections.
Since 1970 Rotterdam has been improving its position in transport-logistic chains for container flows by expansion of its capacity and the hinterland connections (latest is a new freight rail link with Germany). A new expansion (Maasvlakte 2) is being planned.
Antwerp has been constantly expanding its capacity and presently a deepening of the Scheldt river is planned to improve accessibility to the port.
The "decision space" for the two ports is large because of the strong expected growth and large economies of scale. A major factor in the planning is the sensitivity of the performance of the ports to competition and the influence of pricing. Uncertainty on the long term demand projections is an other factor to consider. Under such circumstances, what is an optimal investment strategy?

Manne/Freidenfels have developed an optimal expansion concept in which a trade-off is made between capital financing costs and scale effect. Such optimization needs to be expanded for the present capacity expansion problem because there is a price-demand feedback and there is a cumulative scale effect (inter-related expansions). The optimal expansion problem, starting with Manne, is elaborated below.
The performance of port development in function of the chosen investment strategy is modeled in section 3 and the sensitivity tested in section 4.

Manne/Freidenfels

Figure 4 illustrates the classic approach of a capacity expansion problem with linear demand and independent expansions.
Manne developed an optimal solution for a demand with growth rate g with equal expansions for an indefinitely growing demand at an annual growth rate g. For a cost function of the type $C = ax^{\alpha}$ (scale coefficient α) and interest rate r, the optimum is defined by (Manne, 1967, Freidenfels, 1981):

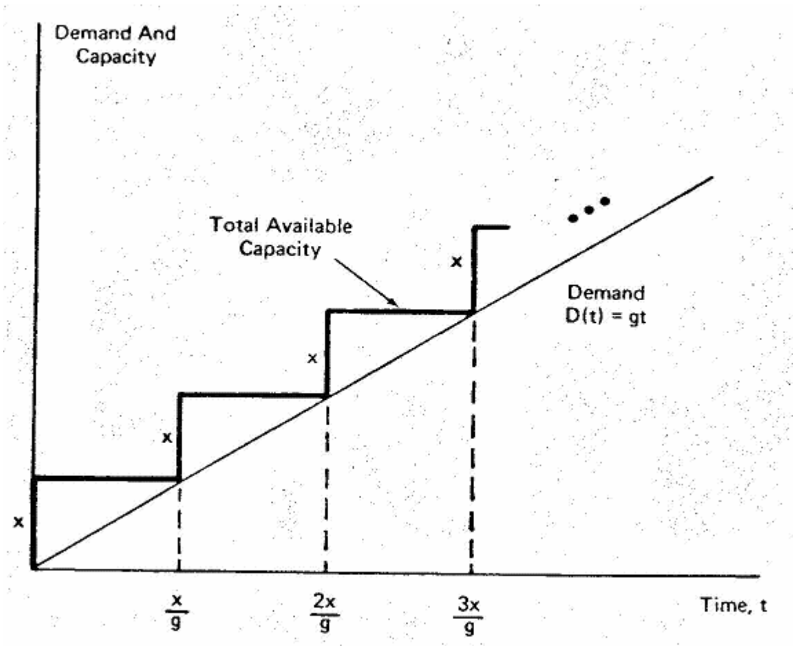

Figure 4: Capacity expansion to meet a linearly growing demand

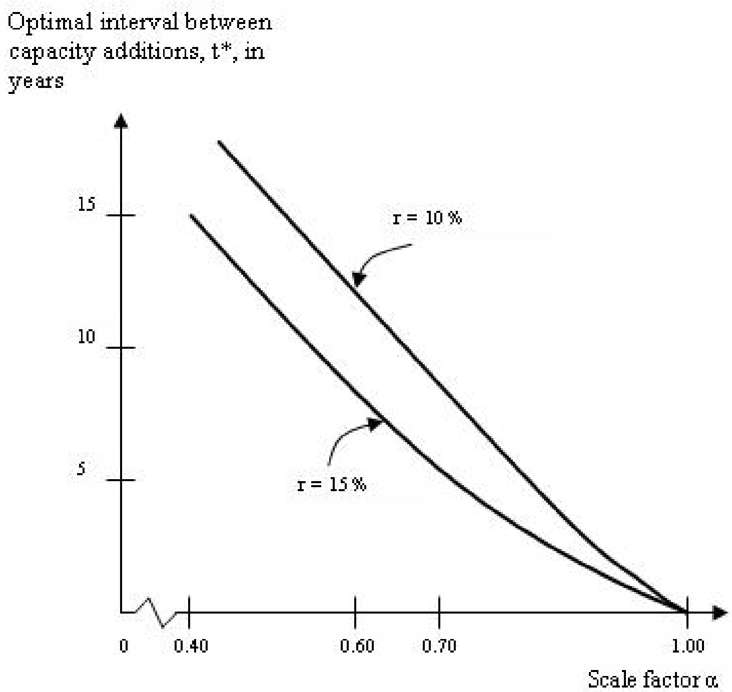

Figure 5: Optimal relationship between scale factor, interest rate and expansion interval

$$\frac{rt^*}{e^{rt^*}-1}=\alpha$$

With t^* = optimal time interval. This can be solved iteratively. The optimum for a particular scale factor α and interest rate r can also be determined graphically as presented in Figure 5.

The capacity expansion problem can be formulated in a recursive format and solved by Dynamic Programming for the non-linear demand case.

Price feedback

In general, and in particular for the port planning problem at hand, there will be a relationship between the price of the service resulting from the expansions and the demand for the service. In the present planning problem competition emphasizes such relationship. The price feedback is illustrated in Figure 6. In the proposed modeling in section 3 such feedback is explicitly taken into account in the dynamic modeling (see further)

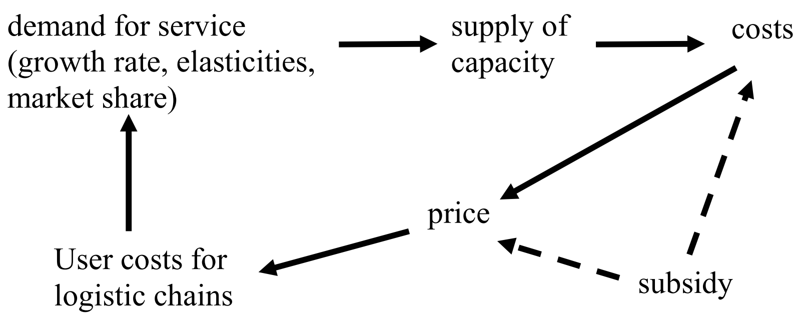

Figure 6: Schematization of the feedback between price and demand

Cumulative expansion

From analysis of a set of container ports de Neufville and Tsunokawa (1981) conclude that there are strong gains in productivity in function of increasing total size of the port. The overall productivity increases when the port is expanded or in other words the unit cost per container decreases. This can be interpreted as a cost function which has increasing economies of scale with increasing capacity. In the present analysis this has been approximated with a Manne type expansion decision incorporating increasing economies of scale (decreasing factor α) for expansions on an increasing total capacity. If everything else stays the same (e.g. no price feedback), such decision making will result in increasing sizes of subsequent expansions.

2.4 Congestion

A typical representation of congestion for highways exhibits the behavior as indicated in Figure 7. Travel time is a function of transport use *N*, and capacity *K*. A much used functional format in applied research, to represent the use of capacity and congestion, is

$$t = t_{ff}(1 + b.(\frac{N}{K})^k)$$

with:

t_{ff}: free-flow travel time
b, k : parameters (e.g. *b*=0.15 and *k*=4)

The cost for transport is the product of travel time (t) and the value of time (vot). The cost (ac) is then:

$$ac = vot * t_{ff} * (1 + b * (\frac{N}{K})^k)$$

Considerable information on congestion behavior is available for highways; the congestion behavior for a port is more complicated, in the present study a similar functional format for time spent in the port has been used as for a highway.

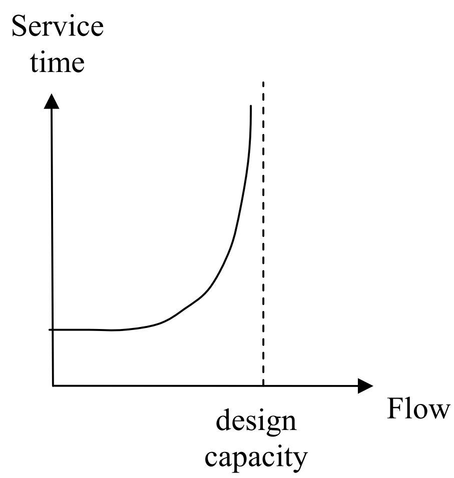

Figure 7: Highly non-linear effect of congestion

2.5 Planning under competition

Considering the above system characteristics an overview of the planning concept for port expansion is presented in Figure 8. The items with particular relevance to competition are indicated. The following observations can be made

- Structural and non-structural measures form an input to the balance of supply and demand; choices in the transport network influence the demand
- The utilization rate represents the effectiveness of the port facility and together with the cost determines the price for service; this price in turn forms an input to the competition over the network (allocation of flow over the network)
- Costs and revenue generated at the particular price allow an evaluation of the commercial performance at a particular port
- Costs and the direct, indirect and external effects are input to an economic evaluation; although the infrastructure service network forms a market with individual/private operators, there is still a potentially substantial involvement of

the government; in the schematization of the costs and benefits a differentiation should then be made between who makes the costs and –receives the benefits. E.g. a considerable portion of the users may be foreign operators, for those the user surplus should not be accounted towards national welfare for The Netherlands

- A main characteristic of the infra service network with competition is the commercial- and economic viewpoint; together they establish the viability of an expansion project (e.g. for Rotterdam)

In the present analysis the focus is on the direct effects.

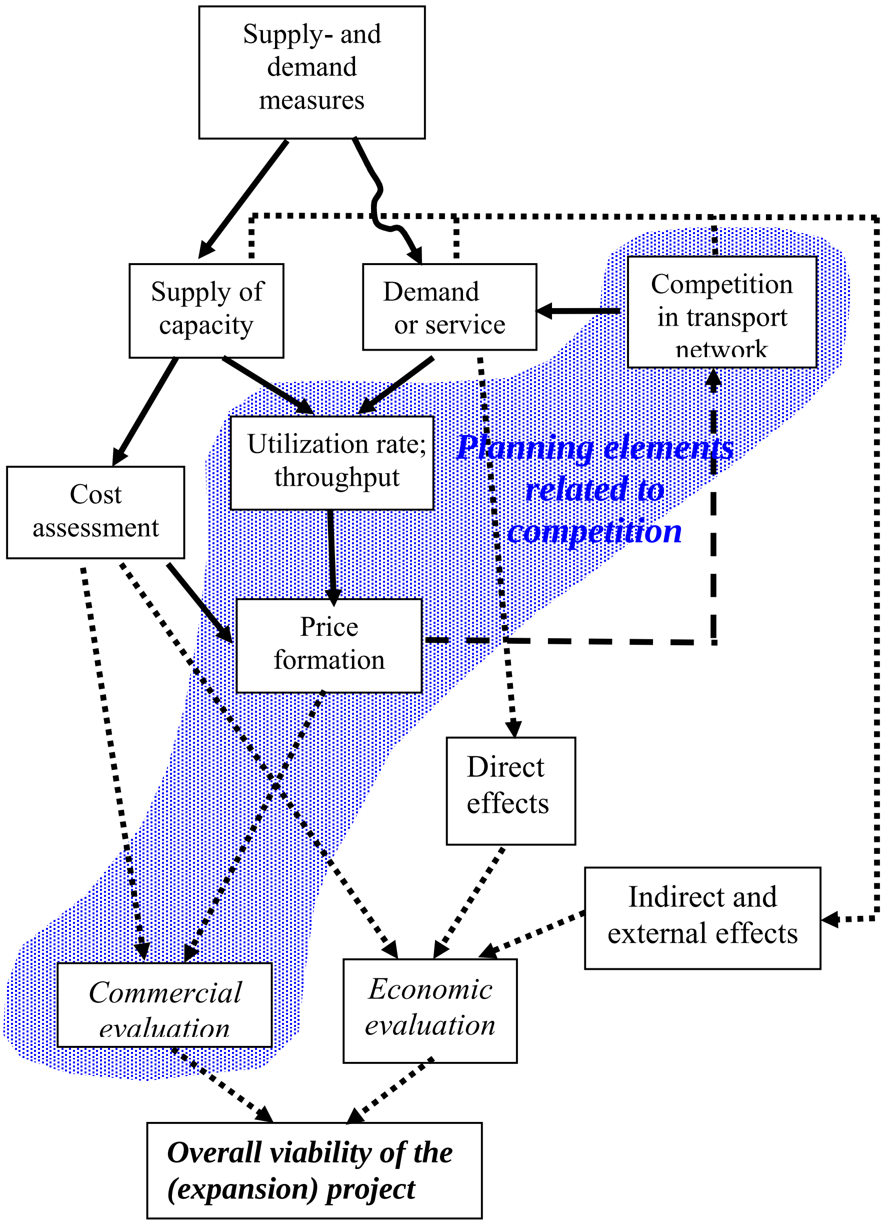

Figure 8: Concept for planning under competition

3. MODELING

As can be derived from the context of the transportation problem in Figures 2 and 3, the geographical positioning of the ports with respect to origin and destination, and the associated hinterland connections, play a significant role in the planning of the ports. The present analysis focuses on the interactive investment dynamics of two ports, Rotterdam and Antwerp, which have a high degree of substitution. Their main (joint) hinterland is considered and only the main mode of hinterland transport, which is truck transport.

The modeling concept is presented in Figure 9:

A simulation of port demand in relation to its capacity is considered over 30 years, starting from the present condition. Present total demand is 10.3 million TEU (Rotterdam 6.1, Antwerp 4.2) with a projected increase (CPB, 2004) to 31 mln TEU over the next 30 years.

The allocation of this total demand to the two ports (logistical chains) is based on the total generalized cost per TEU, using the discrete choice model. This unit cost is composed of

- a cost for recovery of port investments,
- a cost associated with the time spend in the port, including congestion, and
- a cost associated with hinterland transport, including congestion.

An important variable is the capacity utilization rate, defined as the ratio of actual flow through the port over capacity. The utilization rate forms the main input to determine port congestion.

A new capacity expansion step is triggered when the utilization rate reaches a particular maximum threshold value. A certain amount of reserve is however necessary for peak load handling. Present practice maintains a maximum utilization rate of about 90 %.

The utilization rate is a control variable: it may be decided to lower congestion levels in order to attract a larger market share.

The capacity expansion strategy forms a main input to the modeling, one of the possibilities is to use the "expanded Manne method" as elaborated in section 2.3, to determine the optimal expansion step, taking into account a progressive scale effect in combination with price-demand interaction.

The hinterland connection is represented by the distance to the main hinterland centre and the cost for truck transport. Based on a report on the present status of the hinterland connections a present utilization rate of 70% has been adopted for those transport links and the highway congestion formula is used to compute congestion. A gradual expansion of this hinterland capacity has been incorporated from year 10 of the simulation. A congested hinterland connection will have a strong effect on the competiveness of the logistical chain.

An envisaged further detailing of the model includes a specific modeling of the transportation network, including different transport modes using a joint modeling with a specific freight transportation model, see further section 5.

The data for the different components of the model have been derived from several publications. Important input data is associated with the choice modeling for shipping companies. There is practically no consistent revealed data set available to estimate the choice model parameters; there have been many changes in technology and logistic concepts which make data inhomogeneous and even obsolete. In the present analysis a recent stated preference data set has been used to estimate the choice model parameters. Due to the lack of valid empirical data describing the total system, further calibration and validation of the model will need to be based on validation of sub-components and detailing of system concepts (see section 5 for improvements/expansions).

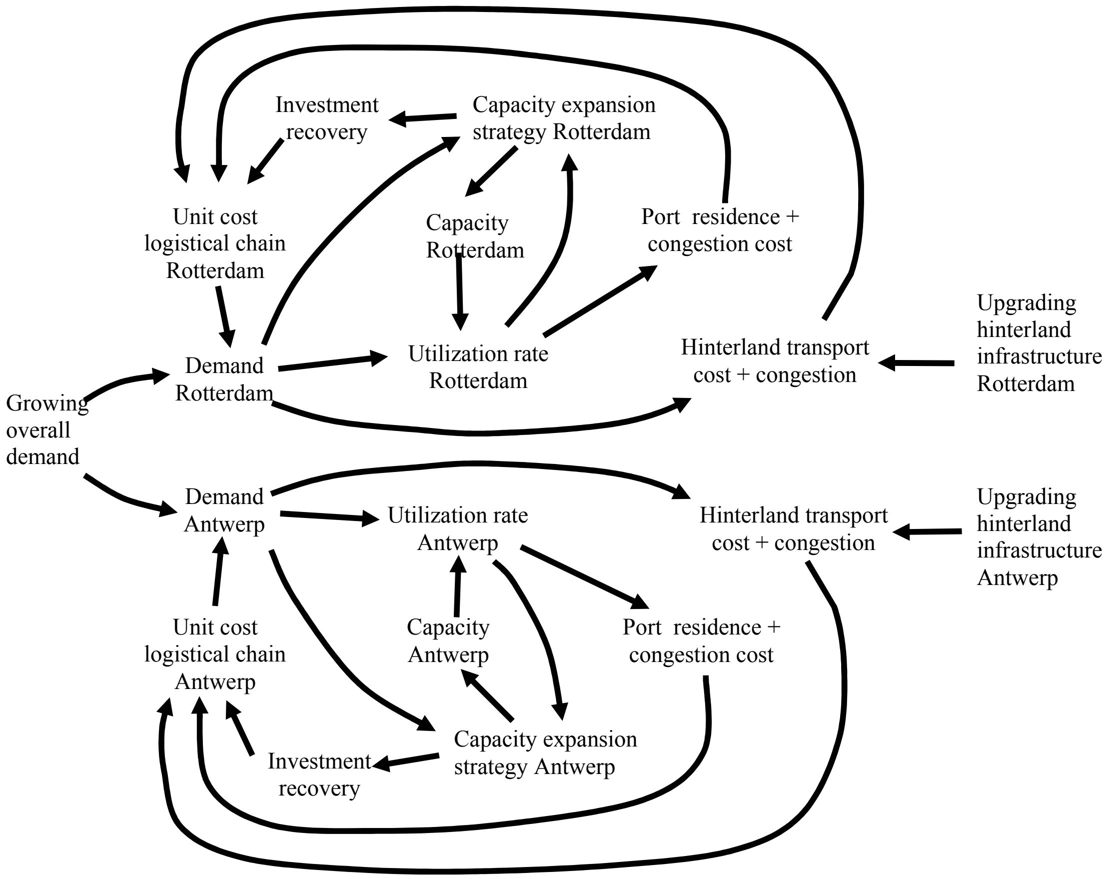

Figure 9: Conceptual systems diagram for the modeling

4. SENSITIVITY ANALYSES

The sensitivity of the competition between the two ports for the particular investment strategy is an important input to decision making. Several simulations have been made to test such sensitivity.

Figure 10 illustrates the impact of a “regular” expansion strategy which is similar for both ports: expansion at a threshold of 90% utilization rate, a fixed step expansion, and a gradual upgrading of hinterland transport to keep up with the rising transport volumes. Figure 11 illustrates the composition of the price (€/TEU) for the logistical chains.

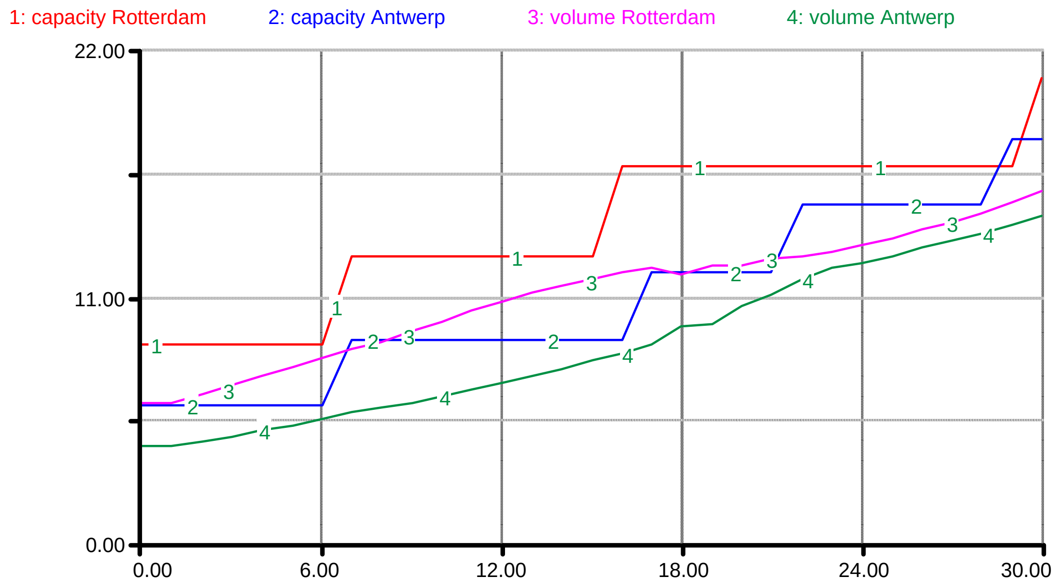

Figure 10: Development performance for a regular expansion strategy

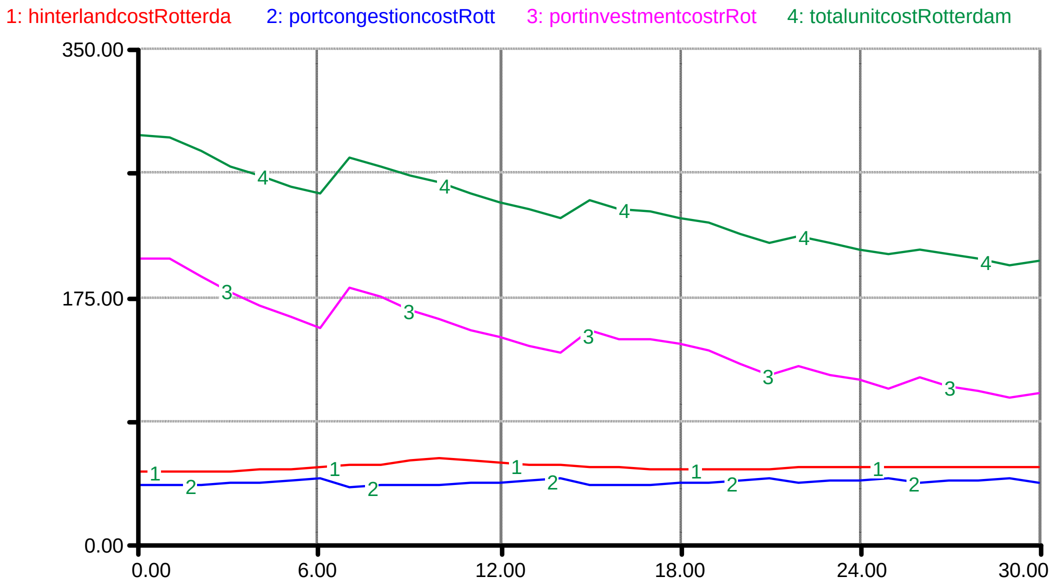

Figure 11: Composition of the total unit cost for the Rotterdam logistical chain

The largest contribution comes from recovery of port investment. Capital investment has been annualized over a period of 30 years. The total unit cost is declining over time due to economies of scale. The port investment component shows some abrupt changes at the time when an expansion is made: at that time the cost for the expanded facility has to be born by the current transport volume.

Figure 12 illustrates the situation when the hinterland connection for Antwerp is not adapted to the increasing volume: an increasing congestion cost for this logistical chain causes a substantial decline of market share for Antwerp.

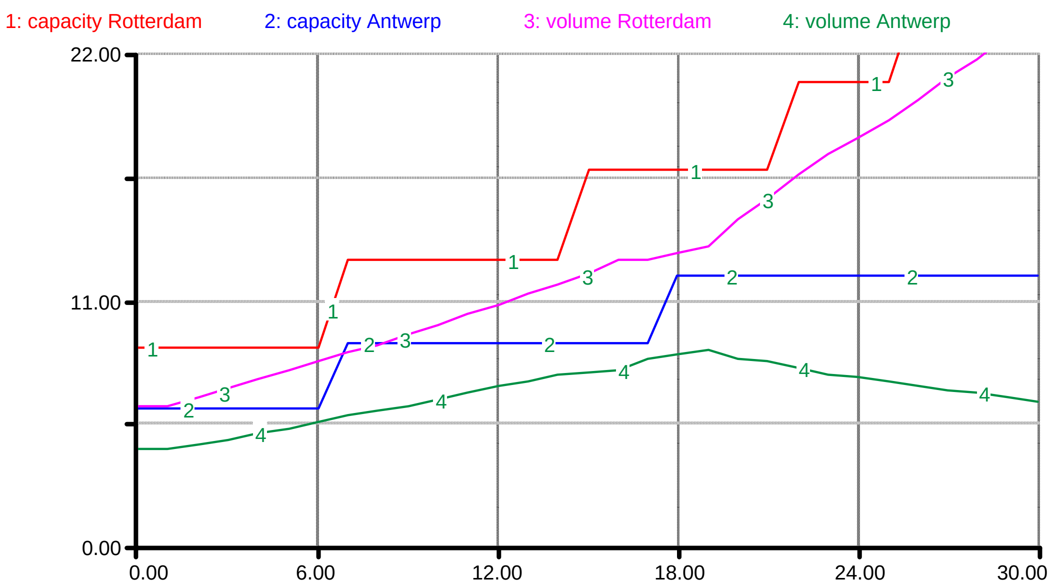

Figure 12: Loss in market share for Antwerp due to congested hinterland

Figure 13 illustrates the expansion for the two ports based on similar criteria and using an optimal expansion strategy based on an “expanded Manne/Freidenfels”. The expansions are larger than what could be expected based on expansions in the past (Figure 10), and are increasing into the future, associated with a progressive scale effect.

Such large expansions do not take into account the uncertainty in the long term projections. Figure 14 and 15 illustrate the impact of an (unexpected) stabilization of the growth in demand. An expansion of Antwerp port which is still based on the previous growth trend is the main cause for a collapse of market share of Antwerp port. A decrease in market share has a strong multiplier effect on the unit cost.

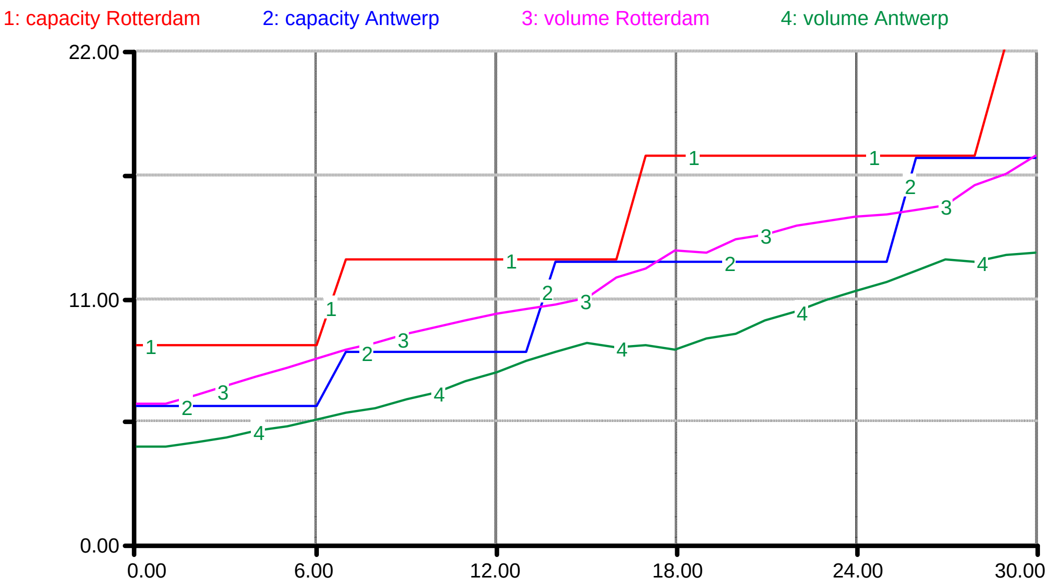

Figure 13: Port development based on an optimal expansion strategy (expanded Manne)

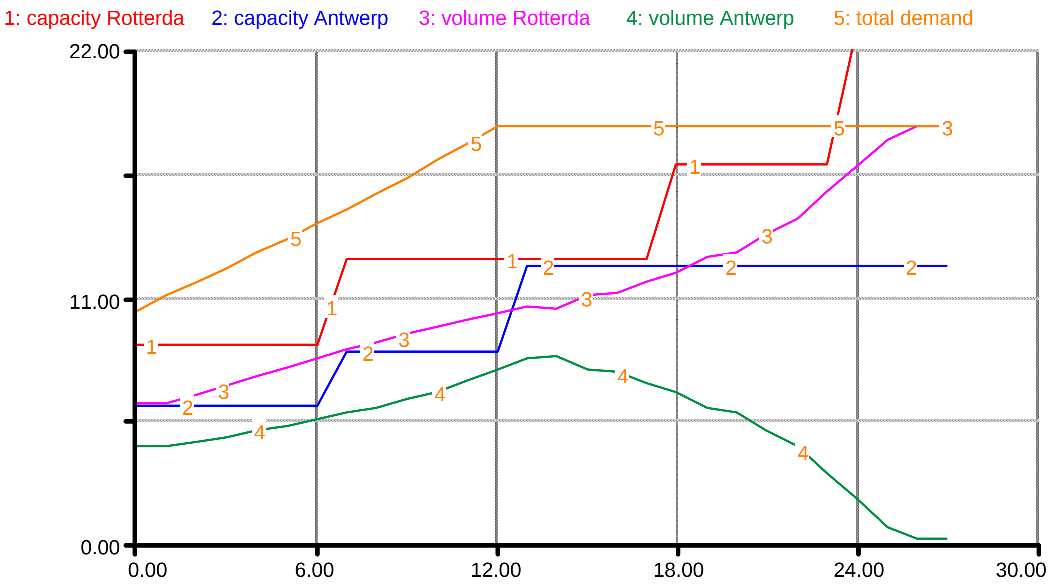

Figure 14: Effect of an unexpected stabilization (from year 12) of the demand

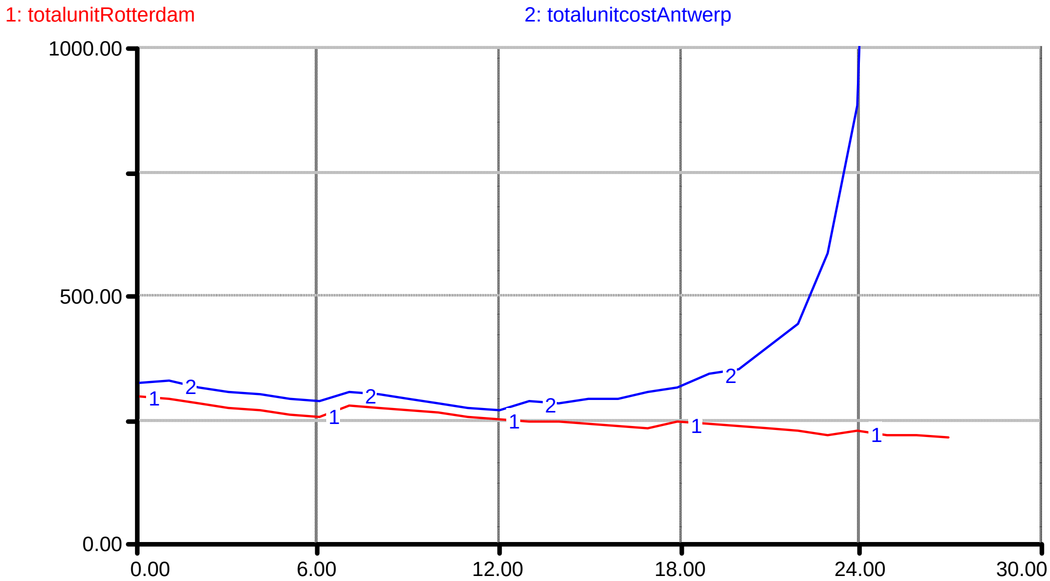

Figure 15: Effect of an unexpected stabilization of demand on the price/cost of the logistic chains

5. DISCUSSION

For the strongly growing market and volatile demand for port service, port development appears particularly sensitive to alternative port capacity expansion strategies as well as the effectiveness of hinterland connections.

The present modeling and test simulations give confidence that using a system dynamics modeling a dynamic planning model can be constructed with more functionality than present "fixed market share" models, and that such model can play an important role in clarifying the effects of different port development strategies and assist in the determination of an optimal investment strategy .

A further upgrade/expansion of the model structure and data base will be necessary in order to prepare an established planning model for practical use. The following upgrade/expansions can be mentioned:

1) *port congestion*: port congestion is an important factor in strategic port planning. An increased insight in port congestion and relationship to capacity, considering the maritime/nautical as well as the land side of the port transfer processes is needed to support strategic planning for the port. This could be established using simulation analyses with detailed models.
2) *Scale effect*: scale effects, especially in a strongly growing and volatile market, play a most important role in port expansion planning. A more

detailed description of scale effects is required. This is also related to the choice process of shipment companies.

3) *Choice process*: factors other than generalized cost play a role in the choice for a particular logistical chain; such are reliability, port approach time, and the potential outlook for further development of the port and business opportunities. The discrete choice model can be further elaborated to include such factors. This may be linked to an expanded modeling of port features.

4) *Transport network modeling*: a strategic port planning tool will need to address the important features of the network transport system and associated options such as the different modes of transport, inter-modal exchanges, short sea shipment (hub and spoke system), different product groups, etc. Specific models (such as SMILE, Tavasszy, 2003) are available to describe freight transport over a network in response to a particular origin-destination trade network. The combined planning for network aspects and time dynamics could be addressed by linking such specific freight transport model with a dynamic investment model as described in this paper. The details from the transport network could be transferred to the strategic investment model using repro-functions.

5) *Strategy formulation*: the competition for port service comprises a limited set of suppliers (oligopoly); strategic decisions by individual suppliers can strongly influence the market situation; strategic alliances may be made (as suggested in some European strategy reports) addressing types of goods, routes, modes or infrastructure facilities, in order to reduce uncertainty and improve overall effectivity. Game theory may provide useful approaches to a systematic formulation of strategies.

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