MARITIME LOCATION DECISIONS FOR LNG BUNKERING FACILITIES

Reinier C. Schneider
Bleeve, Nicolaas Beetstraat 6B, 3511 HE Utrecht, reinier@bleeve.nl

Iris F.A. Vis
University of Groningen, Faculty of Economics and Business, Department of Operations, P.O. Box 800, 9700 AV Groningen, i.f.a.vis@rug.nl

Abstract

Liquefied natural gas (LNG) is one of the upcoming fuels to be used for more sustainable shipping activities in the maritime sector. For a widespread adoption by end-users, a refuelling network requiring capital intensive investments, needs to be in place. From a macro perspective of suppliers of LNG, it makes sense to develop the infrastructure at strategic locations that capture as many vessels and ships as possible. The goal of this research is to develop a facility location model that can contribute to the location selection of LNG facilities in a new fuelling network. The new model will fit the maritime sector and specifically the LNG transition. Experiments, with data obtained from expert interviews, have been performed to study facility location decisions in the North Sea areas.

1. Introduction

The energy demand is increasing worldwide. Natural gas (NG) is an important source of energy which is becoming increasingly important in fulfilling the worldwide demand. The NG is traditionally transported through pipelines. However converting it to liquid natural gas is an efficient way for transporting it over long distances. The gas can be liquefied by cooling it down to -162 $^{\circ}$C at atmospheric pressure. The world market for LNG has strongly increased since its inception in the 1970's. The number of large-scale LNG transportation vessels expanded strongly in the past decade. The industry is known for its large volumes and high the investments that are involved.

In the recent years the LNG is not only used as an alternative supply to the gas networks. For example, in Norway the small-scale applications of LNG have proven to be valuable. Especially in the transport sector, LNG is a good alternative on the conventional fuels. Acknowledged and supported by the EU governments, end-users are stimulated to make the transition towards new and cleaner fuels. New regulations force ship-owners to reduce pollutions. Many different kind of ships face the new regulations and they all exert different fuel demands. Most of all, the ships that remain most of their time within the SECA areas (short sea ships) are forced by the regulations. A lack of infrastructure and fueling facilities could seriously hamper the desired transformation and could form an obstacle for large-scale adoption. On the other hand, if there is very little demand for the new fuel, infrastructure companies will have few incentives to invest in the development of this new network of facilities (e.g., storage tanks, fueling facilities). The LNG transition is facing the chicken or the egg problem. Since the investments needed for the development of the refueling network is very capital intensive, risks are high. From a macro perspective of the suppliers, it makes sense to develop the infrastructure at strategic locations that capture as many vessels as possible. For a more detailed overview of LNG as fuel for the maritime sector we refer to Schneider [1]. Thunnissen et al. [2] present a blueprint depicting a visualization of the LNG supply chain and challenges encountered in LNG network design.

In this paper, we specifically focus on LNG for the maritime sectors. On their trips vessels need to bunker LNG at ports along their routes. Suppliers need to carefully select bunker locations to serve customers in an efficient and effective way. For almost every institution the location of their facilities is an important issue. Specifically in a new network where product-adoption is growing. Melo et al. [3] provides an overview on facility location models in general. Hodgson [4] realized that demand is not always exerted at a fixed node in the network, but also by a flow through the network. This niche within the field of Facility Location problems is called “flow capturing location models (FCLM)” as they deal with flows of demand. We position our paper on facility location models for capturing demand of sailing vessels in this line of research. For a detailed overview on literature in this field we refer to Schneider [1].

In the FCLM demand is represented as flows traveling on origin-destination (OD) paths of the network (flow-based demand). A feature of this type of demand is that the purpose of the trip is not to obtain service, but, if a facility exists along a route, customers may wish to obtain service. The convenience of these models is often measured as the distance to be deviated from the origin-destination path to the facility. This way of optimizing servicing makes more sense for the problem under hand, as these kinds of deviations are inevitable while maximizing flow coverage of the maritime movements. Bunkering fuel is typically not the main purpose of ships. It can rather be seen as a necessary requirement to fulfil their objectives. Cannibalization forms an important challenge in solving flow-capturing models. Flows passing nodes are coming from origins and going to destinations; they have passed, and will pass other nodes along their trip. As demand can be covered by different facilities at more than one node on the same trip, cannibalization can occur ([4]). We consider this particularly true for the maritime movements, as ships will typically not fuel twice during their trip.

In literature a variety of FCLM models can be found to be used in different kinds of applications. For an overview we refer to Zeng [5]. Some papers are explicitly written to contribute to the establishment of hydrogen fueling stations in the US; many others have different perspectives. However, none of the literature is tested at nautical environments. In the maritime sector we deal with quite different characteristics, such as strong preferences for fueling at their origin or destination, than the on-land movements and situations described in the existing models.

2. Research approach

The introduction of a new fuel comes with networking challenges: none to very few facilities are in place challenging the adoption by end-users. Where to locate these facilities can form an important strategic choice. The goal of this research is to develop a facility location model that can contribute to the location selection of LNG facilities in a new fueling maritime network. Because LNG has different characteristics than conventional maritime fuel, a complete new supply chain is to be erected. The sector is known as conservative making this transition of a revolutionary kind. It is this combination that makes that there is not much written about maritime network developments, specifically on new (fuel) facility networks. So far, no research has applied the use of a flow capturing model in this sector.

Based upon interviews in the sector we can conclude ship-owners do have a strong preference to fuel at the Origin or Destination (O-D) of their trips. However, sometimes they do reschedule to bunker at alternative ports because of a variety of reasons. When ship-owners deviate to alternative ports, they do discriminate in their choice of the ports. Three models, namely Tanaka and Furuta [6], Zeng et al. [7] and Zeng et al. [8] do each incorporate some of the these challenges and, therefore, match closest to our case. In the next section these three models are used as starting point from which a new model will be extracted. Looking at the methods for solving these problems almost all authors make use of linear programming. Because the models that closest describe the problem under hand are all using these linear integer programming solutions, this will be the starting point for the model as presented in Section 3. Due to the strategic nature of the model, computation times do not form a direct threat for the usage of the model. In our model maritime-specifics, as derived by interviews with industry experts and end-users in the maritime sector, will be incorporated. The new model designed will be validated by means of experiments with numerical data to test the sensitivity and robustness of the model in Section 4. Furthermore, in Section 5 we show the use of the model in a real life case. The LNG network roll-out at the countries surrounding the North Sea forms a perfect example to test the value of the model for a real-life case. With many big ports along the coasts of countries like Belgium, the Netherlands, UK, Germany, Denmark and Norway, the short-sea traffic is very intensive. At this moment, large infrastructure companies are looking at the possibilities and challenges of the new alternative fuel. We show how the macro view and outputs from the new model potentially could help decision makers in the selection of strategic locations. Section 6 presents discussions on the outcomes and section 7 describes conclusions.

3. Model

In modelling we need to include the following three characteristics for maritime shipping. Firstly, vessels have a strong preference to fuel at the beginning or at the end of their journey. In the model of Zeng et al. [7] differentiation is allowed by enhancing customer preferences on each of the pick-up location they pass by. In our situation, we could build upon this model by adjusting parameters describing the benefits of the customer during their trip. However, if vessels are not able to fuel at O-D, the preference for alternative fueling locations cannot be simply described because in the model of Zeng et al. [7] no alternative routings are evaluated. We suggest that this can be best done by taking into account the willingness of the vessels to deviate from their O-D trip depending on the size of the facility. In the model of Tanaka and Furuta [6] flow can be captured by a facility if the size of the facility is large enough to rationalize the necessary deviation. In the situation under study, the attractiveness of alternative fueling locations is described by the ports' characteristics (e.g., size, bunkering solutions, port fees).

Secondly, the model designed needs to be capable to deal with variety in customer demand. Namely, large cargo vessels do have larger fuel demand than, for example, smaller Ro-Ro vessels. Current literature typically assumes customers with equal demand. We suggest to model this characteristics as follows: the interception of larger types of customers should have a greater contribution to the objective value.

Thirdly, the characteristics of the network itself differ. In most 'flow capturing' models all nodes in the network are potential facility sites, because of the on-land environment. Many models analyze areas of nodes that suit the solution, rather than exact locations. At nautical networks, only ports (mostly at the edges of the network) are potential sites. Facility location selection, therefore, changes from the on-land situation ("somewhere along this road or in this area") to an exact port selection.

3.1 Maritime flow capturing facility location model

The Maritime Flow Capturing Facility Location Model (MFCFLM) aims to maximize the facilitation of fueling ships with a limited number of facilities. Each ship is assumed to have a fixed routing schedule, from Origin (O) to Destination (D). The set of ships that follow the same route form a flow q, the number of ships is given by the frequency of that flow f_q. However, each ship has a different fuel demand; a big cruiser will exert a large demand compared to a small fisherman boat. Both the number and size of the set of ships combine a certain weight to the flow q.

All these routes flow through a network. This network that forms a mathematical representation of the several ports and shipping lanes, consist of a set of nodes and connecting arcs. All ports form potential locations for the facilities, they form a subset of the nodes in the network.

Because the number of terminals will be limited, the majority of the ports will not locate fueling facilities. Because bunkering activities (vessel fueling) can easily take multiple hours, all ships will remain to have a strong preference to fuel at either their origin or destination. However, we assume that ships that do not have the possibility to fuel at their O-D will sometimes opt for a deviation from the shortest path between O-D. These extra sailing miles come at a cost for the ship-owner; they form part of the willingness of ship-owners to deviate and take a non-optimal route for their O-D-trip. This does not mean the willingness for additional miles to alternative ports is always the same. As mentioned, port characteristics like price levels or port fees, do have influence on the choice of their preferred alternative tanking facility. This trade-off between facilities makes that the model does not only minimizes the total deviation distance.

The model therefore optimizes the coverage of a set of p facilities by opening and closing facilities under the different alternatives. It not only locates the facilities, it also allocates all flows to the best fueling facility according to the deviation preferences. The model evaluates all weighted flows to all facilities and then picks the best solutions for the restricted number of facilities. 'Best' in this case forms the set of locations that maximizes the sum of all benefits of the 'captured' ships. 'Captured' in this definition is when a ship is allocated to a facility.

The model can easily be restructured so that the user can arbitrarily select the facilities of choice and look at the impact and consequences with regard to this man-made selection. That opens the possibility to evaluate not only the design of a new network, but also existing networks. This will be evaluated in section 5.

3.2 Assumptions

We have to make some assumptions on modelling this problem. Although ship-owners and vessel movements are hard to generalize, we assume they behave similarly. The ship-owner's preference to deviate to an alternative fueling facility is not an exact science. There may be many arguments (e.g., price, contracts, politics, safety restrictions) upon which ship owners choose their bunkering locations. We have modeled their motivations into a linear equation that relates willingness to distance and preferences. In section 4, we will evaluate the quality of this equation and the impact on the outcomes of the model. Although these arguments might differ slightly from ship-owner to ship-owner, we expect that even if there are some differentiators they will not be of such weight that they will scramble the overall picture. The model could be extended by specifying each ship-owner's personal preferences, at the cost of increased calculation times. However, most of the decision-making in the sector is value driven and almost equal for most ship-owners (based on expert interviews at bunkering companies and large ship-owning companies Royal Wagenborg and Anthony Veder). Since we have no strong argument to follow this and with no dataset at hand indicating otherwise, we assume preferences are equal among ship-owners. Facility capacity can form a restriction for the number of ships that can be serviced. For our experiments we relax this constraint as this is not of influence due to the large-sized facilities we have in our scope (based on interview at Gasunie NV).

Summarizing, the following assumptions are made in this model:

- The willingness to deviate to an alternative port is equal to all ships sailing the same trip.
- Port preferences have a linear relation to the attractiveness of the port and the willingness of ship-owners to go to that port.
- Ships that pass one or more facilities with a positive contribution (pending willingness and port preferences) are assumed to be captured.
- Ships have to be captured by one facility only.
- Ports within a small radius are combined to one potential location or are strategically clustered.
- Ships do only sail on links connecting network nodes; so, no shortcuts are made.
- All ships sailing the same O-D, use the same route through the network.
- Ships fueling consumptions are generalized into categories (e.g. small, medium and large).
- Facility capacity is unlimited (optional).

3.3 Parameters

- Parameter q describes a particular O-D trip; f_q is the flow frequency of that trip. Together they form the set of all routes Q.
- A facility is described by k, located only within the set of potential locations (L) which in its own is a subset of all nodes in the network (N). A cap p is set on the maximum of facilities that can be located.
- The fuel demand of the flowing demand is not just a function of the number of ships that follow that route, but also of the type of ships. Parameter ω_s gives the opportunity to refine that 'weight' by fuel consumption of ship s. The sum product U_q therefore describes both frequency and consumption.
- Furthermore distances are measured in miles: d_{ij} is the shortest distance between O-D d_{ik} is the distance between O and facility k and d_{kj} is the distance between facility k and D
- The willingness for ship-owners to deviate is a function of both multiple port preferences (weighted in γ_k) and the deviations distance $\delta\_q\text{^}k$. Combined with general parameters α and β, they describe the ship-owners willingness to divert from trip q to port k.

3.4 Modelling

The aim of the MFCFLM is to maximize not only the number of consumers who encounter at least one facility, but also the benefits of customers bunkering at that location. The model locates p (identical) facilities across the nodes in the network to maximize the total flow captured. To formulate the MFCFLM as an integer programming problem, the following two sets of decision variables are introduced:

$$Y_k = \begin{cases} 1, & \text{if a facility is located at node } k \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

$$X_{q,k} = \begin{cases} 1, & \text{if flow } q \text{ is captured at facility } k \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

The formulation of the optimization problem is as follows:

$$Max\ Z^{(G,U)} = \sum_{q \in Q} \sum_{k \in L} X_{q,k}\, G_{q,k}\, U_q \quad (3)$$

In which the benefit of capturing of flow q at facility k is described as:

$$G_{q,k} = \begin{cases} 1 & \text{if } k \cup \{i,j\} \\ \beta - \alpha\, \delta_q^k / \gamma_k & \text{otherwise} \end{cases} \quad (4)$$

Where:

$$\delta_q^k = (d_{ik} + d_{kj}) - d_{ij} \quad (5)$$

$$\gamma_k = \left(\sum_s \gamma_{k,s}\, \omega_s\right) / s \quad (6)$$

The weight on the different flows q is described as:

$$U_q = f_q\, \omega_s \quad , \forall q \in Q, \forall \omega_s \quad (7)$$

Subject to the following constraints:

$$\sum_{k \in L} X_{q,k} \leq 1 \quad (8)$$

$$X_{q,k} \leq Y_q, \forall q \in Q, \forall k \in L \in N \quad (9)$$

$$\sum_{k \in L} Y_k = p \quad (10)$$

$$Y_k \in \{0,1\}, \forall k \in L \quad (11)$$

$$X_{q,k} \in \{0,1\}, \forall q \in Q, \forall k \in L \quad (12)$$

$$0 \leq \gamma_k \leq 1, \forall k \in L \quad (13)$$

$$0 \leq \alpha \leq 1; 0 \leq \beta \leq 1 \quad (14)$$

Constraints (1), (2), (8) and (9) follow from the traditional FCLM model by Hodgson [4]. The optimization is done through alternating potential locations (1) and allocations (2). The objective function (3) is aimed at maximizing the total benefits of intercepting flows in a network considering where in the journey they are intercepted. Equation (4) shows the value of interception of a certain flow q at possible location k.

The function is a combination of the product of deviations (5), port preferences (6) and the parameters α and β.

Constraint (8) prevents cannibalization and ensures that each trip can only be intercepted once; constraint (9) that the trip can only be intercepted by facilities it visits. Equation (10) stipulates that the total of facilities cannot exceed p. Constraints (11) and (12) are the integrality conditions. Parameters α and β are also constrained.

The unique characteristics of the maritime environment are reflected in (4), (5) and (6). The value that a ship-owner obtains from a service is largely a function of the attractiveness of the alternative port (9) and the extra miles to sail to that alternative port (8). In any scenario the benefit of intercepting a flow at origin or destination is set at the maximum (1.0) and is of less value (4) for alternative ports. This value decreases for every port when deviation miles are increasing or the port's attractiveness is lower. This attractiveness is a function of port parameters such as price levels, service facilities and port fees. Regardless the number of parameters that affect the function, linearity can be secured through averaging the scores (6). Also new is the way of assigning a weight to each flow (7). Remember this is not only described by the number of vessels but also by a factor that differentiates the type of vessels by its fuel demands

3.5 Using the MFCFLM

The general procedure for using the MFCFLM model contains a few steps:

1. Formulate an overall network by identifying all ports as potential facilities and links representing routes of the ships.
2. Load the dataset into the model. The dataset should contain ship movements between ports within the scope of the network over time (routings). In the form of a from-to matrix containing all information, the information can easily be loaded into the model.
3. Define the values of the parameters that describe the ports attractiveness (γ_k) and the willingness by ship-owners to deviate (α) and (β). See section 4 and 5 for a more detailed description.
4. Fill in the shortest path distances between all ports, or use the iterative Floyd-Warshall algorithm ([8]) for the calculation of the shortest path between all ports.
5. Calculate the deviations from the shortest path between O-D to all alternative ports.
6. Solve the optimization problem as described.

4. Numerical Experiments

4.1 MFCFLM for a small Network

In Figure 1 a small network containing 8 nodes (of which 5 ports) and 8 links is presented. In experiments (1 and 2) we have five ships (a to e) flowing through the network with different O-D routings. In experiment (3) a sixth ship is added that is also following route (a). Port preferences are set equal. The O-D-preference is set at 1.0. If the ships cannot fuel at either O or D they have the opportunity to visit any of the other ports. Since the ship has to deviate from its shortest path between O-D, the value for capturing a deviating ship decreases 0.1 for each extra mile. A ship sailing 2 extra miles to fuel at location *X* will therefore contribute 1- 0.2 =0.8 to the objective function.

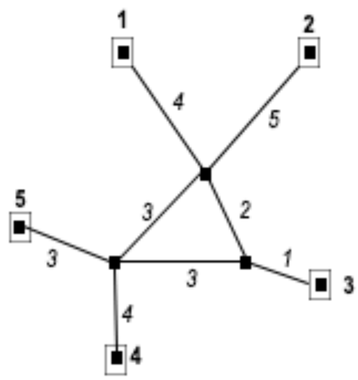

Figure 1: Small Network containing 5 Potential Locations

Table 1: Routings in the Small Network

Experiment	Routings (# of ships)	Port preference
1	a. 1 to 2 (1) b. 2 to 5 (1) c. 3 to 4 (1) d. 3 to 5 (1) e. 5 to 4 (1)	1 = 0.5 2 = 0.5 3 = 0.5 4 = 0.5 5 = 0.5
2	a. 1 to 2 (1) b. 2 to 5 (1) c. 3 to 4 (1) d. 3 to 5 (1) e. 5 to 4 (1)	1 = 0.5 2 = 0.5 3 = 1.0 4 = 0.5 5 = 0.5
3	a. 1 to 2 (2) b. 2 to 5 (1) c. 3 to 4 (1) d. 3 to 5 (1) e. 5 to 4 (1)	1 = 0.5 2 = 0.5 3 = 0.5 4 = 0.5 5 = 0.5

The input for the model is given in Table 1, the output of the models' optimization is shown in Table 2.

Table 2: Output of the MFCFLM Test Network

Experiment	Port	Objective function	Ships Intercepted
1	5	3.4	4 (b,c,d,e)
2	3	4.1	5 (a, b, c,d,e)
3	3	3.6	6 (2*a, b, c, d, e)

The first experiment forms the base scenario (all ports are equal, all flows equal) in which port 5 was selected as 'best' location capturing flows b to e. As we can see that making port 3 more attractive (e.g., reducing its port fees) makes that port 3 now becomes the locations that captures the largest contribution to the objective function (by capturing flows a to e). Intensifying flow from O-D routing a (experiment 3) also makes that port 3 was selected over port 5.

4.2 Numerical Experiment

The numerical experiments we use to test the model is based upon a simplification of the shipping network in the North sea. The network is displayed in Figure 2 consisting of 90 nodes - of which 28 ports- and 189 links. Distances between nodes are measured in sea miles (equivalent to 1.8 km) using ArcGIS 10.1. The mathematical programming software to solve the network problem is AMPL. Exact optimal solutions are obtained using the commercial mathematical solver ILOG CPLEX 11.2.1 (IBM; http://www.ibm.com/). The ILOG CPLEX is loaded in the AMPL software. Solving times are within seconds.

After demonstrating how the model works, we will look closer at the outcomes and sensitivity of the model in the larger network from Figure 2. For the numerical experiments in this section we will set all flows through the network and port preferences are equal. In each port one boat departs to every other port. Through the network containing 28 ports, a total of 28*(28-1) = 756 ships will flow.

Recall that the model optimizes the sum of the benefits of 'captured' ships by appointing ships (allocation) to one of the selected ports (location). By relaxing the constraint on the number of potential locations *p*, the model searches not for the next single port that has the greatest contribution in addition to the previous selection. It rather searches the next 'set' of ports that together make the greatest sum of benefits. The graph of the sum of benefits under the limited number of potential locations *p* is given in Figure 3. It shows an exponential growth with a limit that corresponds to the maximum benefit (1.0) times the number of ships (756). As explained below, different parameter settings lead to different benefit functions (High Willingness, Central Willingness and Low Willingness).

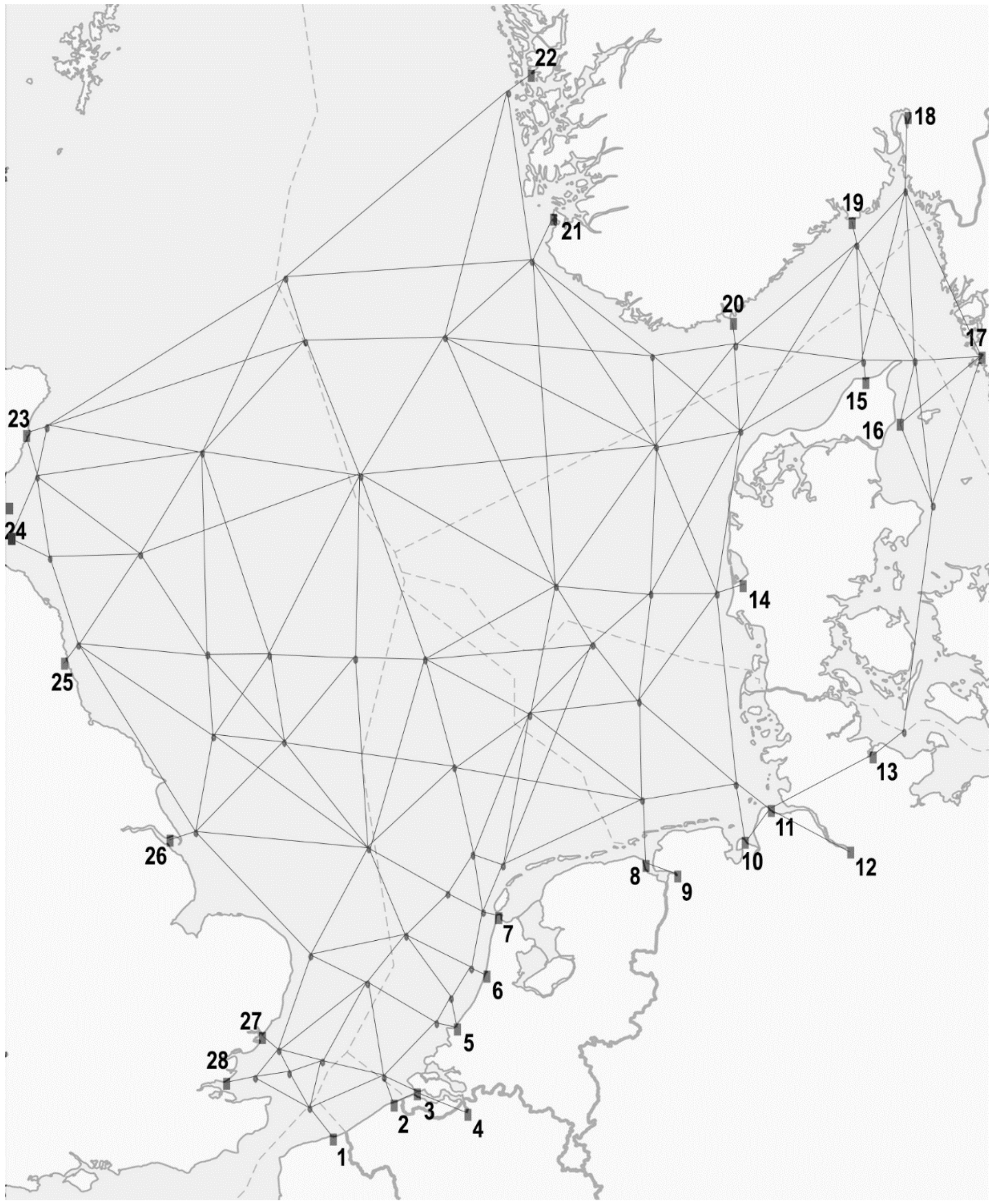

Figure 2: North Sea and its 28 Main Ports (Port Names are included in Table 3 below)

However, the location-selection by the model is probably much more valuable for the user. To evaluate the selection of ports in the situation for a new network, we run the model from 1 pick to 9 picks (which represents approximately 1/3 of the total ports). Since we evaluate the construction of a new network, the first set of locations has most of our interest. The contribution of the next ports is of much less importance. We, therefore, allow the model to freely choose facilities up to 9! times. Most important ports will be reflected very often, less important sites only few times.

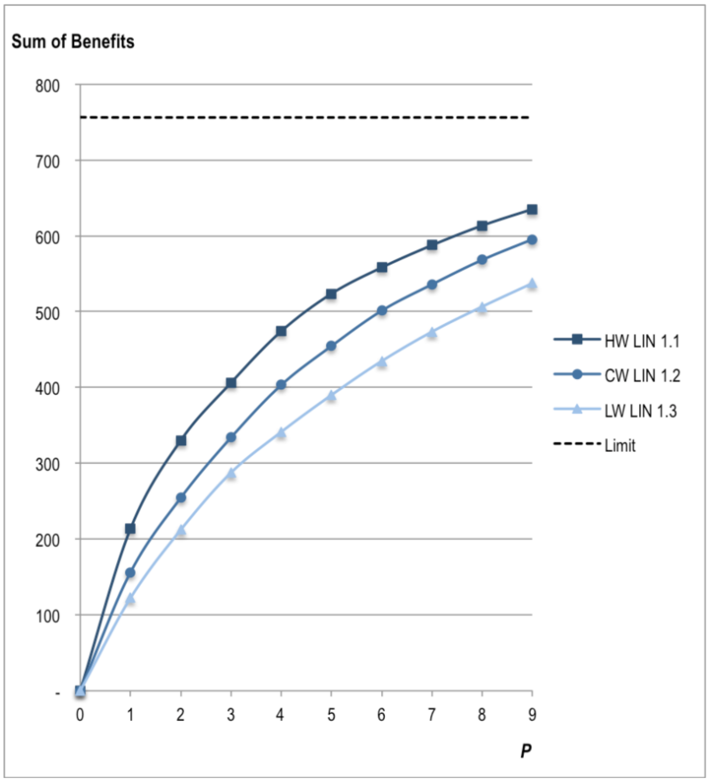

Figure 3: Optimization of the Model: the Sum of Captured Benefits

The willingness by ship-owners to deviate from the original shortest route, is influenced by the deviation distance to reach the alternative port (5) and the attractiveness of that port (6). In this model we use parameters to determine the benefit to alternative fueling. Because the user of the model is free to choose the parameter-settings pending on the business information at hand, we will to evaluate the influence of these parameters in two different ways. Firstly, we run the model for nine different settings of α and β and see the impact to the outcomes. Secondly, we will evaluate the choice for the linear formula. We will compare the linear benefit function (4) with an exponential function (15).

Following from (4) parameter β sets the maximum benefit for fueling at an alternative port, the differential parameter α translates the reduced benefits per mile. The importance of proximity along the route becomes higher when alpha is increased: ships will be more likely to stick to their original route. Although port preferences and deviation willingness can be evaluated with ship-owners or other institutions and based upon business data, the exact parameter settings of α and β are set by the user of the model. When we follow intuition, the benefit for fueling at the alternative port after a certain 'x' extra deviation miles, will make no more sense (refer to assumptions).

Cost/benefit arguments will point out a maximum deviation distance after which benefits will grow sour. This intuition is reflected in the linear function (4). Expert interviews at large ship owning companies learned us that, here, under normal port attractiveness we can translate this into three levels of willingness:

- Low Willingness (LW) - Positive benefit for a deviation <25 miles
- Central Willingness(CW) - Positive benefit for a deviation <50 miles
- High Willingness(HW) - Positive benefit for a deviation <100 miles

All three levels of willingness are again described under three different settings of α and β. The functions that describe these benefits are shown in Figure 4, their settings and outputs in Table 4 in the appendixes. We evaluate the sensitivity of the parameters by looking at the times ports are selected by the model under the different linear settings of α and β. In Figure 5 we see the reflections (%) of the ports after 9! picks under nine different linear settings. The two dotted reference lines indicate the character of the two most extreme outcomes. The sloping reference line indicates a very strict selection behavior of the model; always the same ports are selected, despite the different settings of the parameters. If the selections of the model follows the horizontal reference line, it indicates selection-behavior characterized by a high sensitivity around the parameter setting.

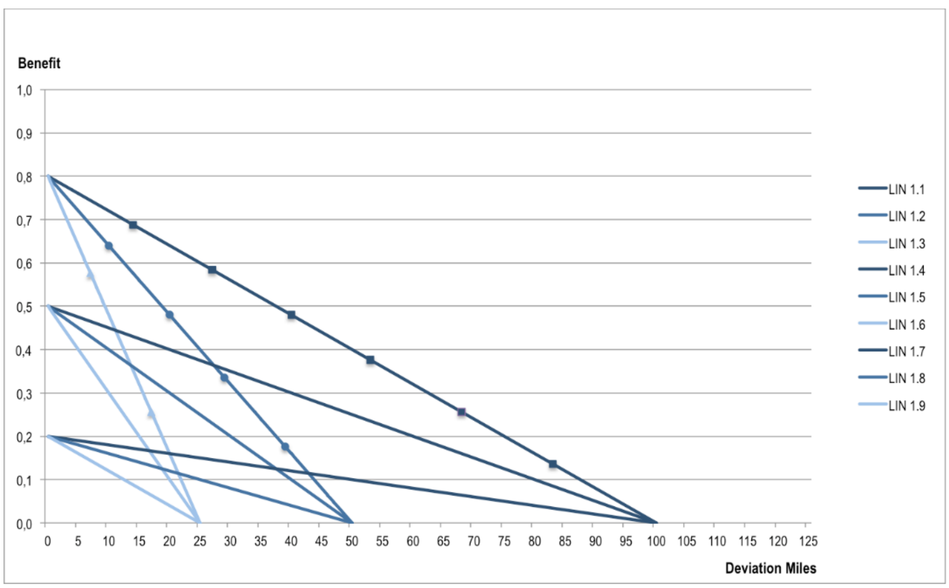

Figure 4: Linear Benefit Functions for Alternative Ports

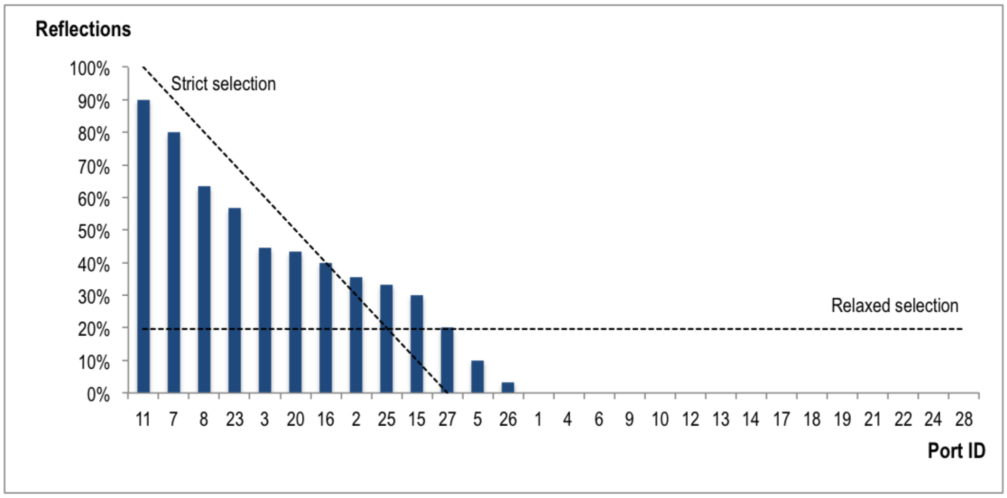

Figure 5: Output Experiment 1: Port Reflection Percentage

As we can see, the model in the numerical experiment is following the strict selection behavior quite well. Looking at the output of the model in Table 4, especially parameter β has very limited influence on the location selection. The exact setting of parameter α does influence the selection of the model, however out of all the experiments the same 'usual suspects' are selected. It is the same set of ports that are selected, no matter the linear settings. Geographically well-located ports to come out on top: the reflections show ports like Cuxshavn[11], Den Helder[7], Eemshaven[8], Aberdeen[23] and Vlissingen[3] are good locations. All locations do indeed have either other ports or large shipping lanes nearby, intensifying traffic nearby these ports and therefore explaining their large contributions to the sum of benefits.

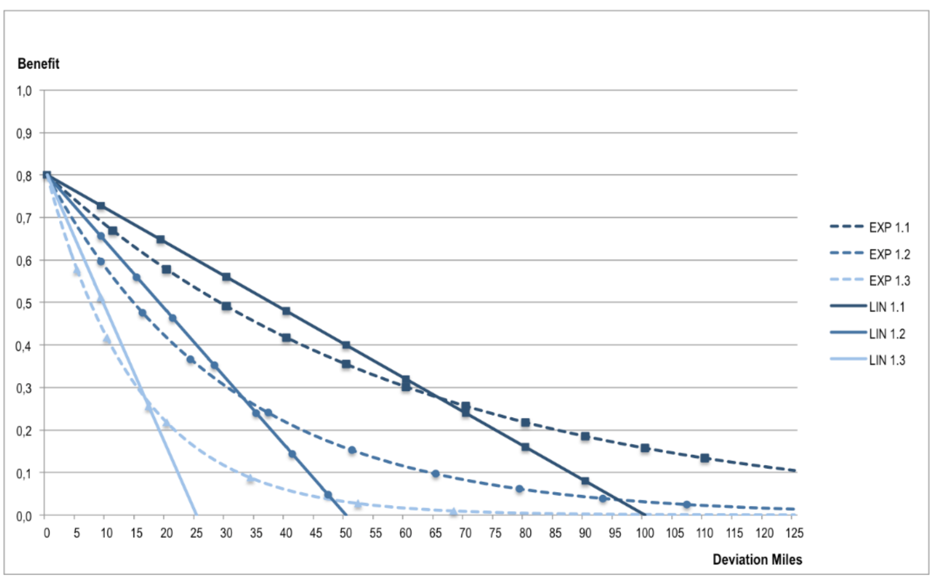

Figure 6: Linear Benefit Functions for Alternative Ports

So, the exact linear settings do not have a large impact on the picks of the model. Challenging the assumption that benefits do have a linear relation to deviation, an exponential counterpart of the linear formula (15) an alternative benefit function is described that has no 'turning-point'. It follows the argument the further you sail for alternative fueling, the less benefit you will return.

$$G\_(q,k) = \{1, \quad if\ k \cup \{i,j\}\ \beta * exp\,(-\alpha * 1/\gamma\_k\ * \delta\_q\hat{}k)\,,\ \ otherwise \qquad (15)$$

To compare the outcomes of the model under both 'benefit functions', we again look at the selection of ports. Linear parameter settings 1.1, 1.2 and 1.3 of α, β are replaced by three exponential settings. In Figure 6 the benefit functions under linear and exponential formulas are visualized. In Table 5 in the appendix we find the settings and outputs of the model under both settings, the reflections of ports under are given in Figure 7. In the graph we can see that there are some little shifts in the reflections of specific ports. Although some ports might change from position in the ranking, we can say the model holds on to the exact same selection it has made in the linear setting.

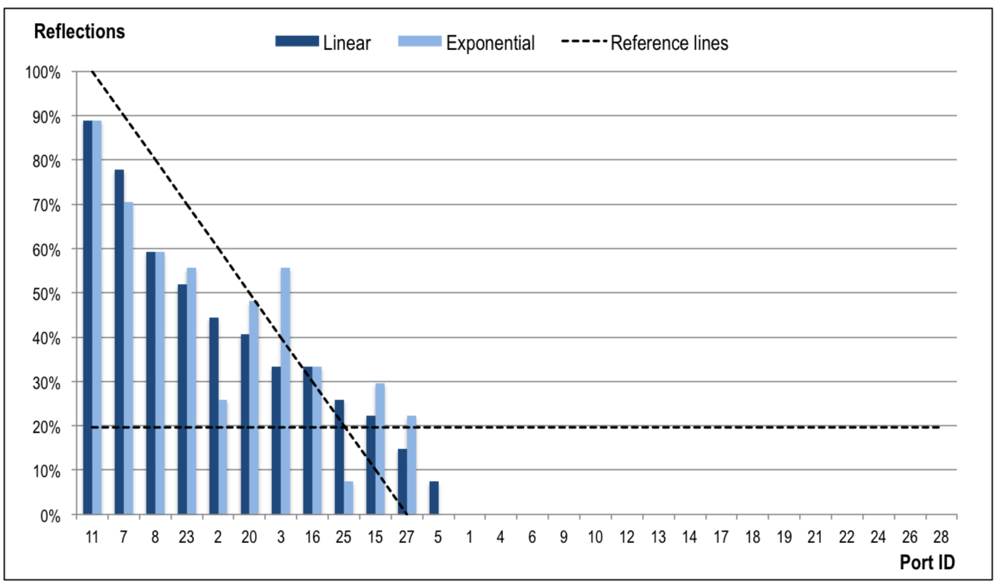

Figure 7: Comparison between the Linear and Exponential Formula

By alternating the benefit functions, one can see that these do influence the outcome of the model. It is mostly the sum of benefits that is influenced by the parameter setting (refer to Tables 4 and 5 in the appendix). The selection of ports does not show great sensitivity under the benefit function: almost exact the same selection of ports is selected. Because the exponential settings do not have much impact on the selection of ports, for the analysis of the next section the linear benefit function will be used only.

5. MFCFLM for the North Sea LNG Network

The nature of the information we look for was hard to gather because not many organizations possess these. We used expert estimates of the Maritime Research Institute Netherlands, describing the number of ship movements between the ports in the year 2012. A from-to matrix was used as flow-input for the model. We have no good way of validating the accuracy of the data and, therefore, carries a disclaimer. Unfortunately, in the gathered estimates the data does not separate small from large vessels within the short sea shipping, therefore we can not use the relative weight of each movement as described in (7). Due to the sourcing data, the expert had to cluster some ports; no separation could be made between the traffic for Antwerp and Vlissingen and Larvik and Oslo.

5.1 Port Preference Scores

Port preferences were set equal in the numeric experiment. After interviews with large bunkering companies and traders (Mabanaft, Oliehandel Klaas de Boer and Sea Bunkering International BV) all ports were evaluated with a preference score. From the perspective of a ship-owner, many of the ports could not be differentiated and were given the same score. However, experts agree that the largest ports within our scope do have better bunkering opportunities. Because of their large operations many customers would like to fuel at their port (O-D preference). The large bunkering activities do reduce cost because of the economies of scale, attracting both customers as well as suppliers. Prices and port fees are very competitive, making the ports of the ARA area (Antwerp, Rotterdam and Amsterdam), Zeebrugge, Gothenburg and Hamburg attractive bunkering locations for ship-owners.

One of the major barriers for fueling in alternative ports is the fees ship-owners have to pay for each call they make to enter a port. One exception in the set is the port of Skagen (near Frederikshavn) where ship-owners do not have to pay port fees for entering for fueling purposes. This makes that many ships do bunker there. For determining the attractiveness of the port for alternative fueling this is a driving argument separating this potential location from the rest. In Table 3 the scores of all the ports can be found.

Table 3: Ports and their port preference score

ID	Port	Port Pref.	ID	Port	Port Pref.	ID	Port	Port Pref.
1	Dunkerque	0.4	11	Cuxhaven	0.4	21	Stavanger	0.4
2	Zeebrugge	0.6	12	Hamburg	0.6	22	Bergen	0.4
¾	Vlissingen/Antwerpen	0.6	13	Kiel	0.4	23	Aberdeen	0.4
5	Rotterdam	0.6	14	Esbjerg	0.4	24	Dundee	0.4
6	Amsterdam/IJmuiden	0.6	15	Hirtshals	0.4	25	Tyne	0.4
7	Den Helder	0.4	16	Frederikshavn	0.8	26	Grimsby/ Immingham	0.4
8	Delfzijl/Eemshaven	0.4	17	Goteborg	0.6	27	Felixstowe/ Harwich	0.4
9	Emden/Leer/Papenburg	0.4	18/19	Larvik/Oslo	0.4	28	London	0.4
10	Bremer-/Wilhelmshaven	0.4	20	Kristiansand	0.4			

5.2 Results

The model will run with the focus on a new network without any existing facilities in place. The outcomes of the model will describe a set of effective locations for the short sea shipping on the North Sea and can be compared with currently available LNG facilities.

Assuming that no facilities are in place, the model was run on the data provided by expert estimates. In Figure 8 the outcome of the selection is displayed. Again, under 9 different (linear) parameter settings, i.e., we evaluated from the first to the ninth pick. One can see that the selection behavior of the model follows the strict reference line indicating low sensitivity of the benefit function and its parameters.

The ports of Rotterdam [port # 5] and Hamburg [#12] are the number 1 and 2 top locations. In Rotterdam, the LNG break bulk terminal as part of the Gate terminal will be operational mid 2016 to serve vessels. Following the strict selection-behavior; parameter settings do not influence the selection of the model. Top locations Rotterdam and Hamburg are followed by respectively Grimsby [#26], London [#28], Antwerp [#4], Bergen [#22], Oslo [#18], Amsterdam [#6], Zeebrugge [#2], Dundee [#24], Stavanger [#21] and Tyne [#25]. Bunkering facilities already exist near Bergen [#22] and Stavanger

[#21]. Also the port of Zeebrugge [#2] has already an LNG terminal in place (Fluxys Terminal).

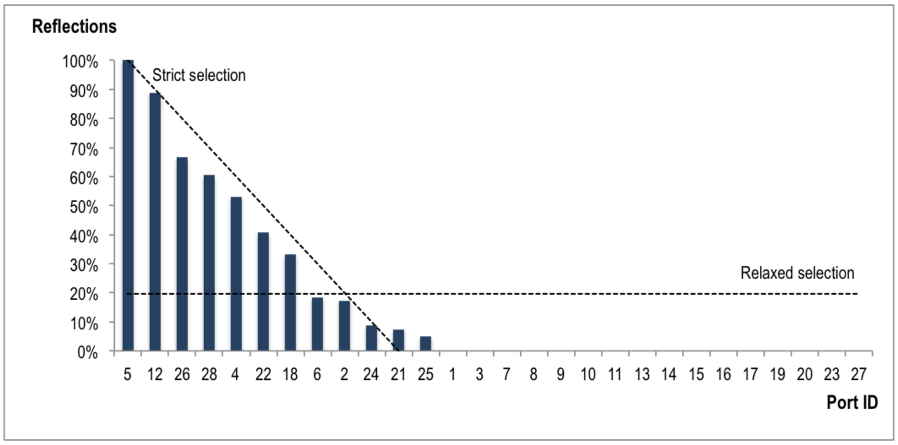

Figure 8: Reflections of Ports

Notice these are all large-size ports, leaving smaller ports unpicked. It seems port size (and thereby traffic of ingoing and outgoing ships) is a good predictor for the model. To visualize this, the reflections and the relative port activities are plotted in the same graph (Figure 9). The picks of the model do quite well follow the relative scoring of the ports traffic activities. The two outliers with large traffic movements (Bremerhavn [#10] and Felixstowe [#27]) are geographically nearby located to other picks (Hamburg [#12] and London [#28]), explaining their absence in the location-selection of the model.

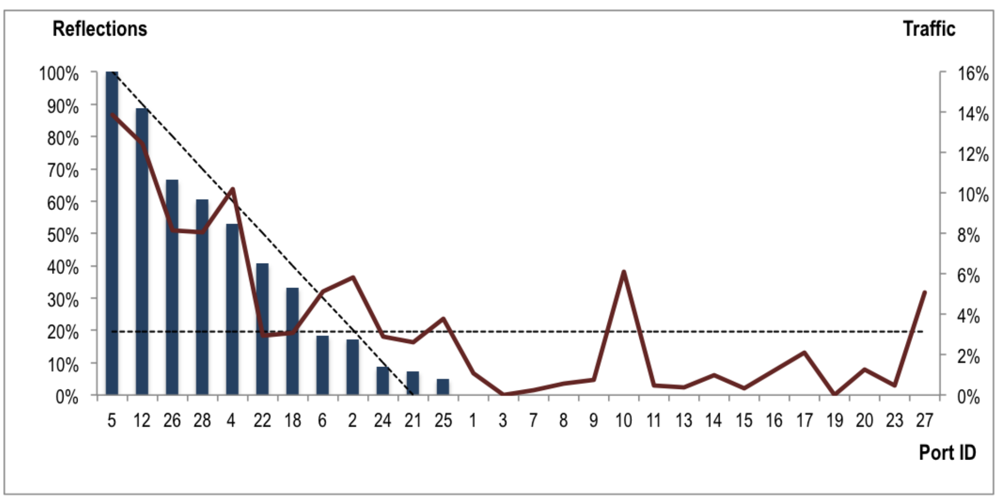

Figure 9: Reflections of Ports (bars) and Relative Traffic Activities (line)

We run the model to get insights in the best locations for the remaining ports that do not have terminals yet or which have not decided upon yet. High ranked ports of the earlier analysis that do not have infrastructure yet do score well (Figure 10). Indeed, there is a relation with graph (Figure 8). However it is not a perfect predictor as the ranking of potential locations differs. With 3 out of the next top 5 picks of the model, especially the UK ports show the greatest contribution to the LNG network. Respectively, Grimsby [#26], London [#28], Antwerp [#4], Amsterdam [#6] and Dundee [#24] form the top 5 of ports that do not yet facilitate LNG terminals. According to this model where we use the expert estimates for short sea shipping traffic movements on the North sea; they seem to form the top priority locations for the roll-out of the LNG network.

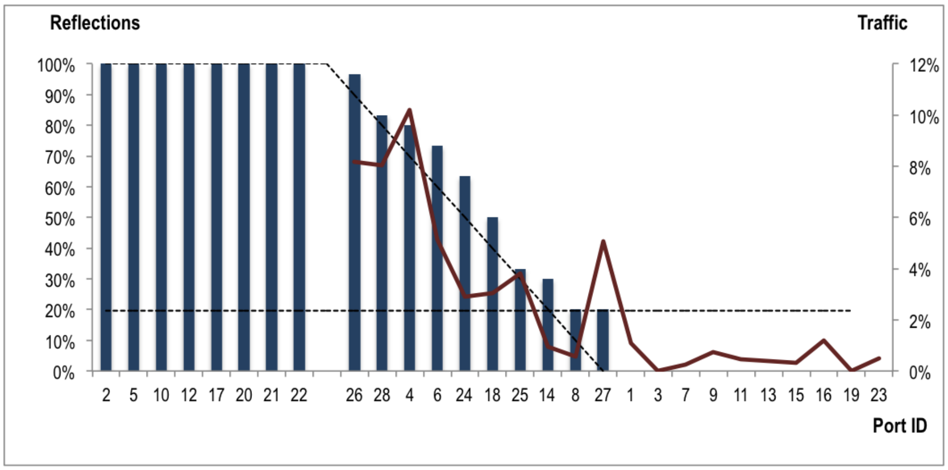

Figure 10: Reflections of Ports

6. Discussion

The MFCFLM has followed our intuition most of the times. The traffic intensity has proven to be a good predictor for the ports ranking. The benefit for fueling at alternative ports can be adjusted by the user. Not only is it determined by the deviation distance following from the network, it is also influenced by the port preference and parameters that describe the willingness to deviate by ship-owners. The parameter settings are evaluated on their sensitivity to the outcomes of the model. The selection-behavior of the model has shown not to be very sensitive to their exact settings. Under different settings and even different benefit functions, the model has shown its robustness by identifying almost exact the same set of ports.

The greatest challenge during this thesis was to acquire accurate data describing the ship movements in the area. If information on ship movements is indeed difficult to gather, an alternative could be to map cargo movements (tons) instead. In this model ship movements are weighted by their vessel size to translate them into fuel volume demands. In a way, cargo tonnages are linked to fuel consumption and could therefore also be a good indicator of the moving fueling demands. This could easily be adopted in the model, reformation of equations (7) and (4) will do the job.

Scoping the network was a difficult issue. The maritime sector is not limited to borders or natural limitations of the network. In an open area like the North Sea, vessels continuously move 'in' and 'out' of the area. This also makes that it is hard to focus on vessels, whom are taken into consideration and whom are not? The nature of the sourcing dataset could help in determining the right scope of the network. This was a difficult issue this research because the dataset was not easily acquired.

7. Conclusion

In this paper we have developed a Maritime Flow Capturing Facility Location Model and demonstrated its use. Existing theories on facility location were not applicable for maritime environments. A new model needed to be designed using knowledge from literature. In the first academic approach a translation was made from moving demand in the sector into facility location choices by the use of the MFCFLM. We demonstrate that the location-allocation model is useful for the construction of a new network, as well as for extending existing networks. With the model the user can also compare two or more potential locations and evaluate their contribution to the (existing) network. In section 5, the model was used to identify and evaluate good strategic locations for LNG terminals.

The results show that the model picks the most efficient set of port locations in a fairly short time. Traffic intensity at the ports has proven to be a good predictor for the ranking. The model has proven to be robust under its assumptions behind the benefit function. With the first maritime facility location model, we have opened the door to analyze facility location choices for the sector. The model can form an accurate decision making support tool. It can form a substantial contribution to the discussion at stakeholders level, especially because of the different perspective of the model in comparison to the existing decision making process.

Further research should focus on two challenges, a reliable dataset and the scope of the network. The quality and accuracy of the output is directly linked to the data input. Also the scope forms a challenge. The North Sea area is not a closed system with strict boundaries; ships move in and out of the area all the time. In this research we only considered ships moving 'within' our area. It is likely that the ships that are moving 'through' the area, would also exert fuel demands 'within' the area. Further research can combine the challenges of the dataset and the scope by first looking at the datasets at hand and determine the scope and network upon the information gathered.

Acknowledgements

This research is partly funded by Dinalog, Dutch Institute for Advanced Logistics.

Appendices

Table 4: Output Numerical Experiment: Port Selections and the sum of benefits under 9 different parameter settings, $\sum f\_q = 756$

ß = 0.8	**Linear 1.1/ α = 0.004**			**Linear 1.2/ α = 0.008**			**Linear 1.3/ α = 0.016**		
P	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**
1	7;	213.86	350	7;	156.40	294	11;	122.51	188
2	7;20	330.18	543	7;11	254.56	394	2;11	212.40	318
3	7;11;20	406.31	596	2;11;15	334.10	502	2;8;11	287.74	396
4	2;7;11;20	474.19	659	2;7;11;20	403.30	592	3;8;11;23	341.47	454
5	2;7;11;15;25	523.75	703	2;7;8;11;20	454.71	624	3;8;11;16;23	390.13	503
6	2;7;8;11;15;23	558.26	718	2;7;8;11;20;23	501.30	671	3;7;8;11;16;23	434.90	566
7	2;7;8;11;15;23;25	587.60	729	2;7;8;11;15;20;23	535.97	698	3;7;8;11;16;23;25	473.57	630
8	2;7;8;11;16;20;23;27	613.55	743	3;7;8;11;16;20;23;27	568.22	714	3;5;7;8;11;16;23;25	506.69	647
9	3;7;8;11;16;20;23;25;27	635.20	750	3;7;8;11;16;20;23;25;27	595.44	726	3;5;7;8;11;15;16;23;25	537.55	677

ß = 0.5	**Linear 1.4/ α = 0.0025**			**Linear 1.5/ α = 0.005**			**Linear 1.6/ α = 0.01**		
p	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**
1	7;	153.91	350	7;	118.00	294	11;	96.82	188
2	7;20	246.12	543	7;11	198.85	394	2;11	172.50	318
3	7;11;20	312.45	596	2;11;15	267.31	502	2;8;11	238.34	396
4	2;7;11;20	372.87	659	2;7;11;20	328.56	592	3;8;11;23	289.92	454
5	2;7;11;15;25	421.10	703	2;7;8;11;20	377.94	624	3;8;11;16;23	337.58	503
6	2;7;8;11;15;23	459.17	718	2;7;8;11;20;23	423.56	671	3;7;8;11;16;23	382.06	566
7	2;7;8;11;15;23;25	493.25	729	2;7;8;11;15;20;23	460.98	698	3;7;8;11;16;23;25	421.98	630
8	3;7;8;11;16;20;23;27	524.47	743	3;7;8;11;16;20;23;27	496.14	714	3;5;7;8;11;16;23;25	457.68	647
9	3;7;8;11;16;20;23;25;27	552.25	750	3;7;8;11;16;20;23;25;27	527.40	726	3;5;7;8;11;15;16;23;25	491.22	677

ß = 0.2	**Linear 1.7/ α = 0.001**			**Linear 1.8/ α = 0.002**			**Linear 1.9/ α = 0.004**		
p	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**
1	7;	93.97	350	7;	79.60	294	11;	71.13	188
2	7;20	162.05	543	7;11	143.14	394	2;11	132.60	318
3	7;11;20	218.58	596	2;11;15	200.00	502	2;8;11	188.94	396
4	2;7;11;20	271.55	659	2;7;11;20	253.82	592	3;8;11;23	238.37	454
5	2;7;11;15;25	318.44	703	2;7;8;11;20	301.17	624	3;8;11;16;23	285.03	503
6	2;7;8;11;15;23	360.07	718	2;7;8;11;20;23	345.82	671	3;7;8;11;16;23	329.22	566
7	2;7;8;11;15;23;25	398.90	729	2;7;8;11;15;20;23	385.99	698	3;7;8;11;16;23;25	370.39	630
8	3;7;8;11;16;20;23;27	435.39	743	3;7;8;11;16;20;23;27	424.06	714	3;5;7;8;11;16;23;25	408.67	647
9	3;7;8;11;16;20;23;25;27	469.30	750	3;7;8;11;16;20;23;25;27	459.36	726	3;5;7;8;11;15;16;23;25	437.28	677

Table 5: Output Numerical experiment: Port selection and sum of benefits under linear versus exponential benefit functions, $\sum f\_q = 756$

ß = 0.8	Linear 1.1/α = 0.004			Linear 1.2/α = 0.008			Linear 1.3/α = 0.016		
p	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**
1	7;	213.86	350	7;	156.40	294	11;	122.51	188
2	7;20	330.18	543	7;11	254.56	394	2;11	212.40	318
3	7;11;20	406.31	596	2;11;15	334.10	502	2;8;11	287.74	396
4	2;7;11;20	474.19	659	2;7;11;20	403.30	592	3;8;11;23	341.47	454
5	2;7;11;15;25	523.75	703	2;7;8;11;20	454.71	624	3;8;11;16;23	390.13	503
6	2;7;8;11;15;23	558.26	718	2;7;8;11;20;23	501.30	671	3;7;8;11;16;23	434.90	566
7	2;7;8;11;15;23;25	587.60	729	2;7;8;11;15;20;23	535.97	698	3;7;8;11;16;23;25	473.57	630
8	3;7;8;11;16;20;23;27	613.55	743	3;7;8;11;16;20;23;27	568.22	714	3;5;7;8;11;16;23;25	506.69	647
9	3;7;8;11;16;20;23;25;27	635.20	750	3;7;8;11;16;20;23;25;27	595.44	726	3;5;7;8;11;15;16;23;25	537.55	677

ß = 0.8	Exponential 1.1/α = 0.0025			Exponential 1.2/α = 0.005			Exponential 1.3/α = 0.01		
p	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**	**Port**	**Benefit**	**# ships**
1	7;	214.35	756	7;	153.20	756	11;	116.46	756
2	7;20	322.92	756	7;11	251.00	756	3;11	208.70	756
3	2;11;15	404.01	756	2;11;15	331.57	756	3;8;11	282.73	756
4	2;7;11;20	464.21	756	3;7;11;20	394.40	756	3;8;11;23	340.41	756
5	2;7;11;15;23	510.95	756	3;8;11;15;23	49.01	756	3;8;11;15;23	391.99	756
6	2;7;8;11;15;23	617.06	756	3;7;8;11;15;23	491.99	756	3;7;8;11;16;23	435.39	756
7	2;7;8;11;16;20;23	575.21	756	3;7;8;11;16;20;23	526.64	756	3;7;8;11;16;20;23	474.39	756
8	3;7;8;11;16;20;23;27	663.10	756	3;7;8;11;16;20;23;27	558.37	756	3;7;8;11;16;20;23;27	508.76	756
9	3;7;8;11;16;20;23;25;27	680.34	756	3;7;8;11;16;20;23;25;27	585.32	756	3;7;8;11;16;20;23;25;27	539.83	756

References

[1] Schneider, R.C., "A maritime flow capturing facility location model", *master thesis* Industrial Engineering, University of Groningen (2013).

[2] Thunnnissen, S.K., Van de Bunt, L.G., Vis, I.F.A., "Sustainable fuels for the transport and maritime sector: A blueprint of the LNG Distribution Network", in: *Logistics and Supply Chain Innovation*, Part of the series Lecture Notes in Logistics, H. Zijm, M. Klump, U. Clausen, M. ten Hompel, Springer Verlag, 85-103 (2016).

[3] Melo, M., Nickel, S., and Saldanha-da Gama, F., "Facility location and supply chain management - A review", *European Journal of Operational Research*, 196(2), 401-412 (2009).

[4] Hodgson, M. J., "A Flow-Capturing Location-Allocation Model", *Geographical Analysis*, 22(3), 270-279 (1990).

[5] Zeng, W., "GIS Based Facility Location Planning with Different Types of Consumers", *PhD Thesis*, Faculty of Graduate Studies and Research, Department of Earth & Atmospheric Sciences, University of Alberta (2007).

[6] Tanaka, K.-i. and Furuta, T., "A Hierarchical Flow Capturing Location Problem with Demand attraction Based on Facility Size, and Its Lagrangian Relaxation Solution Method", *Geographical Analysis*, 44(1),15-28 (2012).

[7] Zeng, W., Hodgson, M. J., and Castillo, I., "The Pickup Problem: Consumers' Locational Preferences in Flow Interception", *Geographical Analysis*, 41(1),107-126 (2009).

[8] Zeng, W., Castillo, I., and Hodgson, M. J., "A Generalized Model for Locating Facilities on a Network with Flow-Based Demand", *Networks and Spatial Economics*, 10(4), 579-611 (2010).

[9] Ahuja, R.K., Magnanti, T.L., Orlin, J.B., *Network Flows: Theory, Algorithms and Applications,* Prentice Hall, Englewood Cliffs, NJ (1993).