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INVENTORY ROUTING ANALYSIS FOR MARITIME LNG SUPPLY OF GERMAN PORTS

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After the implementation of Emission Control Areas (ECA) in Northern Europe in 2015, ship operators have to decide for new compliance methods. Among different abatement technologies, also the use of LNG as maritime fuel is one option. Hence, the number of LNG-fueled vessels plying in North Sea and Baltic Sea is growing, so ports have to cope with the increasing demand for LNG. Until now, German ports have been a little bit delayed in the installation of LNG infrastructure. Currently, a new LNG-terminal at Brunsbüttel, the western entrance to the Kiel Canal, is under construction.

The distribution of LNG from the new LNG-hub to the other German ports can be modelled as an Inventory Routing Problem (IRP) that is usually solved by combinatorial optimization methods. This paper investigates the research question, how the distribution can be modeled as an IRP, which distribution mode is the most economic for the German ports and which modal mix for the LNG supply leads to the greenest distribution. The results of this paper are empirically validated by data that were collected in several EU-projects on sustainable supply chain management and green logistics.

Keywords: Inventory Routing Problem, LNG distribution, clean shipping, operations research

1. Introduction

The International Maritime Organization (IMO) and the European Parliament (EP) decided in 2005 and 2012 to establish Emission Control Areas (SECA) in Northern Europe comprising North Sea and Baltic Sea from 2015 on. The first step towards green shipping was the implementation of the SECA regulation in the Baltic Sea Region (BSR) in 2015 where operating ships, from 2015 on, must use fuel with a low sulphur content not exceeding 0.1%. Next steps towards cleaner shipping are the NECA regulation for ECA that will be in force from 2021 and the global CAP that will limit the sulphur content in maritime fuel to 0.5% in all seas (Prause & Olaniyi, 2019).

Before the implementation of ECA regulation, many studies highlighted the tentative negative impact of these environmental rules on the maritime industry. Consequently, the European Union approved in the frame of the BSR Interreg Programme the projects "EnviSuM – Environmental Impact of Low Emission Shipping Measurements and Modelling Strategies" and "GoLNG" to assess the technical efficiency and the socio-economic impacts of clean shipping solutions in the Baltic Sea Region (BSR). After more than three years of project activities, some of the published results of the socio-economic impacts of the regulation focused majorly on emission measurements, the efficiency of abatement technologies and economic impacts of SECA regulations on the maritime stakeholders (Atari *et al.*, 2019; Olaniyi *et al.*, 2018).

Nevertheless, no significant logistics issues for maritime sector were detected until now. One important reason for that was that most of the vessels that operate in the Baltic Sea now use low sulphur maritime fuel that was, since 2015, most of the time less expensive than the formerly used heavy fuel oil due to low oil prices. Latest research results on administrative burden, additional fuel costs and a real option-based evaluation of abatement technology investments also showed neglectable impact on the maritime industry. Hence, the SECA regulation have not met the maritime sceptics that were expected before 2014 (Atari *et al.*, 2019; Prause & Olaniyi, 2019).

One important change until 2015 was the increasing perception of LNG as an alternative maritime fuel that is compliant with SECA regulation and upcoming NECA regulation as well. The increasing

number of LNG-fuelled vessels plying in North Sea and Baltic Sea forced the ports to cope with the growing LNG demand but the readiness of LNG supply for the maritime sector was not equally developed, especially in BSR (Olaniyi & Gerlitz, 2019). Until now, German ports have been a little bit delayed in the installation of LNG infrastructure so that recently a new LNG-terminal at the Port of Brunsbüttel (Elbehafen), situated the western entrance to the Kiel Canal, will be the main entrance point for LNG into the German market with a terminal capacity of 5 billion m³. With the establishment of a new German LNG-hub, the distribution of the LNG between the LNG-hub and the other German ports moves into the focus representing a classical Inventory Routing Problem (Bertazzi *et al.*, 2002, Dror *et al.*, 1985).

By estimating the LNG-consumption of each German main port at the Baltic and the North Sea, three different models will be calculated and discussed that will meet the LNG demands of the considered German ports and that could be supplied by vessels, trucks and a mixture of both transport modes. The models will take under account the costs of each distribution channel as well as the related CO₂ emissions. Surprisingly, it will turn out that currently the main costs of LNG distribution are caused by the storage of the LNG. The mathematical models are built and solved by Mixed Integer Programming (MIP) that is well known in business logistics (Pochet & Wolsey, 2006).

This paper investigates different scenarios for the LNG-distribution from Elbehafen to the other German ports together with different modes of operation by comparing transport costs of vessels and trucks as well as the cost of LNG storage at the ports. The different scenarios will be further analyzed and discussed to determine the CO₂ emissions that occur in each scenario, giving the reader a possibility to estimate the ecologically dimensions of the different distribution channels. Hence, the research discusses the research questions, how the LNG distribution among the German ports can be modeled as an IRP, which distribution mode is the most efficient and which modal mix is the greenest. The results of this paper are empirically validated by data that were collected in several EU-projects on sustainable supply chain management and green logistics. The research data are from desktop research and from primary data collected mainly in the EU-projects “EnviSuM” and “GoLNG” within the last two years.

2. Literature Review

The IRP is a topic that gained a lot of attention in recent years and which has been investigated in a great variety of applications. Surveys of papers and comparisons of algorithms can be found in (Bertazzi *et al.*, 2002, Dror *et al.*, 1985). The IRP is usually solved by combinatorial optimization methods, other formulations of the problem as a Markov decision process and a two-phase approach for the decomposition of the problem are the topics in (Campbell & Savelsbergh, 2004; Kleywegt *et al.*, 2000). Further, there is a lot of recent work on adapting and expanding the IRP to subjects like green logistics and perishable products (Cheng *et al.*, 2016; Soysal *et al.*, 2016). De *et al.*, (2017) considered special cases in maritime logistics and for scenarios where network disruptions occurs, simultaneous pick-ups and deliveries have to be made or closed supply chain loops have to be investigated (van Anholt *et al.*, 2016; Morales *et al.*, 2018; Soysal, 2016).

The main idea of the IRP is to consider a fix length of each time-step, i.e., the amount of time that can at most be used to fulfill all deliveries in that time-step. Hence, consider a sequence of time-steps to figure out the best routes for supply such that the operation, transport and storage costs of the solution are as small as possible, using one distributing vehicle. The advantage of considering more time-steps in the model gives rise to solutions that use different routes in each time-step, such that some retailers do not have to be supplied every time-step, resulting in lower total cost of the whole model.

Normally there is a fixed storing-capacity given and the amount of the routed inventory that is stored in the fixed storage is accounted in the objective function of the minimization. In our case, we assume that there are no storing facilities at the ports; and consider the maximal amount of gas that can be stored at each port in the objective function of our MIP approach, such that the size of storage, with respect to the considered price for storing LNG, at each port is optimized as well. Hence, we obtain an optimal solution concerning the costs that also delivers the best corresponding size of the storages. Subsequently, the results will be compared to a model in which the gas is delivered by trucks and for which a MIP-formulation of a Vehicle Routing Problem (VRP) is used to determine the minimal total costs of the supply.

The VRP, like the IRP, has been research object for many scholars with a great variety of special cases and scenarios comprising green logistics and even electric vehicles (Braekers *et al.*, 2016; Laporte, 1992; Bektaş *et al.*, 2016; Hiermann *et al.*, 2016). (Desrochers *et al.*, 1992) give an insight view on scenarios where the supply has to be made in given time-windows, whereas (Lalla-Ruiz *et al.*, 2016)

investigated VRPs with more than one depot from which the customers can be supplied. Since VRPs are usually hard to solve in the case of many time-steps or a large number of customers, heuristics like TABU or simulated annealing approaches are widely used to solve the problem (Gendreau *et al.*, 1994; Osman, 1993).

In the situation of German ports where the LNG distributing trucks are able to reach every port within one day, the optimization tasks can be solved on daily basis because the ports can be equipped with LNG-storages to buffer the daily demand. Consequently, it is possible to perform a preprocessing, in which all the demand of the ports, representing an integer value of full truckloads, is delivered, i.e. we only have to consider the demand in the VRP that is less than a truck load (LTL), i.e. in-between an empty and a full truckload. Then, we solve the VRP and obtain a solution that determines how many trucks are needed, and which route each truck has to use to satisfy the demand such that the total costs of this distribution model are minimal.

3. Methodology

The paper follows for the representation of underlying geographical data a graph-theoretical model with a set of vertices consisting important German ports. We consider besides the new LNG-hub Brunsbüttel (BRB) the four largest German North Sea ports Bremen/Bremerhaven (BRE), Cuxhaven (CUX), Hamburg (HAM) and Wilhelmshaven (WIL) as well as the four German Baltic Sea ports Kiel (KIE), Lübeck (LUE), Rostock (ROS) and Sassnitz (SAS). Based on these nine ports we construct a graph $G = (V, E)$, where the vertex set V is the set of the ports and E is the set of all possible edges representing the linkages between the ports. Since the Kiel Canal (NOK) connects the western and eastern German ports, the underlying graph consists of two complete graphs that are only connected by a single edge, starting and ending in Brunsbüttel. A tour containing the Baltic ports has to use the NOK-edge twice (Figure 1):

Figure 1. The transport graph of German main ports

The distances between the ports are determined by a sea-distance-matrix, i.e., we first consider LNG transport only between ports via vessels. Besides the sea-distances in one model also the road-distances for a tentative truck transport of LNG between German ports are considered. For the calculation of the sea-distances as well as those for the road-distances, we use well-known internet sources (Sea-distances 2019; OpenStreetMap 2020). Based on the distances via sea or road we use average CO₂ emissions for each edge that are estimated by using emission tables for different transport modes depending on distance and cargo load provided by (Cefic 2011). The costs in our models represent full costs and all cost references are taken from internationally recognized studies of business logistics. Since we discuss different transport modes as well as several distribution technologies, we have to rely on a couple of studies covering the investigated topics.

The special structure of the graph G and the role of the Kiel Canal (NOK) requires for the modelling a small modification. We add an additional node for Kiel (KI2) to the vertex set V of the graph, i.e., there are two nodes representing Kiel, such that a tour through the Baltic ports starting at Brunsbüttel (BRB) is possible and we can apply the IRP model. The node KI2 has the same distances and edge-costs to all other Baltic ports as Kiel (KIE), i.e., an edge (KI2, BRB) is labeled with the same costs as (KIE, BRB) and there exists an additional edge (KI2, KIE) with costs equal to zero and a demand of 0 tons per time-step.

In the sequel, we will analyze and discuss three different models for LNG supply that are all extensions of the model of a Traveling-Salesman-Problem (TSP). The TSP model is applied to the graph having its start and end in Brunsbüttel in order to find the shortest tour through all given ports, what is exactly a Traveling-Salesman-Problem (TSP). The TSP model is considered as an Integer Program (IP) that leads according to Dantzig, Fulkerson and Johnson (Dantzig *et al.*, 1954) to a set of equations that are describes in the following Table 1:

Table 1. The set of equations for the TSP program

(TSP)

$$\min \sum_{(i,j) \in E} d_{ij} x_{ij} \quad (T.1)$$

$$s. t. \sum_{j \in V} x_{ij} = 2 \quad \forall i \in V \quad (T.2)$$

$$\sum_{i,j \in S, i \neq j} x_{ij} \leq |S| - 1 \quad \forall S \subseteq V, S \neq \emptyset \quad (T.3)$$

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in E \quad (T.4)$$

Here x_{ij} is a binary decision variable determining if the edge (i,j) is included in the resulting tour or not and d_{ij} is the length of the edge (i,j) .

Finally, the LNG demand of the German mains ports has to be estimated. There are several studies estimating the annual demand of LNG in ports. A realistic prognosis represents the LNG potential analysis of MEG (2017) so that we use this study to estimate the LNG-consumption of each German main port at the Baltic and the North Sea. Based on this estimation we develop, calculate and discuss three different models meeting the LNG demands of all considered German ports. The models take under account different transport modes for supply as well as the corresponding costs and CO2 emissions of each distribution channel. After the calculations, the main costs of the LNG distribution will be compared with the storage costs of LNG in the ports.

Since demand of LNG is given either in tons or in m^3 , every now and then it is necessary to convert volumes of LNG between m^3 and tons. We will use in these situations the density factor $0.4681 \frac{t}{m^3}$ in accordance with the LNG Density Calculator (2019). In order to get an overview of the LNG demand in the German ports, we apply the results of the potential analysis of Merkel Energy (2017) that forecasts the LNG demand of the German North Sea ports for the year 2030. Based on this data, we calculate first the daily LNG demand by assuming an equal distribution. The missing values for the German Baltic ports we extrapolate by investigating the data of the AIS Marine Traffic for the Baltic Sea, which delivers the number of calls in German ports.

An analysis of the Marine Traffic data for the time between 22.12.2018 and 21.01.2019 yields the average number of daily calls by ships for all considered German ports (MarineTraffic 2019), which is integrated in the following table 1. Furthermore, we calculate the average demand of LNG per ship call within the German North Sea ports, which results in a median of 2.66 tons and a mean of 2.7 tons of LNG per call. This result we extrapolate to the German Baltic ports by forecasting conservatively the LNG demand since we use the median value of 2.66 tons of LNG per call. All calculations and results are visible in the following Table 2:

Table 2. LNG demand estimation for German ports (author's calculation)

Port	Annual demand in 1000 tons	Daily demand in tons	Average daily Calls	Daily demand Per Call	Estimated daily demand
BRB	2.70	7.40	9.35	0.79	
BRE	63.90	175.07	62.66	2.79	
CUX	8.10	22.19	22.87	0.97	
HAM	74.40	203.84	76.55	2.66	
WIL	17.40	47.67	7.58	6.29	
KIE			66.61		177.18
LUE			28.29		75.30
ROS			28.45		75.68
SAS			5.26		14.00
Sum	166.50	456.17			342.16

For setting up the models, we further need a distance matrix for the shipping distances between the German ports that we express in nautical miles (nm) and that we obtain by sea-distance calculator (Sea-distances 2019). Further, the distance Brunsbüttel (BRB) – Kiel (KIE) is given by the length of the Kiel Canal (NOK), which has a sea distance of 54 nm and which can be travelled in about 10 hours. In addition to the sea distances, we also investigate the delivery of LNG by trucks, i.e., we additionally need the street-distances between the ports, which can be obtained by OpenStreetMap (2020) and that are visualized in Table 3:

Table 3. Distance matrix between German ports (author's calculation)

nm/km	BRB	BRE	CUX	HAM	WIL	KIE	LUE	ROS	SAS
BRB		81/210	16/205	36/95	78/270	54/100	151/135	138/240	198/375
BRE			65/45	117/135	63/80	135/265	232/250	219/365	279/490
CUX				52/115	62/110	70/160	167/285	154/405	214/525
HAM					114/205	90/105	187/90	174/200	234/325
WIL						132/315	229/300	216/415	276/540
KIE							97/80	84/215	144/340
LUE								60/140	131/260
ROS									88/120

Based on the distances we will calculate and discuss in the sequel three different inventory routing models for the LNG distribution among the German main ports. We will not only concentrate on LNG distribution by ships, but we also consider multimodal supply to the ports realized by vessels and trucks.

4. Findings

Based on the underlying data set, we will consider three different IPR models for the LNG distribution between the German main ports. The three approaches of the models differentiate between the distribution modes, i.e. we first consider the LNG-distribution by a vessel (model A), then the LNG-distribution by trucks (model B) and finally a mixed mode distribution (model C). We will evaluate and discuss the outcome of all investigated models in the sequel.

Our first model will be dedicated to the distribution of LNG by a single vessel and will be modeled in accordance with the Inventory Routing Problem (IRP) representing a combinatorial optimization model that naturally occurs in situations where we are confronted with internal deliveries, i.e., where the supplying and receiving facilities belong to the same company.

4.1. Model A: LNG-distribution by a vessel

The first approach to model the distribution of the LNG is based on deliveries via a vessel. Therefore, we follow (Archetti *et al.*, 2007) and use their MIP formulation of the IRP. Since this model assumes that all deliveries can be done during one time-step, it is necessary to figure out and define how long this period is regarding our modelling, i.e., we have to find out what might be the longest tour a vessel can be confronted with. This task is equivalent to the determination of the shortest sea tour through all given cites in our underlying graph $G = (V, E)$, which is exactly the solution of a Traveling-Salesman-Problem (TSP).

As already mentioned, we apply the TSP model for both subgraphs as an Integer Program (IP), according to (Dantzig, Fulkerson and Johnson 1954) and using the SCIP Optimization Suite 6.0 (Gleixner *et al.*, 2018), we obtain the following tours:

- a. North Sea ports: BRB → HAM → CUX → BRE → WIL → BRB
- b. Baltic Sea ports: KIE → LUE → ROS → SAS → KIE
- c. Overall tour: BRB → HAM → CUX → BRE → WIL → BRB → KIE → LUE → ROS → SAS → KIE → BRB.

The sub-tour through the North Sea ports has a length of 294 nm and the tour through the Baltic ports has a length of 389 nm, which sums up to 683 nm. If we now assume a vessel with a speed of 12 knots, then it would need 57 h for this distance and assuming that one passage of the NOK takes 10 h we get 77 h, which is 3 days and 5 h. However, we have to be aware that we did not include the time for loading and unloading the vessel. The total demand of LNG per day in all ports is 790.93 tons, as we do not need to supply Brunsbüttel. Hence, in 4 days we need to move 3163.72 tons on and from board.

Currently, it can be assumed that 1000 m³ LNG can be loaded/unloaded per hour, which corresponds to 468.1 tons of LNG (Olaniyi & Gerlitz, 2019). This would last 14 hours, so a tour to supply all ports would take 3 days and 19 h and a time-step equalling 4 days would be sufficient. As we have the possibility to refill the LNG-vessel each time we pass through the port of Brunsbüttel the vessel only needs the maximum demand of the subgraphs it is supplying. The maximum is achieved on the North Sea subgraph with 448.77 tons per day and since the time-horizon is four days, the vessel needs to have a capacity of 1795.08 tons, which corresponds to 3834.82 m³, so a capacity of about 4000 m³ would be sufficient. The resulting TSP tour is shown in Figure 2:

Figure 2. The resulting TSP tour

Figure 2 highlights that the result of the TSP analysis leads to an optimal tour graph that is connected and which consists of two sub-graphs, the western sub-graph consists of all vertices representing all North Sea ports whereas the eastern sub-graph represents all Baltic ports. The connecting edge of these two sub-graph represents the Kiel Canal (NOK) that has to be passed by a LNG supply vessel. A passage of the NOK in one direction requires 10 hours and generates additional costs because of canal dues that have to be taken under account.

We will consider the usage of two different vessel types for the LNG distribution, i.e. first we consider a vessel with a LNG capacity of 5000 m³ = 2340.5 t, which represents cargo-carrying capacity of 3000 dwt. The second vessel type is assumed to have a LNG transport capacity of 7500 m³ = 3510.75 t, representing a cargo-carrying capacity of 6000 dwt. Both vessel types are able to pass the Kiel Canal (NOK) as well as there are no problems for these ship types to call all German ports.

Next step is the determination of the costs for distributing the LNG with the vessel among the different ports. Maritime economics split the main costs for running a ship into operation costs and voyage costs (Stopford, 2009). Literature review reveals that there are different studies concerning operation costs for vessels. One well-known international study (PBSL, 2017) fixes as daily operation costs to 7620 US\$ for Handysize vessels (25000 dwt) and to 8400 US\$ for Supramax vessels (55000 dwt). Since the analysis of the daily vessel costs are expressed in US\$ and our research takes place in Europe, we are using for our calculations Euro as a currency by applying an exchange course of 1 US\$ = 0.90 €. Now it is possible to derive the daily operation costs of our two vessels by assuming a logarithmic correlation between the daily operating costs in US\$ and the deadweight tonnage (dwt) of a vessel, which yields the regression function $f(x) = -2398 + 989.27 \cdot \ln(x)$. As a result, we gain for the 5000 m³-vessel daily operation costs of 5522 \$, i.e. 4970 €, and for 7500 m³-vessel 6208 \$, i.e. 5587 €.

After having fixed the daily operation costs of the vessels, it is necessary to determine the edge-weights for the underlying graph representing the costs for travelling along the edges. These costs are called voyage costs in shipping sector and they include fuel costs and canal dues (Stopford, 2009). For the estimations of the voyage costs for each edge in the graph, we assume that both vessels will use ULSFO due to the SECA regulations for Northern and Baltic Sea that only allow the usage of low Sulphur fuel up to 0.1% Sulphur content.

As reference price per metric ton ULSFO, we take the average of ULSFO – price for the time 2016–2019 at the Port of Rotterdam, which ranged in the average around 450 € per ton (ECG, 2020). Furthermore, we assume a fuel consumption of 10 tons per day for the 5000 m³-vessel and a fuel consumption of 12 tons per day for the 7500 m³-vessel, yielding a consumption of 0.42 and 0.5 tons per hour (MAN, 2019). From this we derive that one hour of traveling by each ship costs 189 € and 225 € respectively just for the fuel.

Since the voyage costs also comprise the canal dues, we have to take under account also the fee for the passage through the NOK, which represents for both vessels 5729 € (NOK, 2019). Hence, we set the voyage costs for travelling each edge to its length multiplied with the fuel costs of one hour, divided by the assumed average speed of the vessels. Additionally, we add the Kiel Canal (NOK) due to the edge (BRB, KIE) representing a passage through the Kiel Canal. Thus, we obtain the following costs for each edge for a 5000 m³ and a 7500 m³ vessel in €, where the upper figure represents the voyage costs along an edge of the graph for the smaller vessel and the lower amount in each cell of Table 4 shows the voyage costs for the larger vessel:

Table 4. Voyage costs between the German ports (author's calculation)

5000m ³ 7500m ³ -vessel	BRB	BRE	CUX	HAM	WIL	KIE	LUE	ROS	SAS
BRB		1276 1519	252 300	567 675	1229 1463	7619 7979			
BRE			1024 1219	1843 2194	992 1181				
CUX				819 975	977 1163				
HAM					1796 2138				
KIE							1528 1819	1323 1575	2268 2700
LUE								945 1125	2063 2456
ROS									1386 1650

The LNG supply of the German ports with one vessel requires a couple of days so in order to be able to safeguard the LNG distribution with one vessel it is necessary to install LNG storage facilities in the ports to buffer the daily LNG demand for several days. Since both vessels enjoy the same service speed, pre-calculations in the graph reveal that it is possible to limit the time span for the LNG storage to four days. Hence, based on the daily demand of the ports, we calculate to each port the demand of four days so that the availability of LNG fuel through the storages in each port is guaranteed for minimum four days. The corresponding figures of the four-day LNG demand in metric tons of the ports can be found in the following Table 5:

Table 5. Four-day LNG demand of German ports (author's calculation)

	BRE	CUX	HAM	WIL	KIE	LUE	ROS	SAS
Demand in each time-step	700.28	88.76	815.36	190.68	708.72	301.2	302.72	56

These four-day demands will be integrated in our model together with the costs of the storing facilities of LNG at each port. From the business perspective, it has to be mentioned that installation of LNG storage facilities is related with additional costs, but related logistics services also come along with the possibility of emerging entrepreneurial activities (Prause, 2014b). For the estimations of the storage costs of LNG in the ports, we refer to an international study of Enagas (2016) that fixes the storage costs of LNG with a calorific value of 1 GWh to an amount of 32.40 € per day. By transferring these LNG storage costs on a base of metric tons, we obtain a price of 453.60 € per day and per ton LNG. The transformation from GWh into tons is realized by taking under account the calorific value of $14 \frac{kWh}{kg}$ for LNG.

Equipped with this data, we are finally able to set up a more sophisticated Mixed Integer Program formulation of the IRP. For the calculation, we will again take the graph $G = (V, E)$, where V is the set of the ports and E is the set of edges that we described in methodology part of the paper. However this time, we consider the complete graph between ports in the North and Baltic Sea and the two edges (BRB, KIE) and (BRB, KI2) connecting the two subgraphs.

For the mathematical formulation of the new model, we have to introduce larger number of sets parameter and variable that are presented in the following list:

Sets

- $NS := \{BRE, CUX, HAM, WIL\}$ the set of the ports at the North Sea
- $BAL := \{KIE, KI2, LUE, ROS, SAS\}$ the set of the ports at the Baltic Sea
- $M := NS \cup BAL$
- $M' := M \cup \{BRB\}$
- E the set of edges between the ports
- $T := \{1, \dots, H\}$ the set of discrete time-steps
- $T_0 := \{0, \dots, H\}$
- $T' := \{1, \dots, H + 1\}$
- $T_0' := \{0, \dots, H + 1\}$

Parameters

- H is the time-horizon, i.e., the last time-step of the model
- c_{ij} is the shipping cost of the edge $ij \in E$ given by the cost-matrix
- r_i is the LNG-demand of port $i \in M$ for 4 days given above
- cap is the capacity of the vessel
- $c_{stor,daily}$ are the daily storage costs for one ton of LNG
- $c_{opex,daily}$ are the daily operation costs of the used vessel

Variables

- $x_{it} \geq 0 \forall i \in M, t \in T_0$ a continuous variable determining how much LNG is distributed to port i at time t
- $y_{ijt} \in \{0,1\} \forall ij \in E, t \in T$ a binary decision variable determining if edge ij is used at time t , where additionally $y_{BRB,j,t}, y_{i,BRB,t} \in \{0,1,2\} \forall i,j \in M, t \in T$
- $z_{it} \in \{0,1\} \forall i \in M', t \in T$ a binary decision variable determining if port i receives a delivery at time t or not
- $I_{it} \geq 0 \forall i \in M, t \in T_0'$ the inventory at port i at time t
- $I_i^{cap} \geq 0 \forall i \in M$ a continuous variable determining the max. capacity of LNG-storage at port i
- $c_{opex} \geq 0$ is the operation costs of the time-period of the current vessel
- $c_{stor} \geq 0$ are the storage costs of the considered time-period
- $c_{voy} \geq 0$ are the voyage costs of the considered time-period

With these definitions, we are able to formulate our mixed integer program (MIP) for the calculation of the underlying IPR for model A. Again, the main objective of our calculations is the minimization of the overall costs of the LNG-distribution to the German ports. The overall or total costs are driven by the operation costs and the transport costs for the LNG-deliveries. In addition to that, also the storage costs have to be taken under account since in case of inter-arrival times of LNG-supply of more than one days the LNG demands in the port have to be bridged by taking fuel from the LNG-storage in the port. Hence, the equations of the IPR model have to safeguard that the LNG-storage in the ports will never be empty which cause additional equations.

The LNG-storing at the ports represents a decent issue in the whole analysis. We saw already that we have to estimate 453.60 € per day and per ton LNG for storing. These storage costs are so high that from the economic point of view a daily LNG-supply to the ports are more cost efficient than the utilization of storages. Hence, by reducing the research question only to the financial dimension the LNG-supply via vessels like advocated in model A would be no option because the LNG-supply with ships is not possible on daily basis with reasonable cost levels. Therefore, we include in our assessment also other dimensions like environmental aspects. Nevertheless, the LNG-storage costs have to be mentioned and the research has not to answer who will be responsible for the coverage of the LNG-storing at the ports, i.e. if the costs for LNG-storage are paid e.g. by public sources then they out of our cost considerations.

Coming back to the formulation of our mixed integer program (MIP) for the description of the underlying IPR, we are now able to present in the following table 6 the IPR equations for model A for the LNG-distribution by ships. As already mentioned, we use the above-defined sets, parameters and variable in the equations for model A in Table 6:

Table 6. IPR equations for model A

(IRP)

$$\min \quad c_{voy} + c_{stor} + c_{opex} \quad (A.1)$$

$$s.t. \quad I_{i0} = r_i \quad \forall i \in M \quad (A.2)$$

$$x_{i0} = 0 \quad \forall i \in M \quad (A.3)$$

$$I_{it} = I_{i,t-1} + x_{i,t-1} - r_i \quad \forall i \in M, t \in T' \quad (A.4)$$

$$I_{it} \geq 0 \quad \forall i \in M, t \in T' \quad (A.5)$$

$$x_{it} \geq I_i^{cap} * z_{it} - I_{it} \quad \forall i \in M, t \in T \quad (A.6)$$

$$x_{it} \leq I_i^{cap} - I_{it} \quad \forall i \in M, t \in T \quad (A.7)$$

$$x_{it} \leq I_i^{cap} * z_{it} \quad \forall i \in M, t \in T \quad (A.8)$$

$$\sum_{i \in NS} x_{it} \leq cap \quad \forall t \in T \quad (A.9)$$

$$\sum_{i \in BAL} x_{it} \leq cap \quad \forall t \in T \quad (A.10)$$

$$\sum_{i \in NS} x_{it} \leq cap * z_{BRB,t} \quad \forall t \in T \quad (A.11)$$

$$\sum_{i \in BAL} x_{it} \leq cap * z_{BRB,t} \quad \forall t \in T \quad (A.12)$$

$$\sum_{j: j \in E} y_{ijt} + y_{jit} = 2 * z_{it} \quad \forall i \in M, t \in T \quad (A.13)$$

$$\sum_{i \in S: i \in E} \sum_{j \in S} y_{ijt} \leq |S| - 1 \quad \forall S \subseteq M: 2 \leq |S| \leq |M| - 1, \forall t \in T \quad (A.14)$$

$$y_{ijt} + y_{jit} \leq 1 \quad (A.15)$$

$$c_{voy} = \sum_{ij \in E} \sum_{t \in T} c_{ij} y_{ijt} \quad (A.16)$$

$$c_{stor} = 4 * c_{stor,daily} * H * \sum_{i \in M} I_i^{cap} \quad (A.17)$$

$$c_{opex} = 4 * c_{opex,daily} * H \quad (A.18)$$

$$x_{it} \geq 0 \quad \forall i \in M, t \in T_0 \quad (A.19)$$

$$y_{ijt} \in \{0,1\} \quad \forall ij \in E: i \wedge j \neq BRB, t \in T \quad (A.20)$$

$$y_{ijt} \in \{0,1,2\} \quad \forall ij \in E: i \vee j = BRB, t \in T \quad (A.21)$$

$$z_{it} \in \{0,1\} \quad \forall i \in M', t \in T \quad (A.22)$$

$$I_{it} \geq 0 \quad \forall i \in M, t \in T_0' \quad (A.23)$$

$$I_i^{cap} \geq 0 \quad \forall i \in M \quad (A.24)$$

$$c_{opex} \geq 0 \quad (A.25)$$

$$c_{stor} \geq 0 \quad (A.26)$$

$$c_{voy} \geq 0 \quad (A.27)$$

The objective function of our model (A.1) aims at minimizing the total costs, consisting of the transportation costs (A.16), the storage costs (A.17) and the operation costs (A.18).

The constraints (A.2) and (A.3) ensure that all storages can satisfy the demand at time $t = 0$. In addition to that, the first delivery takes place at time $t = 1$, while (A.4) determines the inventory at time t to be the old inventory plus the supply that arrived in the previous time-step minus the amount of LNG that is used during this moment of time. And that the amount of stored LNG is never negative is satisfied by constraint (A.5). Further, constraints (A.6)–(A.8) ensure that only deliveries up to the possible storage-capacities are possible and (A.9)–(A.12) are capacity-constraints guaranteeing that we only load as much LNG as the vessel can load. In contrast to (Archetti *et al.*, 2007), we split the constraint into two because we have to subgraphs that are only connected by a single bridge, i.e., the Kiel Canal (NOK), so whenever the vessel is switching between the two subgraphs we are able to reload it because the vessel has to go through BRB.

Constraint (A.13) determines that the vessel has to leave each city it supplies as two of the incident edges have to be active if it is supplied. This constraint has to hold for all cities apart from Brunsbüttel

(BRB), as the vessel might visit BRB more than one time to reload and switch between the Baltic and North Sea subgraphs. (A.14) is the sub-tour-elimination constraint of (Dantzig *et al.*, 1954) that is used to get rid of sub-tours in the resulting route. Further, we only allow one of the parallel edges to be active, which is safeguarded by constraint (A.15).

Based on this model it is again possible to obtain a solution by using again SCIP (Gleixner *et al.*, 2018). Since we are interested in the analysis on annual base and we consider a maximal period of a four-day delivery at each port, our time-horizon H has to be 91, i.e. $H = 91$, to cover one year. By taking under consideration all these frame conditions we the results that are consolidated in table 7:

Table 7. LNG-distribution costs for model A (author's calculation)

Vessel size	5000 m ³	7500 m ³
Voyage costs	2 365 636 €	2 617 615 €
Operation costs	1 809 080 €	2 033 668 €
Total distribution costs	4 174 716 €	4 651 283 €

An short analysis of the costs of the results of model A reveals a cost advantage of about 500 000 € for the LNG-distribution with the 5000 m³ vessel compared the use of the larger 7500 m³ vessel. However, the results of table 7 are not taking under account the storage costs that appear at the different ports and that sum up to 522 363 075 €. This result points out that in both cases the LNG-storage costs in the ports are responsible for more than 99% of the accruing costs. Hence, the question raises who will pay for the storage costs and how it reduce these posts.

Related to the optimal cost solution of model A, there corresponds also an optimal tour that has to be travelled by the vessel within each 4 days to safeguard the LNG supply in the ports. The LNG-storages at the ports are dimensioned so that they are able to buffer the needed LNG-demand at each port. The optimal tour consists of three different routes, namely the North Sea ports, the Hamburg tour and the Baltic ports tour, i.e. the German Baltic ports are served in one tour, there exists one tour only suppling Hamburg and the third tour calls all North Sea ports except Hamburg. All tours comprise the time for unloading LNG in the ports and in addition to that, especially for the Baltic tour, the time for passing the Kiel Canal (NOK) of twice 10h. A more detailed view allow the following overview:

- North Sea ports tour
 - BRB → CUX → BRE → WIL → BRB
 - Length of tour: ca. 22h
- Hamburg tour
 - BRB → HAM → BRB
 - Length of tour: ca. 8h
- Baltic ports tour
 - BRB → KIE → LUE → ROS → SAS → KIE → BRB
 - Length of tour: ca. 56h

The length of all three tours serving all German ports sum up to a total length of about 86h, i.e. a roundtrip with calling all German ports requires 4 days, so that enough time is available for charging the vessel with LNG in Brunsbüttel port.

A consideration of model A concerning the storages at the ports reveals that the maximal capacity of the LNG-storages equals the demand of 4 days which implies that the model tries to minimize the storage costs first, i.e., it is cheaper to deliver the demand of the next 4 days but not more. Therefore, we conclude that the transportation costs must be cheaper than the storage costs, even for ports with little demand and huge distances to other ports, as it appears in the case of the Port of Sassnitz (SAS). Thus, one approach to improve the existing optimal routing solution would be to prolong the periods of LNG-deliveries to these ports to more than 4 days. The answer to this question is related to the storage costs of LNG in the ports.

To answer this question, we execute a sensitivity analysis to calculate the maximal price to pay for the storage per ton of LNG so that it makes economically sense to store the LNG demand for more than one time-step in order to reduce the annual number of LNG-deliveries per port. A binary search in the interval $[0, 453.6]$ of the storage costs yields maximal prices 5.20 € per ton of LNG for a 5000 m³-vessel and 6.19 € for a 7500 m³-vessel. In these cases, it makes sense to cut out SAS of the usual tour and

deliver only every second time-step. Next changes in the tours occur if the storage costs fall onto a price of 1.30 € (5000 m³) and 1.94 € (7500 m³) when the Port of Sassnitz (SAS) is only supplied every fourth time-step and all other Baltic ports only every second time-step. However, it has to be pointed out that all these cases can only occur if the storage price decreases by more than 98 % compared with the current value.

4.2. Model B: LNG-distribution by trucks

After looking at possible supply strategies by vessels, we now want to compare the results to a distribution by trucks. Therefore, we will tackle the problem on a daily basis, as all ports can be reached by truck within one day, including the return to BRB.

For this model, we assume that each truck has a capacity of 30 tons for LNG transportation, as we use a truck with semitrailer and trailer (15 tons capacity each). In order to fix the corresponding costs of a full LNG supply vehicle, we assume the same costs for the trailer and the semitrailer. The depreciation periods of the trailer and the semitrailer are assumed to be 15 years, whereas the depreciation of the towing vehicle is supposed to be only 10 years. The number of drivers depends on the daily operation time as well as on the annual work time of one driver. Since we assume a 24/7 service of the LNG-distribution trucks and the normal annual working time of an employee in German is 1690 h we assume that we need 5 drivers to safeguard the service. By taking under account the study results of Bünger *et al.* (2016) together with outcome of the employment study of the Comité National Routier (2016) we are able to estimate first the related fix costs as well as the costs for the drivers:

- Investment for a trailer/semitrailer: 207 000 €
 - Amortization period: 15 years
- Investment for towing vehicle: 101 000 €
 - Amortization period: 10 years
- Annual employment costs for the drivers: 230 000 €
 - Annual costs for one driver: 46 000 €
 - 5 drivers needed to cover 24/7 service
- Annual tax, insurance, management:
 - Trailer/semitrailer: 10 794 €
 - Towing vehicle: 15 871 €

These considerations lead to daily fix costs for a truck with a towing vehicle, a trailer and a semitrailer of around 840 €. In accordance with the notation of model A we will call daily fix costs also operation costs.

For the calculation of the variable costs per kilometer, we refer again to the already mentioned studies on truck transportation to fix the servicing costs as well as depreciation for the towing vehicle. The last missing variable cost components concern road toll for trucks in Germany and fuel costs. The German road toll can be gained from the public pricing system and the fuel costs are estimated on the assumption that the vehicle consumes 31 litres of diesel per 100 km with a price of 1.20 € per litre. Altogether, the variable cost rate per kilometer sums up to 0.82 € per driven kilometre based on the following costs:

- Fuel costs per km: 0.3720 €
- Servicing:
 - Trailer/semitrailer: 0.0471 €
 - Towing vehicle: 0.1705 €
- Road toll: 0.1870 €

The variable costs per kilometer for the use of the LNG distribution vehicle we will call in the sequel also transportation costs. Provided with this data, we conclude that a truck with trailer and semitrailer has daily operation costs of 840 € and transportation costs of 0.82 € per km.

After having fixed the costs related to the road-based LNG supply, we have to calculate the number of daily full-truck-loads (FTL) that are necessary to feed the LNG demand in the ports. Therefore, we assume that the demand delivered by one truck, is supplied by this truck directly and this truck is returning to the Port of Brunsbüttel (BRB), i.e. by taking under account the given daily demand. Moreover, by assuming an average truck speed of 60 $\frac{\text{km}}{\text{h}}$, we obtain the following number of tours a truck can perform per day to each destination, i.e. we are able to show the result of the calculation in the following Table 8:

Table 8. LNG demand calculation with trucks (author's calculation)

	BRE	CUX	HAM	WIL	KIE	LUE	ROS	SAS	Σ
Demand per day in tons	175.07	22.19	203.84	47.67	177.18	75.3	75.68	14.0	790.93
Daily needed FTL	5	0	6	1	5	2	2	0	21
Daily transport costs in €	1722	-	935	443	820	443	787	-	5150
Max # of daily tours to port	3	3	7	2	6	5	3	1	
FTL needed	0.836	0.74	0.795	0.589	0.906	0.51	0.523	0.467	5.366

Hence, two trucks are needed to supply BRE, and one additional truck for the supply of each destination comprising the Ports of Hamburg (HAM), Wilhelmshaven (WIL), Kiel (KIE), Lübeck (LUE) and Rostock (ROS), which sums to a total number of seven needed trucks. An analysis of the related costs reveals daily total costs of 11 030 € that are composed by 5880 € daily fix costs for the truck use plus 5150 € for daily variable costs due to the LNG transport to the ports. In addition to this information, table 6 also discloses the number of full-truck-loads each port needs to satisfy the demand. Consequently table 6 points out that we need at least six and at most eight additional truck deliveries to satisfy the daily demands.

However, for the determination of the number of needed trucks and the way, how to supply the demand as cheap as possible a linear optimization program has to be solved. Therefore, we will set up a mixed integer program (MIP) formulation of the vehicle routing problem (VRP), which we derive from the IRP formulation of (Archetti *et al.*, 2007) using again the sub-tour elimination constraints of (Dantzig *et al.*, 1954). The related distances we take from street-distance-matrix of table 3 and the costs for the edges of the underlying graph is depicted in the following Table 9:

Table 9. Travel costs for trucks (author's calculation)

in €	BRB	BRE	CUX	HAM	WIL	KIE	LUE	ROS	SAS
BRB		172	168	78	221	82	111	197	308
BRE			37	111	66	217	205	299	402
CUX				94	90	131	234	332	431
HAM					168	86	74	164	267
WIL						258	246	340	442
KIE							66	176	279
LUE								115	213
ROS									98

Like in model A we have to define for the truck based model as well sets, parameters and variables in order to formulate the equations for the :

Sets

- $R := \{1, \dots, p\}$ the set of possible vehicles,
- $M := \{BRE, CUX, HAM, WIL, KIE, LUE, ROS, SAS\}$ the set of ports,
- $M' := M \cup \{BRB\}$,
- E the set of edges, given by the street-distance-matrix from above.

Parameters

- p is the maximal number of available trucks,
- c_{ij} the costs of traveling edge $ij \in E$ given by the costs from the begin of this model,
- d_i the demand of port $i \in M$,
- $c_{opexdaily}$ are the daily operation costs of one truck.

Variables

- $x_{ri} \geq 0$ the amount of LNG truck r delivers to port i ,
- $y_{rij} \in \{0,1\}$ a binary decision variable determining if vehicle r is using edge ij or not. If $i = BRB$, then $y_{rij} \in \{0,1,2\}$, as we allow a truck to take the same route back to the depot it already used,
- $s_{ri} \in \{0,1\}$ determines if vehicle r takes part in the supply of port i or not,
- $z_r \in \{0,1\}$ determines if truck r is used or not,
- $c_{opex} \geq 0$ is the operation costs of the used trucks,
- $c_{trans} \geq 0$ are the transportation costs.

Equipped with these definitions we are now able to state the mathematical equations of model B by again trying to minimize the total costs of the supply by trucks. The MIP program for the corresponding vehicle routing problem (VRP) can be found in the following Table 10:

Table 10. VRP for model B

(VRP)

$$\min \quad c_{trans} + c_{opex} \quad (B.1)$$

$$s. t. \quad \sum_{j \in M' : i \in E} y_{rij} + y_{rji} = s_{ri} \quad \forall i \in M, r \in R \quad (B.2)$$

$$\sum_{j \in M} y_{r, BRB, j} = z_r \quad \forall r \in R \quad (B.3)$$

$$\sum_{r \in R} x_{ri} = d_i \quad \forall i \in M \quad (B.4)$$

$$\sum_{i \in M} x_{ri} \leq 1 \quad \forall r \in R \quad (B.5)$$

$$\sum_{i \in S : i \in E} \sum_{j \in S} y_{rij} \leq |S| - 1 \quad \forall S \subseteq M : 2 \leq |S| \leq |M| - 1, \forall r \in R \quad (B.6)$$

$$x_{ri} \leq s_{ri} \quad \forall r \in R, i \in M \quad (B.7)$$

$$\sum_{i \in M} s_{ri} \leq |M| * z_r \quad \forall r \in R \quad (B.8)$$

$$c_{trans} = \sum_{r \in R} \sum_{i \in E} c_{ij} * y_{rij} \quad (B.9)$$

$$c_{opex} = c_{opexdaily} * \sum_{r \in R} z_r \quad (B.10)$$

$$x_{ri} \geq 0 \quad \forall r \in R, i \in M \quad (B.11)$$

$$y_{rij} \in \{0,1\} \quad \forall r \in R, i, j \in M' : i \wedge j \neq BRB \quad (B.12)$$

$$y_{rij} \in \{0,1,2\} \quad \forall r \in R, i, j \in M' : i \vee j = BRB \quad (B.13)$$

$$s_{ri} \in \{0,1\} \quad \forall r \in R, i \in M \quad (B.14)$$

$$z_r \in \{0,1\} \quad \forall r \in R \quad (B.15)$$

$$c_{opex} \geq 0 \quad (B.16)$$

$$c_{trans} \geq 0 \quad (B.17)$$

The objective function (B.1) of this model aims at minimizing the total costs, consisting of transportation (B.9) and operation costs (B.10). Constraints (B.2) and (B.3) ensure, that whenever a vehicle delivers LNG to a customer it has to arrive and leave this port and that all used vehicles start and end their tours at Port of Brunsbüttel (BRB). Further, constraints (B.4) and (B.5) guarantee that the demand at each port is satisfied and each truck cannot load more than one full truckload. Here we consider the leftover demand after the direct deliveries as the demand of each port and each demand is in the interval $[0,1]$ as there cannot be a demand greater than one truckload after the supply of the full truckloads.

(B.6) is again a constraint ensuring that the tour of each vehicle does not contain a subtour according to (Dantzig *et al.*, 1954). Finally, constraints (B.7) and (B.8) define the number of vehicles that are used, and which port is delivered by which truck.

In the same way like in the case of model A, we apply again the SCIP software to find an optimal solution. The solution of model B leads to a solution consisting of six routes for the LNG delivery with trucks to the ports, i.e. all of these routes are land-based and have to be travelled by the LNG-supply truck fleet. There are two routes serving only one port, namely Baltic ports in Kiel and Lübeck, and the other four combined routes are serving two ports in one round trip. The ports in Hamburg and Bremen are part of two routes due to high LNG volumes that are needed in these ports:

- BRB → KIE → BRB
- BRB → LUE → BRB
- BRB → ROS → SAS → BRB
- BRB → HAM → CUX → BRB
- BRB → HAM → BRE → BRB
- BRB → BRE → WIL → BRB

The resulting routing-plan uses six trucks and causes daily operation costs of 5 040 € and 2 148 € of transportation costs for the not fully loaded LTL – deliveries, which have to be added to the already known costs that are caused by the full-truck-loads (FTL), which were already identified to amount 11030 € as daily total costs. Thus, the calculation for the resulting daily total costs yields 18 218 € comprising daily operation costs of 10 920 € as well as daily transportation costs of 7 298 €. As these figures stem from a model on daily base, we obtain yearly total distribution costs of 6 649 570 € for with trucks as we can see in the following Table 11:

Table 11. LNG supply costs of model B (author's calculation)

Cost category	Annual supply costs
Transportation costs for direct deliveries	1 879 750 €
Transportation costs for combined routes	784 020 €
Total transportation costs	2 663 770 €
Operation costs for direct deliveries	2 146 200 €
Operation costs for combined routes	1 839 600 €
Total Operation costs	3 985 800 €
Total costs in €	6 649 570 €

A comparison of the pure total distribution costs of the 5000 m³-vessel and the road-based LNG-distribution by trucks reveals the vessel is more economic than the truck with annual distribution costs of about 4 175 t€ compared to 6 650 t€, i.e. expressing a cost advantage of about 2 500 t€ for the vessel. However, the pure distribution costs neglect the needed LNG-storage needs in the ports, which has to be taken also under account.

The inclusion of the LNG storage costs leads to another result that is presented for the truck situation in the following Table 12:

Table 12. Comparison of the LNG supply costs

Cost categories in €	Trucks	5000 m ³ -vessel	7500 m ³ -vessel
Operation costs	3 985 800 €	1 809 080 €	2 033 668 €
Transportation costs	2 663 770 €	2 365 636 €	2 617 615 €
Total distribution costs	6 649 570 €	4 174 716 €	4 651 283 €

A comparison of model A and B including the storage costs in the ports reveals that LNG-supply by trucks is less than half as expensive than the distribution with the 5000 m³-vessel. The reason is easy to explain because the truck distribution is faster than the vessel use, which reduces the capacity of the storage facilities in the ports to one day plus safety stock compared to four days plus safety stock in the case of the sea-bound distribution of model A.

Since the storage costs are the main reason for the disadvantage of model A, we again perform a sensitivity analysis to investigate at which storage price the vessels outperform the truck distribution from an economical point of view. Like in the case of model A, a binary search in the interval [0,453.6] is executed with the result that the costs of storage have to be 2.89 € and respectively 2.38 € to achieve that the 5000 m³-vessel and the 7500 m³-vessel would be cheaper than the truck concerning the total costs of the two LNG-distribution models. Consequently, we are able to conclude that the LNG-distribution by vessels becomes only economically more favorable than the truck supply of model B if the costs for storing LNG may decrease dramatically. The situation with storage costs shows Table 13:

Table 13. Comparison of the LNG supply costs including storage

Cost categories in €	Trucks	5000 m ³ -vessel	7500 m ³ -vessel
Operation costs	3 985 800.00	1 809 080.00	2 033 668.00
Transportation costs	2 663 770.00	2 365 636.00	2 617 615.00
Total distribution costs	6 649 570.00	4 174 716.00	4 651 283.00
Storage costs	130 949 534.52	522 363 074.69	522 363 074.69
Cost of safety stock (1 day)	130 949 534.52	130 949 534.52	130 949 534.52
Total storage costs	261 899 069.04	653 312 609.21	653 312 609.21
Total costs	268 548 639.54	657 487 325.21	657 963 892.21

The high LNG storage costs in the ports are often solved by using LNG trucks together with their trailers as mobile LNG storage, i.e. it would result in a truck-to-ship LNG bunkering. With such a solution, it would possible to eliminate the LNG storage costs in model B but it requires a higher number

of truck equipment to safeguard the LNG supply for the calling ships. An additional calculation shows that such a truck-to-ship bunkering of LNG requires 19 fully equipped trucks and would yield total LNG supply costs of 7.43 million €. A calculation furthermore shows that such a truck-to-ship solution would lead to additional distribution costs of 25.60 € for every supplied ton of LNG in the ports. An amount of ca. 25 € per ton for the LNG supply service seems to be still realistic compared to other solutions including LNG storage at the ports.

4.3. Model C: Combined distribution mode

In the third model, we combine the two previous distribution models, i.e. we investigate a multi-model LNG-distribution based on vessel and truck. Since in model A the vessels spent the biggest part of the time with supplying the Baltic Sea ports, these ports are responsible for the length of the time-steps in our IRP model. Therefore, it seems to be interesting to consider a model in which a vessel is only used to supply the North Sea ports, while the Baltic ports are supplied by trucks. Consequently, this would lead to a scenario with reduced storage costs because in this case the LNG storage is only necessary on a daily basis. Hence, our idea is to combine the vessel-based LNG-supply in the North Sea with a truck-based distribution for the Baltic ports.

The assumption that the vessel uses the same route as in model A, yields that at most 294 nm have to be travelled per time-step and that the maximal LNG-load of the vessel would be 244.93 tons, i.e. 524 m³ of LNG. As we would lose 1.5 h per day for the loading and unloading of the daily demand of the North Sea ports, the used vessel needs to have a speed of at least 13 knots. Let us furthermore assume that we take under account a 600 m³-vessel with 2 500 dwt, we obtain operation costs of 4 807.88 € for such a vessel by applying again the logarithmic regression function for the operation cost. Since such a vessel has nearly the same size as the already considered 5000 m³-vessel, we can also assume that the fuel-consumption of such a vessel should be about 0.42 tons per hour. In addition to that we can also assume, that such a smaller ship mostly likely is fueled by MGO or ULSFO so that we can take the same average price of 450 € per ton like in model A. By putting together these observations we are able to calculate voyage costs of 189 € per hour, i.e. we obtain the following voyage costs for the edges of our graph that are disclosed in the Table 14:

Table 14. Voyage costs for North Sea ports

	BRE	CUX	HAM	WIL
BRB	1178	233	523	1134
BRE		945	1701	916
CUX			756	901
HAM				1657

The result for model C is achieved by running again model A for the supply vessel, this time limited to the North Sea ports and by using the data provided in the tables 3. In addition to that, we rerun our model B for the trucks just for the Baltic cities. Hence, we end up with a LNG-delivery situation, in which the North Sea ports are supplied by the same vessel-based solution as for model A; this time restricted to the North Sea, and parallel that the Baltic ports are supplied by a fleet of six trucks in total, using the same routes like in model B. Like in model B, there are three trucks that are dedicated to serve the ports of Kiel, Lübeck and Rostock (in each case one truck) and additional three trucks for common LNG-supply routes.

By focusing on the cost side of the solution for model C, the calculations yield daily costs for using the vessel of 9 081.88 € that are composed by voyage costs of 4 274 € and operation costs of 4 807.88 €. The daily storage costs for the North Sea ports sum up to 203 562.07 €. The cost situation for the truck-based LNG-supply of the German Baltic Sea ports is the same as in model B, i.e. we are able to use the same figures like in previously. Hence, the annual costs for model C are described in Table 15:

Table 15. Annual total costs of model C

Cost categories in €	Vessel	Full truck loads	Combined truck routes
Operation costs	1 754 876.20	919 800	919 800
Total OPEX		3 594 476.20	
Transport costs	1 560 010	748 250	360 985
Total Distrib. Costs		2 669 245	
Storage costs	74 300 156.28	56 649 378.24	
Total storage costs		130 949 534.52	
Safety stock costs (1 day)		130 949 534.52	
Total costs		268 162 790.24	

By comparing the results of model B and model C, we are able to conclude that by taking under account only the cost dimension that model C is dominated by model B that has slightly lower LNG-distribution costs. The storage costs in both cases of model B and model C are the same. The comparison of model A and model C shows that model C dominates model A from an economical point of view.

5. Discussion

The research investigated three different models for the distribution of LNG between the main German ports modeled in the form of an Inventory Routing Problem (IRP). The three LNG-distribution models utilize different transport modes to supply the German ports comprising ships, trucks and a combination of both leading to the three model A, B and C:

- Model A: LNG-distribution by vessels
- Model B: LNG-distribution by trucks
- Model C: Combined distribution ways.

The investigation uses combinatorial optimization methods in order to find the most reasonable LNG-distribution mode under the viewpoint of green logistics. In accordance with the scientific literature, the three pillars of green logistics correspond to economic, ecologic and social issues and two of these dimensions, namely economic and ecological, are considered for the assessment of the three LNG-distribution model (Hunke & Prause, 2013; Prause 2014a). The social dimension can be neglected since the working conditions in all three models are comparable and no model comes along with specific social disadvantages. Hence, the two main dimensions of sustainable logistics decisions are represented in the assessment through the costs and emissions of each model and they are complemented by the time (Daduna & Prause, 2017). Thus, the assessment assigns to each of the three models a 3-dimensional vector with the components costs, emissions and time.

Since the costs and the time between two deliveries are well known through the already discussed models, the open question concerns the emissions. In this paper, we evaluate the models by the annual CO₂ emissions. Literature review reveals estimations for the CO₂ emissions of the trucks to be $62 \frac{g CO_2}{t km}$ and of the vessels to be $20 \frac{g CO_2}{t km}$ as average values (Cefic, 2011). With respect to this emission factors and the fact that both vessels realize a performance of 517 307.5 *tkm* per time-step, we conclude that both vessels would emit about 941.5 tons of CO₂ per year in scenario A. As we further obtain a logistics performance of 125 366.6 *tkm* per day for scenario B, we can determine the annual CO₂ emissions of the distribution by trucks to be 2 837 tons. Similarly, as the trucks in scenario C performs 51 092.7 *tkm* and the vessel 53 223.6 *tkm*, we arrive at annual CO₂ emissions of 1 544.8 tons for model C. Consequently, one can conclude that model A enjoys the lowest emission, while scenario C dominates scenario B from an ecological point of view.

Finally, for the assessment of the time dimension we take the average inter-arrival time between two LNG-deliveries at the ports. All inter-arrival times have been subject already in the discussions of the results of the calculations so that for model A, the average time between two vessel calls at the ports is four days whereas model B leads to an average value of one day and the value for model C is also one day. The time values for the models can be interpreted as flexibility and deliver security since the demands in the ports are only estimated so that random changes in the predicted demands can be balanced within the given timeframes.

Altogether, we now able to assign to each of the three models a 3-dimensional evaluation vector. Since costs, emissions and time represent all short resources, a component is as more favorable as smaller the corresponding value is. The final assessment in form of the evaluation vectors for the three models can be found in the following Table 16:

Table 16. Final assessment of all three models

Model	Distribution costs	Total costs	CO ₂ - emissions	Time
A	4.2 million €	660 million €	940 tons	4 days
B	6.6 million €	270 million €	2840 tons	1 day
C	2.7 million €	270 million €	1540 tons	1 day

Coming back to the research question, we can conclude that by only considering the LNG distribution costs model C is the most economical solution. By enlarging the scope and integrating the storage costs in the ports into the assessment, then model B and C are the most favorable LNG supply modes, while the result of model B is dominated by model C with respect to the ecological dimension as well as to the underlying distribution costs. Thus, our recommendation is the usage of model C since the

evaluation vector of model C offers the lowest values with respect to the distribution costs, the total costs as well as with respect to the time. Hence, model C represents the cheapest solution with respect to the distribution but also concerning the overall costs including LNG storage, its ecological impact is only half as huge as the usage of distribution model B, and the time dimensions are the same. Its solution is only dominated with respect to the ecological dimension by the result of model A since its emission value is greater. However, since model A leads to costs that are about 2.5 times bigger than the costs of model C, which emissions are only about 1.6 times bigger, model C tends to be the model of choice for the considered research question. Thus, we showed how the distribution can be modeled as an IRP, which LNG-distribution mode is the most economical for the German ports and which modal mix for the LNG supply leads to the greenest distribution. The results of this paper are in-line with the empiric data that were collected in several EU-projects on sustainable supply chain management and green logistics.

An important observation in all three cases is related to the storage costs that are responsible for high percentages of the total costs. A closer view to the cost structure of all three options reveals that without the storage costs the order of the results would change, i.e. due to the high storage costs for LNG economic and ecologic advantages of certain distribution model for LNG are not able to emerge since they are superposed by the total high costs. This applies especially to the vessel – based distribution solutions that would be more favorable from the economic point of view in case of lower storage costs. Here, the technological development together with economy of scale effects in LNG – storage technology will have a positive impact on the cost structure of the LNG inventory routing problem so that ecologically better solutions are able to compete also economically with cheaper distribution forms.

Of special practical importance is the truck-to-ship bunkering of LNG that we discussed at the end of model B, which stores the LNG at the ports in additional truck equipment. This form of LNG bunkering is often used in ports since LNG terminals are still often missing even in larger ports. In our case such a truck-to-ship requires a larger truck fleet (in our case about 3 times larger) and also increases LNG supply costs (in our case ca. 10%). Nevertheless, a truck-to-ship LNG bunkering solution leads to reasonable distribution costs per distributed ton of LNG in the ports but the truck-to-ship solution is rather something for a certain transition period as long as the LNG demand is low. In the long run, LNG terminals or LNG storing facilities are the safer and better solution for storing and handling larger volumes of maritime LNG demand so that we do not further discuss this solution here.

Consequently, in the current situation, the cheapest way is to use a distribution by trucks, as both the model using only vessels and the model using a mixture of truck and vessel supply are more expensive. Only if the storage price would fell dramatically the vessel model (model A) would be cheaper, as some ports do not have to be supplied at every time-step, which would also benefit the CO₂-emission of the vessel model, that is already lower than the emission of the truck model. Further, a supply by a mixture of vessel and trucks could be meaningful when considering costs as well as the ecological impact, as it is just a bit more expensive than the distribution using only trucks, but the caused CO₂-emissions are nearly half the size of the truck model.

A critical discussion about the results and its implications has to highlight the problem area of used prices for needed resources. In our calculations, we used daily prices in order to achieve a realistic picture of the underlying business situation. However, these actual figures only fully reflect the situation as a snapshot on the timeline that changes rapidly. Fuel price drops like in the first half of the year 2020 might lead to other conclusions than those we stated here. Nevertheless, a new economic reality can be calculated easily based on presented equation models. Finally, it has be mentioned that we neglected financial long-term aspects including an impact analysis if interest rates. All investments in our models contain long-term assets that are mainly covered by average values for depreciations and capital costs. A more sophisticated approach using methods from capital budgeting of real-option might deliver deeper results but also bears the risk of increasing the complexity of the models in such a way that the results do not longer reflect the economic reality. More research has to be done to develop the models further.

6. Conclusion

The research investigated on the estimated LNG-consumption in the German port at the Baltic and the North Sea and presented three different models on how these demands could be satisfied by vessels, trucks and a mixture of both, based on an IRP and a VRP formulation. After the introduction of the models, it was possible to obtain the costs for each supply mode for distribution and storage as well as to estimate the CO₂ emissions of each scenario together with inter-arrival times between two LNG deliveries. All three LNG supply models revealed a high share of storage costs of the total costs so that the assessment leads different solutions under ecological and economic viewpoints.

By summarizing the results, one can say that currently the main cost driver represents the storage of the LNG at each port and that the most economical way to master the costs is to reduce the amount of LNG stored at each port. For a transition period, until all ports are equipped with LNG terminal or sufficient stable LNG storages a truck-to-ship LNG bunkering represents a reasonable solution. Under the current conditions, an LNG-distribution by vessel in the North Sea and by truck in the Baltic Sea is economically comparable to the fully truck-based distribution.

The vessel – based distribution is from ecologic perspective the most favourable but is not able to compete in economic as well as in time dimension. Hence, the mixed vessel-truck distribution represents currently the most favourable LNG-supply mode for the German ports by taking under account all relevant dimensions of sustainable logistics. This outcome will only change in favour of the vessel-based model if the storage costs would drop dramatically.

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