Shortsea Liner Network Design with Transhipments at Sea

A Case Study from Western Norway

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Short Sea Pioneer (SSP) is a novel concept for shortsea shipping. The concept is based on daughter ships acting as feeder vessels that meet with the mother ship at suitable locations at sea to tranship cargo. Such a system requires that the routes of both mother ship and daughter ships are synchronized. We provide a path flow formulation for the problem of determining the optimal set of routes for both ships. Non-dominated routes are generated a priori using a dynamic programming label-setting algorithm and used as input for the model. We use the model and solution approach to solve a real-world case from the Norwegian west coast. The results can be used to determine the optimal routes for mother and daughter ships as well as the optimal size of the daughter ships.

Keywords Liner network design · Synchronization · Shortsea shipping · Fleet size and mix

1 Introduction

This paper studies a problem emerging from a novel concept for shortsea shipping referred to as the Short Sea Pioneer (SSP) logistics system. The study is performed in collaboration with NorthSea Container Line (NCL), a Norwegian container shipping company, which considers implementing the SSP logistics system in the near future. In the NCL case, the SSP system will consist of mother ships serving a main route between the European continent and Norway, and daughter ships operating feeder routes between ports along

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the Norwegian coastline. Contrary to a conventional shipping system, mother and daughter ships can tranship containers at sea while being coupled together. The problem considered in this paper is the Shortsea Liner Network Design Problem with Transhipments at Sea (SLNDP-TS), in this particular case based on the SSP system.

A simplified example to illustrate a conceptual outline of the SLNDP-TS is shown in Figure 1. Continental Europe is represented by Maasvlakte port located in Rotterdam, Netherlands. As seen in the figure, daughter ships sail on feeder routes to serve small ports inside fjords. At sea, a daughter ship can meet a mother ship to load and unload cargoes. Hence, there is a need for synchronizations between mother and daughter ships to ensure they are at the same location at the same time.

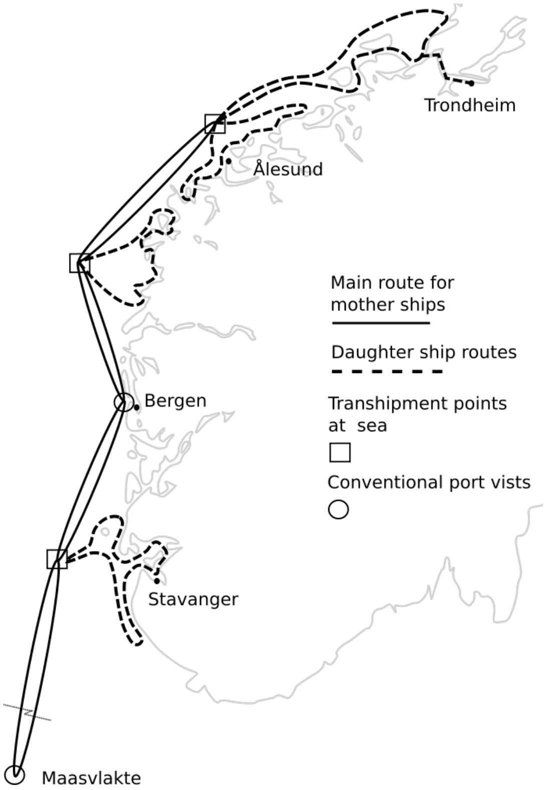


Fig. 1: A potential route network for the SSP logistics system.

The overall goal with the SSP logistics system is to make shortsea container shipping in general, and the Norwegian one in particular, more attractive and cost efficient. The Norwegian short sea sector can basically be defined to include shipping between Norwegian ports, and shipping between

Norwegian ports and the European continent. Currently, the Norwegian shortsea sector is heavily exposed to competition and operates with low margins (Sjøtransportalliansen 2012). An important challenge are high costs related to port visits, and according to NCL these costs constitute about 30% of their turnover (Stensvold 2015). Another challenge is an aging fleet ready for renewal to keep up with current standards (Sjøtransportalliansen 2012). Furthermore, road-based door-to-door transportation is often less expensive than alternative shipping solutions (Haram, Hovi & Caspersen 2015) making it hard to offer competitive shipping services.

New and innovative solutions can improve the competitive position of shortsea shipping and trigger a transition of cargo from road to sea-based transportation. In this regard, the SSP logistics system is an innovative alternative for the future of Norwegian container shipping. There are several advantages with the SSP logistics system: Conventionally, transhipment is done in ports where cargo delivered by ships is stored until another ship picks up the cargo for further transportation. This cargo storage induces inventory costs which could be avoided if the transhipment is done directly between the ships at sea instead. Even more importantly, the costs related to port visits can be significantly reduced as there is no longer a need for two ships visiting the same port to tranship the cargoes.

Another advantage with the SSP concept relates to port accessibility. Along the Norwegian coastline, and especially inside the fjords, many ports are too small to be visited by large container ships. This results in road transportation of cargoes from a location near small ports to bigger ports. In many cases, the cargoes are instead transported by trucks all the way to its destination. Expanding small ports to be suitable for large ships takes several years, is costly, and in some places it might not even be possible (Stensvold 2015). The SSP logistics system can therefore be a more flexible and accessible transportation system for cargo owners located near small ports.

The SLNDP-TS we consider in this paper is a new version of the liner shipping network design problem that consists of determining a set of cyclic ship routes to provide transportation of goods between origin and destination ports. This is known to be a complex problem and several versions of the problem have been studied in recent years. Agarwal & Ergun (2008) propose a multi-commodity space-time network model for the liner shipping service network design problem with cargo routing. The model incorporates a heterogeneous fleet, a weekly service frequency, and cargo transhipment operations, but the transhipment costs are not considered in the network design stage. Álvarez (2009) extend the model by Agarwal & Ergun (2008) by explicitly incorporating transhipment costs and sailing speed decisions in the network design. Meng & Wang (2011) also include empty container repositioning in the liner shipping network design, while Reinhardt & Pisinger (2012) present a model that allows so-called butterfly routes where one port can be visited twice. Plum et al. (2014) consider the design of a single service, while Zheng, Meng & Sun (2015) study the liner shipping network design by simplifying (for solving purposes) the network structure so that only designated hub ports can be visited by more than one service. Thun, Andersson & Christiansen (2017) present a new mathematical model for the liner shipping network design problem which allows for all kinds of services without limitations on the number of visits to each port or the number of services. Finally, Karsten, Brouer & Pisinger (2017) explicitly handle the transhipment times and optimize speeds on each sailing leg in order to properly address the trade-off between competitive transit times and fuel costs. For a more detailed review on the literature on liner shipping network design problem, we can refer to the survey paper by Meng et al. (2014) and to Brouer et al. (2014), which also present a suite of benchmark instances.

Most studies on liner shipping network design, including the ones briefly discussed above, are mainly for deep sea (long-haul) shipping in contrast to our problem. Two exceptions are Polat, Günther & Kulak (2014) and Fagerholt (2004), which both deal with shortsea feeder network design. Anyhow, all of the previous studies assume conventional transhipment, i.e. where one ship picks up the cargo at its origin, transports it to a transhipment port where it is unloaded and later picked up by another ship and transported to to its destination (or another transhipment port). This is in contrast to the SLNDP-TS studied in this paper, where the transhipment takes place directly between a daughter and mother ship at sea, which gives complicating synchronization issues between the routes of the ships. In some two-echelon vehicle routing problems typically arising in city logistics applications, first-level vehicles must transfer requests to a second-level vehicles, resulting in synchronization between the vehicles in a similar way as for the SLNDP-TS, see for example Grangier, Gendreau, Lehuédé & Rousseau (2016). There are also a few other studies, such as Bredström & Rönnqvist (2008) for vehicle routing with time windows and Andersson, Duesund & Fagerholt (2011) for ship routing, which consider synchronization between vehicles or ships, although in a very different context than ours.

The contribution of this paper is to present and solve the SLNDP-TS, which is a new and interesting version of the liner shipping network design problem. We propose a novel solution approach for the problem based on a path flow model where we put special emphasis on the synchronization between mother and daughter ships so they can perform the transhipments. Furthermore, we test the solution approach on a real case study. It is shown how the solution approach can be used to gain insight into how the SSP logistics system might be realized and to provide valuable input to support important strategic decisions, such as determining the network design and the number and size of the ships.

The remainder of this paper is structured as follows: Section 2 presents the SLNDP-TS, followed by a description of the proposed solution approach and the path-flow formulation for the problem in Section 3. The computational study is presented in Section 4, while Section 5 covers the concluding remarks.

2 Problem Description

The SLNDP-TS consists of designing a liner shipping network based on the SSP logistics system with transhipments at sea for the case of transportation between Western Norway and the Continent. The aim is to determine the optimal fleet configuration (i.e., the numbers and sizes of mother and daughter ships) and a service network consisting of a route for each ship, as illustrated in Figure 1. The objective is to minimize the total cost of the system, including time charter costs for the selected ships, sailing costs, port fees and cargo handling costs.

In the following, we describe each of the main components of the SLNDP-TS in detail.

2.1 Ports, Routes and Service Frequency

Ports can be categorized according to four different port types. *Ocean hubs* are not real ports, but correspond to suitable locations at sea where a transhipment between a mother and a daughter ship can occur. An artificial distinction is made between north-going and south-going ocean hubs. A north-going ocean hub is visited by a north-going mother ship and a south-going ocean hub is visited by a south-going mother ship. *Coastal daughter ports* are small ports which can only be visited by daughter ships, while *coastal main ports* are larger ports that can be visited by *either* a mother ship or a daughter ship. Coastal daughter and coastal main ports can be referred to as *coastal ports.* The last port type is the *continental main port.* This is the port on the European continent that only a mother ship can visit. All coastal ports and the continental main port must be visited once a week, while not all ocean hubs need to be visited.

A route sailed by a daughter ship is referred to as a *daughter route*, and a route sailed by a mother ship is referred to as a *mother route.* A daughter route can only be served by one daughter ship and must be completed within one week. Only one mother route can be used, and to maintain a weekly frequency, it must be serviced by the number of mother ships corresponding to the duration of the chosen route rounded up to the nearest integer.

2.2 Demand and Ship Capacities

We assume there is a known and constant weekly cargo demand between the continental main port and each of the coastal ports. All cargoes have to be transported. Shipping of cargoes between coastal ports along the Norwegian coast is not considered in the liner network design problem since the vast majority of the cargoes transported by the case company are either going to or coming from the continental main port.

A ship cannot transport more cargo than its given capacity. Due to technical issues with the SSP concept, all daughter ships in the fleet must have the same cargo capacity. There is a finite number of different types of daughter ships with different capacities available to choose among. The mother ships are always chosen large enough to carry the given cargo volumes going between the continental main port and the coastal ports.

2.3 Transhipments

Transhipment between the mother and daughter ships can only occur in an ocean hub, and each cargo can be transhipped at most once. However, each daughter ship can meet a mother ship once or twice every week for transhipments. If a daughter ship meets a mother ship twice, it must occur in the following way: a north-going mother ship (i.e., coming from the continental main port) can only *deliver* cargoes to a daughter ship, and a south-going mother ship (i.e., sailing towards the continental main port) can only *pick up* cargoes from a daughter ship. Carrying out transhipments in this way reduces the cargo's transit time compared to having only one meeting between a daughter ship and mother ship. It also reduces the capacity requirements for the mother ship.

When a daughter ship meets a mother ship twice a week, i.e., on both the north- and south-going directions of the mother ship's route, the time a daughter ship has available between the visits has to be considered. In this regard, *loop 1* is referred to as the part of a daughter route that is between a north-going and a south-going ocean hub visit, and *loop 2* as the part that is between a south-going and a north-going ocean hub visit. The duration of the daughter route on loops 1 and 2 must be less than the time it takes the mother ship to return to the corresponding ocean hub. Furthermore, the total duration of loops 1 and 2 for the daughter ship must be at most one week to maintain a weekly service. This is also illustrated in Figure 2.

If an ocean hub is the northernmost point on the mother route it is only visited once. Consequently, there are no loops 1 and 2 in this case, and all daughter routes including this ocean hub and with a duration of maximum one week can be synchronized with the mother route.

2.4 Example

An example of a feasible solution is given in Figure 2. In the figure, daughter ship D1 meets a mother ship (M) twice a week while daughter ship D2 meets a mother ship once a week. For simplicity, the mother route in this example does not include any coastal ports.

Daughter ship D1 receives cargoes from a north-going mother ship in ocean hub 1n. Delivery of cargoes to the mother ship is not possible in this ocean hub. Next, on loop 1, the daughter ship delivers these cargoes at ports 2 and 3 while at the same time picking up cargoes from these ports that are going to the continental main port 5. In ocean hub 1s, daughter ship D1 delivers the

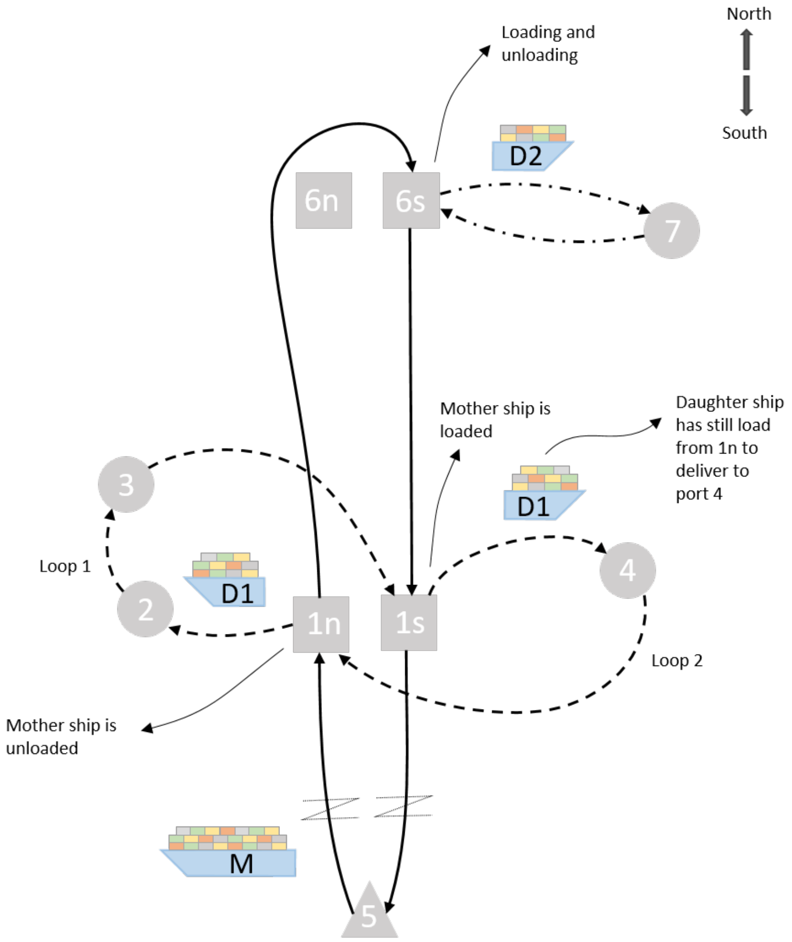


Fig. 2: Illustration of a feasible solution.

cargoes picked up from ports 2 and 3 to a south-going mother ship. In this case, the daughter ship still has cargoes on board destined for port 4 that it received from the mother ship in ocean hub 1n. On loop 2, the daughter ship is therefore delivering these cargoes at port 4 while at the same time picking up cargoes at this port. The cargoes picked up from port 4 will be delivered next time the daughter ship meets a south-going mother ship in ocean hub 1s. After visiting port 4, daughter ship D1 meets a north-going mother ship at ocean hub 1n to repeat its cycle.

Since ocean hub 6 is the northernmost port on the mother route, daughter ship D2 meets the mother ship only once at this ocean hub port. Daughter ship D2 both loads and unloads cargoes to and from the mother ship. Next, the daughter ship delivers and picks up cargoes at port 7, before it returns to ocean hub 6s and repeats its cycle.

3 Solution Approach and Model Formulation

We propose a solution approach based on a path flow formulation to solve the shortsea liner shipping network design problem. In this solution approach, feasible individual candidate routes for both mother and daughter ships are constructed a priori in a route generation procedure and used as input to the path flow model, where subsets of these candidate routes are selected and combined.

The assumptions made in modeling the problem are described in Section 3.1, while the mathematical formulation is presented in Section 3.2. Finally, Section 3.3 briefly describes the procedure for generating the individual candidate routes for the mother and daughter ships.

3.1 Assumptions

Some assumptions have been made in close collaboration with the case company when modeling this problem. Firstly, it is assumed that a limited number of possible locations for ocean hubs are given. Even though ocean hubs could potentially be located anywhere at sea, some locations are more suitable than others. Since the transhipments at sea are performed at these ocean hubs, candidate locations cannot be very exposed to bad weather.

Next, even though the problem includes determining the size of the daughter ships, we assume in this model that this is given as an input, and that one instead can determine the best size by comparing the optimal solutions for a given number of candidate sizes for the daughter ships. The size of the mother ship is assumed to be large enough to handle all the demand that needs to be transported between Norway and the European continent.

Furthermore, a mother ship never visits coastal main ports when sailing north, but can do so on the southbound sailing towards the continental main port. This is most beneficial in terms of average cargo transit time since the case company transports more southbound cargo. In addition, if a mother ship visits a north-going ocean hub, then the corresponding south-going ocean hub must also be visited. If a daughter ship meets a mother ship twice, the meeting location must be at the same ocean hub, as shown in Figure 2.

Even though we assume fixed service speeds for the mother and daughter ships when generating the candidate routes (Section 3.3), it is still assumed that a mother ship has some flexibility in adjusting its speed to reach an ocean hub in time. To illustrate the need for this assumption, consider the following simple example with the route network as given in Figure 3: The total number of cargoes delivered or picked up at each coastal daughter port is shown besides the port nodes, i. e. 100 units in total. With a cargo handling time of 10 units per hour, the mother ship must spend 10 hours on cargo handling during this round-trip.

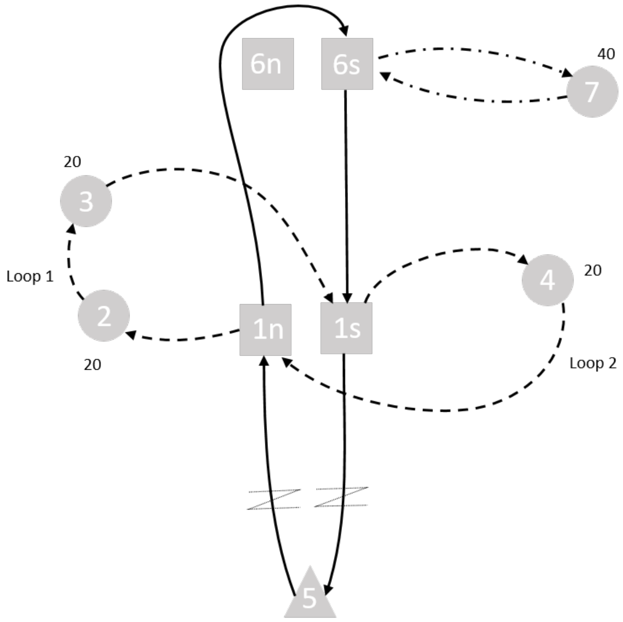


Fig. 3: Illustration of time estimate in ocean hubs.

When generating the candidate mother routes, it is not possible to know exactly how these 10 hours should be distributed among the ocean hubs included in the route before the daughter routes are selected. We assume that the same amount of cargo is transhipped in each ocean hub, irrespective of whether the ocean hub is visited only once or visited on both the north-going and south-going part of the mother route. The estimated cargo handling time in ocean hubs 1 and 6 then becomes $10/2 = 5$ hours in the example in Figure 3. We further assume that the same amount of cargo is transhipped in north-going and south-going ocean hubs. This implies that $5/2 = 2.5$ hours are needed for both the north- and south-going visit in ocean hub 1. However, with the two daughter routes shown in Figure 3, 6 hours are needed in ocean hub 1, and 4 hours are needed in ocean hub 6s. To compensate for the deviation between the actual needed time in each ocean hub and the estimate, the mother ship has to adjust its speed to reach each port in time. With long distances between each ocean hub and with a fairly even distribution of the amount of cargoes that are transhipped at each ocean hub, this is a reasonable assumption.

3.2 Mathematical Model

We introduce the following notation for the SLNDP-TS:

Indices:

p	Port.
m	Mother route.
d	Daughter ship route.

Sets:

$\mathcal{P}^{OH}$	Set of ocean hubs.
$\mathcal{P}^{CD}$	Set of coastal daughter ports.
$\mathcal{P}^{CM}$	Set of coastal main ports.
$\mathcal{R}^{M}$	Set of mother routes.
$\mathcal{R}^{D}$	Set of daughter routes.
$\mathcal{R}^{M}_{p}$	Set of mother routes that includes port p. $\mathcal{R}^{M}_{p} \subseteq \mathcal{R}^{M}$.
$\mathcal{R}^{D}_{p}$	Set of daughter routes that includes port p. $\mathcal{R}^{D}_{p} \subseteq \mathcal{R}^{D}$.
$\mathcal{R}^{D}_{pm}$	Set of daughter routes that includes port p and can be synchronized to a mother route m. $\mathcal{R}^{D}_{pm} \subseteq \mathcal{R}^{D}_{p} \subseteq \mathcal{R}^{D}$.

The synchronization between the daughter and mother routes is ensured through generating the sets $\mathcal{R}^{D}_{pm}$ in a certain way, and requires therefore additional explanation: Figure 4 shows a mother route m_1 that includes continental main port 5, as well as one north- and south-going ocean hub, 1n and 1s, respectively. The mother route m_1 is one of many candidate routes generated in the route generation procedure. The mother ship leaves the continental main port 5 at time $t = 0$, arriving at ocean hub 1n at time t_1 and at ocean hub 1s at time t_2. In addition to the mother route, two candidate daughter routes, d_1 and d_2 are shown. These two daughter routes can be synchronized with the mother route (and thus belong to the set $\mathcal{R}^{D}_{p=1,m_1}$) if the durations of loops 1 and 2 are less than or equal to $t_2 - t_1$ and $168 + t_1 - t_2$, respectively. In the example of Figure 4, daughter route d_1 belongs to the set $\mathcal{R}^{D}_{pm_1}$ for $p = 1, 2, 4$, while daughter route d_2 is included in the set $\mathcal{R}^{D}_{pm_1}$ for $p = 1, 3, 4$.

It should be emphasized that even though the synchronization between the daughter and mother routes could be handled at a tactical ship scheduling level, it is important to consider this already in the strategic network design (i.e. when generating the routes of the daughter and mother ships). Otherwise we would risk ending up with routes that are very expensive (or even impossible) to synchronize in the scheduling phase.

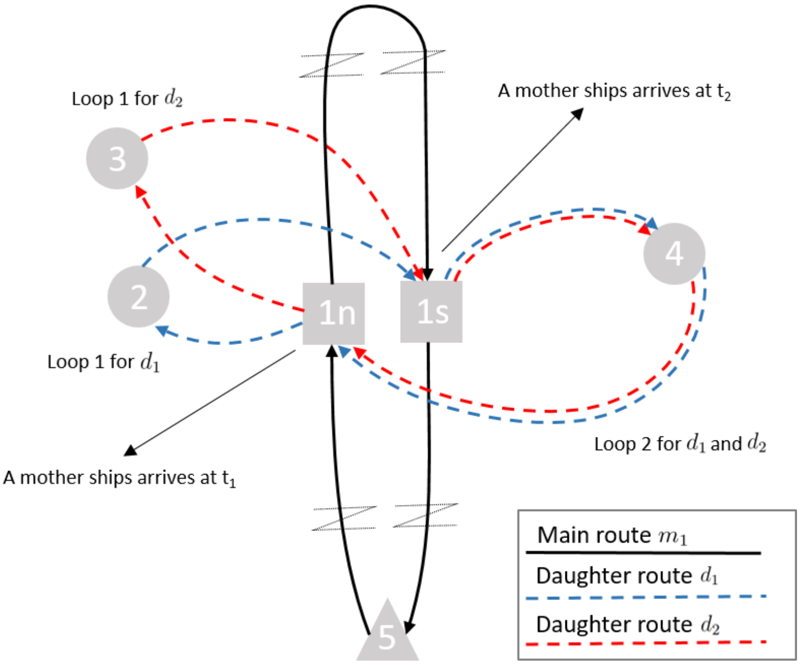


Fig. 4: Two daughter routes that are synchronized with a given mother route.

The remaining notation for the problem is given as follows:

Parameters:

Q^V	Daughter ship cargo capacity.
Q_d^D	Cargo capacity needed to serve a daughter route $d \in \mathcal{R}_d$.
C_m^{M}	Total cost of using a fleet of mother ships on a mother route $m \in \mathcal{R}^M$. It includes a weekly time charter cost, bunker costs and port costs.
C^{TC}	Weekly time charter cost of using a daughter ship.
C_d^{OC}	Operating cost for a daughter ship deployed on daughter route $d \in \mathcal{R}_d$. It includes port costs and bunker costs.
M^{OH}	Maximum number of daughter ships visiting an ocean hub.

Variables:

x_m	A binary variable which takes the value 1 if a mother ship sails mother route $m \in \mathcal{R}^M$, and 0 otherwise.
z_d	A binary variable which takes the value 1 if a daughter ship sails daughter route $d \in \mathcal{R}^D$, and 0 otherwise.

With this notation the problem can be formulated as follows:

$$\min \sum_{m \in \mathcal{R}^M} C^{\mathrm{M}}_m x_m + \sum_{d \in \mathcal{R}^D} \big(C^{TC} + C^{OC}_d\big) z_d \tag{1}$$

subject to

$$\sum_{m \in \mathcal{R}^M} x_m = 1, \tag{2}$$

$$\sum_{d \in \mathcal{R}^D_p} z_d - M^{OH} \sum_{m \in \mathcal{R}^M_p} x_m \leqslant 0, \qquad p \in \mathcal{P}^{OH}, \tag{3}$$

$$\sum_{d \in \mathcal{R}^D_{pm}} z_d - \sum_{d \in \mathcal{R}^D_p} z_d \geqslant M^{OH}(x_m - 1), \qquad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}^M_p, \tag{4}$$

$$\sum_{d \in \mathcal{R}^D_{pm}} z_d - x_m \geqslant 0, \qquad p \in \mathcal{P}^{OH}, \quad m \in \mathcal{R}^M_p, \tag{5}$$

$$\sum_{m \in \mathcal{R}^M_p} x_m + \sum_{d \in \mathcal{R}^D_p} z_d = 1, \qquad p \in \mathcal{P}^{CM}, \tag{6}$$

$$\sum_{d \in \mathcal{R}^D_p} z_d = 1, \qquad p \in \mathcal{P}^{CD}, \tag{7}$$

$$x_m \in \{0, 1\}, \qquad m \in \mathcal{R}^M, \tag{8}$$

$$z_d \in \{0, 1\}, \qquad d \in \mathcal{R}^D. \tag{9}$$

The objective function (1) minimizes the total weekly cost of operating the transportation system. The first term is the total weekly cost of all deployed mother ships, while the second term is the total weekly time charter and operating costs for the deployed daughter ships.

Constraints (2) ensure that one and only one mother route is used. Even though only one mother route is chosen, the number of mother ships to be deployed on the route depends on its duration, as explained earlier. Constraints (3)-(5) connect daughter ship routes to an ocean hub on the mother route. This ensures that every daughter ship can perform a transhipment with a mother ship. Constraints (3) state that if a mother ship does not visit an ocean hub, no daughter ships can visit the same ocean hub. Constraints (4) ensure that if a mother route includes an ocean hub, only daughter routes that can be synchronized with that route can be chosen. Constraints (5) make sure that if no daughter ships visit an ocean hub, no mother routes including that ocean hub can be used.

Finally, constraints (6) make sure a coastal main port is visited by either a mother or a daughter ship. Constraints (7) assign each coastal daughter port to a daughter ship route to ensure that every coastal daughter port is visited. Lastly, constraints (8) and (9) restrict the variables to take binary values.

Note that the model is solved once for each available daughter ship type. By comparing the resulting solutions, the best daughter ship type can be chosen. Based on preliminary testing, this approach is faster than including variables and constraints for ship type selection in the model. Solving the model iteratively for each ship type also provides information about the solutions belonging to each ship type. This information is of interest from a decision maker's perspective as cost differences and other aspects of the solutions for the different ship types can easily be compared.

3.3 Generation of Candidate Routes

The mathematical formulation presented in Section 3.2 requires a set of feasible routes to combine. Sets of mother and daughter routes are generated independently with a label-setting dynamic programming algorithm (see for example Irnich 2008). Dynamic programming requires the problem to be divided into sequential stages, and in the generation of candidate routes, a stage corresponds to a partially generated route including a given number of ports.

The starting point of the generation of routes for the daughter ships is a partial route, only consisting of an ocean hub node. A daughter route can only include one ocean hub, but possibly including both a north-going and south-going ocean hub visit. Daughter routes connected to each of the ocean hubs are generated and each coastal port can be connected to any of the ocean hubs. Since daughter routes and mother routes are generated independently, the only time restriction for the daughter routes is the maximum allowed duration of one week. The times to sail loops 1 and 2 are stored and utilized later when synchronizing mother and daughter routes. All non-dominated daughter routes that are feasible with respect to the maximum duration and capacity are generated and used as input to the mathematical model.

Generating the set of feasible mother routes works in a similar way as the generation of daughter routes. Each candidate route originates in the continental main port. The partial candidate route can be extended to include both coastal main ports and ocean hubs. Coastal main ports are only visited on the south-going part of the mother route and if an ocean hub is visited, it must be visited on both the north and south-going part of the mother route. An exception is if an ocean hub is the northernmost point on the mother route. In this case, the ocean hub is only visited once. There are no restrictions regarding capacity and maximum duration in the generation of the mother routes.

After the mother and daughter routes are independently generated, they are combined to determine which daughter and mother routes can be synchronized in the ocean hubs, as explained in Section 3.2. The result of this combination of routes is the sets $\mathcal{R}^D_{pm}$.

4 Computational Results

In this section, we present and discuss the results from solving the SLNDP-TS using the solution approach presented in the previous section. The commercial optimization software Xpress-IVE version 1.24.08, 64-bit, with Xpress Mosel version 3.10.0 and Xpress Optimizer version 28.01.04, has been used for implementing and solving the mathematical model from Section 3.2. The label-setting dynamic programming algorithm for the generation of candidate mother and daughter routes (Section 3.3) has been implemented using MATLAB version R2016b, 64-bit.

In Section 4.1, the test instances are described. The solution times for the route generation procedure and for solving the path flow model are shown in Section 4.2. The solutions for each of the test instances are presented and analyzed in Section 4.3.

4.1 Description of the Test Instances

A set of ports along the Norwegian west coast and one continental main port have been selected based on ports that the case company currently services. The ocean hubs are chosen based on suitable locations regarding weather conditions. In total, one continental main port, nine coastal ports and five ocean hubs are chosen as shown in Figure 5.

Transportation demand to and from the European continent is based on number of exported containers from the Norwegian west coast during the first quarter of 2016 (Statistics Norway 2016). We further assume that the case company's share of this demand is approximately 40%, given as *current* demand level in Table 1. Furthermore, to represent a future *high* demand scenario, this is increased by 40% to represent the expected increase in transportation demand by 2040 according to the Norwegian national transport plan for 2014-2023 (Meld.St. 26 (2012-2013)). The numbers under the columns *To* and *From* in Table 1 show the demand volumes going to and from each port, respectively.

Since the SSP logistics system is still at a conceptual stage, no real test data is available regarding the handling rates for the transhipments. We have therefore generated instances with two different handling, with a *low* cargo handling rate of 10 TEU/hour and a *high* cargo handling rate of 50 TEU/hour. 10 TEU/hour corresponds to the most likely current scenario, while 50 TEU/hour is a future scenario foreseen by the case company. This, in combination with the two demand scenarios, gives a total of four test instances. In the coastal ports and the continental main port, the cargo handling rates are 15 TEU/hour and 20 TEU/hour, respectively.

Each of the four test instances is given a unique short-name in the format X-Y. X denotes the demand level, either C for *current* demand or H for *high* demand. Y is either 10 or 50 depending on the cargo handling rate in the ocean hub. As an example, H-10 denotes a test instance with high demand

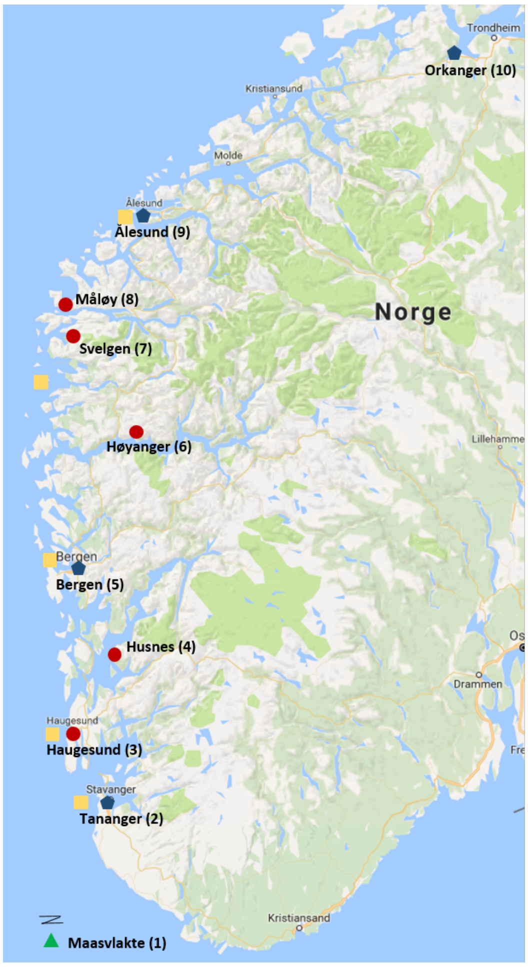


Fig. 5: Ports chosen for the test instances. Red dots denote coastal daughter ports, blue pentagons denote coastal main ports and yellow squares denote ocean hubs. The green triangle is the continental main port Maasvlakte located in Rotterdam, Netherlands.

and an ocean hub cargo handling rate of 10 TEU/hour. The test instances are summarized in Table 2.

Three different daughter ship types with capacities of 100, 200, and 300 TEUs (Twenty-foot Equivalent Unit) are evaluated. As explained previously, only one daughter ship type can be chosen, so each instance is solved for each available daughter ship type and is then compared with the others. The capacity of the mother ship is chosen based on the total demand that needs to be transported. For example in the current (high) demand scenario, we assume that the capacity is at least 616 (862) TEUs, since this is the maximum weekly

Table 1
Cargoes transported to and from the Continent.

Ports	**Current**		**High**	
	To:	From:	To:	From:
Tananger	126	127	176	178
Haugesund	48	45	67	63
Husnes	20	15	28	21
Bergen	126	105	176	147
Høyanger	17	12	24	17
Svelgen	21	35	29	49
Måløy	64	67	90	94
Ålesund	130	69	182	97
Orkanger	64	55	90	77
Maasvlaakte	530	616	743	862

Table 2
Test instances with varying demand and cargo handling rate in ocean hubs.

Instance	**Demand level**	**Cargo handling rate**
C-10	current	10 TEU/hour
C-50	current	50 TEU/hour
H-10	high	10 TEU/hour
H-50	high	50 TEU/hour

demand that needs to be transported on each trip in the current (high) demand scenario, see Table 1.

4.2 Solution Times

The model is solved to optimality for each of the four test instances, with the results summarized in Table 3. The table shows the number of mother and daughter routes generated as well as the computational times for the route generation procedure and for solving the mathematical model with the commercial solver. Daughter ships with capacity of 300 TEUs have been used in these tests, as this is the case with the largest number of routes generated, and hence also the longest computational times.

We see from Table 3 that the proposed solution approach is able to solve all instances to optimality in reasonable times. The number of main routes is the same for all instances except the H-10 instance. When the demand level is high and the cargo handling rate in ocean hubs is low, fewer main routes can be completed within the maximum allowed duration since each port visit takes longer time due to the higher cargo volumes that need to be handled. The same is valid for the daughter routes. Significantly fewer daughter routes are feasible for the test instances with high demand level due to tighter capacity restrictions. Increasing the cargo handling rate in ocean hubs makes more daughter routes feasible, but since the cargo handling time in the ocean hubs only constitute a small part of the total time, the increase is relatively small.

Table 3
Solution times (in seconds) and number of routes generated for each of the test instances.

Instance	Mother Routes	Daughter Routes	Route Generation Time	Model Solving Time	Total Solution Time
C-10	496	5,813	123	57	180
C-50	496	6,216	131	48	179
H-10	116	1,911	19	4	23
H-50	496	1,982	45	15	60

The computational times for both route generation procedure and solving the master problem decrease with decreasing number of routes.

4.3 Results from Solving the SSP Problem

The problem is solved once for each available daughter ship type, providing the opportunity to use expert judgment in addition to the model's objective value to determine which ship size is the most suitable. The objective values for the different ship types on the four test instances are shown in Table 4. The objective value represents the total weekly costs in NOKs, and consists of port costs, cargo handling costs, bunker costs and time charter costs for both mother and daughter ships.

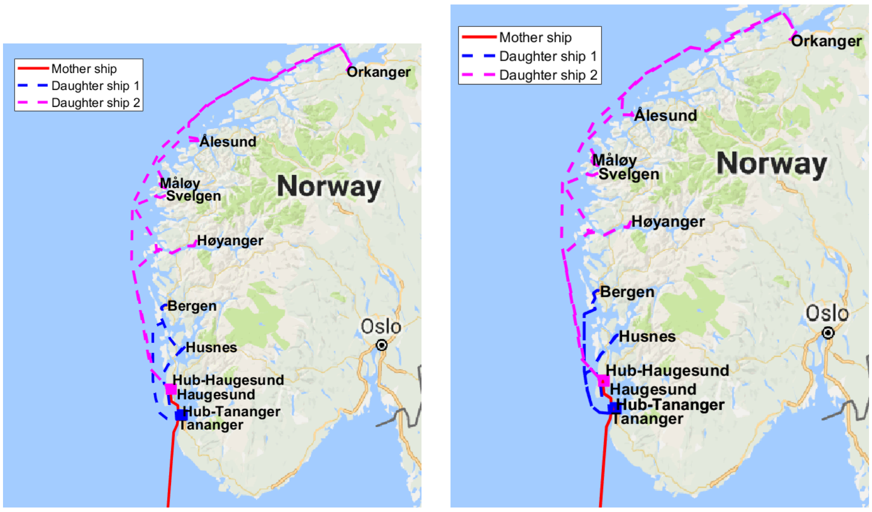
Table 4
Comparison of the objective values for different test instances and ship sizes.

Instance	Obj. Val		
	100 TEU	200 TEU	300 TEU
C-10	484,315	467,639	457,802
C-50	484,315	469,828	411,687
H-10	614,400	591,157	585,998
H-50	604,025	591,727	585,340

For each test instance, the solutions using 300 TEU daughter ships have the lowest costs. The differences between the different ship types are, however, relatively small, except for the C-50 instance where we see that the costs for the 100 and 200 TEU daughter ships are significantly higher compared to the solution for the 300 TEU daughter ships.

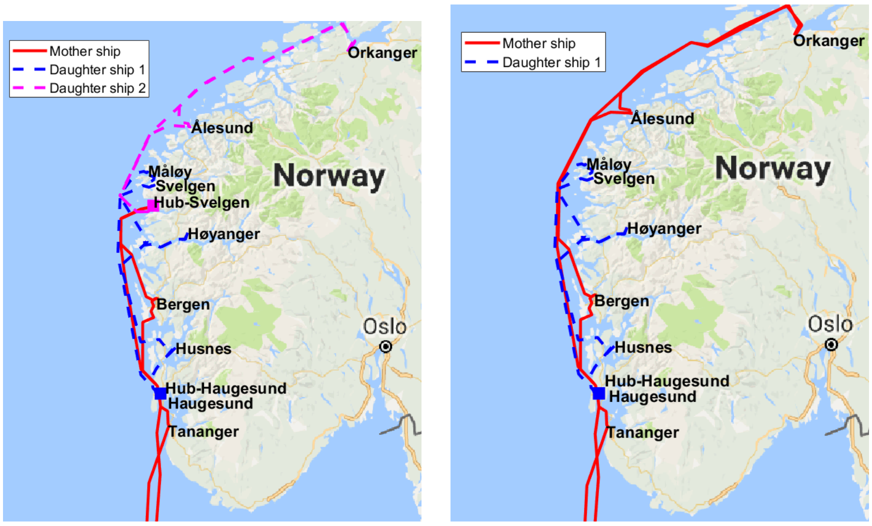
Since the solution with the 300 TEU daughter ships is cost optimal for each test instance, these results are studied further. The optimal route compositions are shown in Figure 6 for the test instances with current demand level and in Figure 7 for the test instances with high demand level.

All mother routes chosen in the optimal solutions, except the one for the H-50 instance, are visiting two ocean hubs. For the instances with low cargo



(a) Route composition for the C-10 test instance (b) Route composition for the C-50 test instance

Fig. 6: Route composition for the C-10 and C-50 test instances.



(a) Route composition for the H-10 test instance (b) Route composition for the H-50 test instance

Fig. 7: Route composition for the H-10 and H-50 test instances.

demand, the mother route does not extend further north than Haugesund. For the test instances with high cargo demand, the mother route extends as far north as Hub Svelgen in case of low cargo handling rate and Orkanger in case of high cargo handling rate. These results show that sailing as short mother routes as possible might be beneficial since these ships are larger and have higher costs than the daughter ships. An exception is if the number of deployed daughter ships can be reduced by letting the mother route extend further north. This is seen for the H-50 instance, where the mother route includes all coastal main ports and hence one less daughter ship is needed.

The daughter routes for the C-10 and C-50 instances, shown in Figure 6, both include a long and a short route. The long daughter route serves the coastal ports all the way from Orkanger in the north to Hub-Haugesund in the south.

In the high demand problem instances (Figure 7), the daughter ships visit fewer coastal ports because of the capacity restrictions. With a low cargo handling rate, the daughter routes are geographically spread out. One daughter route services the southern coastal ports while the northern ones are serviced on the other route. With high cargo handling rate in ocean hubs, only one daughter ship is needed.

To get a deeper insight of the solutions to the SLNDP-TS, it is important to look at more detailed solution characteristics than just the total cost. Some important solution characteristics related to the capacity utilization of the mother and daughter ships are shown in Table 5 for the cost optimal solutions of the different test instances. In the table, *Ships* refers to the number of ships deployed. *Size* refers to the capacity of the daughter ships. The average time a ship is idle and not performing cargo handling or sailing as percentage of the total time available is referred to as *Average Idle Time*. The average capacity utilization for a daughter ship is *Average Capacity*, while *CM Cargo* gives the percentage of the total cargoes handled by a mother ship in coastal main ports.

Table 5
Solution characteristics for the optimal solution in each test instance.

Instance	**Daughter Ships**				**Mother Ships**		
	Ships	Size	Average Idle Time	Average Capacity	Ships	Avg. Idle Time	CM Cargo
C-10	2	300 TEU	28 %	82 %	2	29 %	22 %
C-50	2	300 TEU	46 %	99 %	1	0 %	22 %
H-10	2	300 TEU	29 %	86 %	2	5 %	42 %
H-50	1	300 TEU	51 %	81 %	2	9 %	70 %

For all test instances except H-50, two daughter ships are deployed in the optimal solution, while for all instances except C-50, two mother ships are used. In all solutions, the daughter ships have a significant amount of idle time. With a low cargo handling rate in ocean hubs (i.e. the C-10 and H-10 instances), the average idle time is about 30%, while it is about 50% for the test instances with high cargo handling rate. Comparing the results from instances C-10 and C-50, the route composition is clearly similar (see Figure 6). The increased idle time for the C-50 test instances is a result of faster transhipments in the ocean hubs. The daughter ship's high idle time in the H-50 instance can be explained by the fact that the mother route includes all coastal main ports. The resulting daughter route visits only the coastal daughter ports and is therefore rather short (see Figure 7).

The mother routes in all solutions, with exception of the C-10 instance, exhibit only small amounts of idle time. This shows that the mother ships are highly utilized, and might imply that even small increases in cargo demand or decreases in cargo handling rates in ocean hubs are likely to cause changes in the optimal solution. For example, if the demand level in the C-50 instance increased slightly, a second mother ship might have to be deployed. Similarly, the mother route in the H-50 instance might not be able to visit all coastal main ports within the maximum duration of the route if the demand level increases. In this case, a second daughter ships is likely to be deployed to visit some of the northern coastal main ports.

For all instances, the average capacity utilization for the daughter ships, *Average capacity*, is quite high (above 80%). However, it should be noted that this is an average value and might differ between the daughter ships.

Unused capacity and idle time can create opportunities for the daughter ships to also transport cargo between local ports along the coast of Western Norway. In other words, the idle time provides the daughter ships with flexibility to perform additional transport missions as long as the schedule with the mother ship is followed. For the mother ships, idle time can potentially be used to visit several continental main ports and not just one. In addition, instead of a mother ship being idle, it might be possible to return to some of the coastal main ports, and by doing this, offer a higher port visit frequency.

5 Conclusions and Further Research

We have studied a new liner shipping network design problem based on the novel Short Sea Pioneer (SSP) concept denoted Shortsea Liner Network Design Problem with Transhipments at Sea (SLNDP-TS). We propose a two-step approach that can be used to solve the SLNDP-TS and to provide decision support in the design of the SSP logistics system. The first step consists of generating all feasible candidate routes using a label-setting dynamic programming algorithm, while the second step is to solve a path flow model with the candidate routes as input. The proposed solution approach has been tested on a real case from Western Norway, and it was shown that it was able to provide optimal solutions in reasonable time.

The model and its results can provide valuable insights to a decision maker when planning the implementation of the Short Sea Pioneer concept. Because of the reasonable runtime, the model is particularly well suited to study changes in the optimal solution if the underlying parameters, such as demand level or cargo handling rate, change.

It should be emphasized that since one important feature of the SLNDP-TS is the synchronization between ships for transhipment of cargo at sea, its solutions can be very sensitive to delays, for example from bad weather. In a future study, it can therefore be interesting to suggest extensions to the proposed solution approach to ensure that the solutions are reasonably robust with respect to such delays. Furthermore, the performance of the proposed method is very sensitive to problem size (e.g., the number of ports). One will therefore probably need to rely on heuristics to study SLNDP-TSs of larger size.

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