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## An economic analysis of introducing autonomous ships in a short-sea liner shipping network

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### Abstract

The development of autonomous ships is at an advanced stage. It seems to be just a question of time before such ships become available at an industrial scale. In this paper, we investigate the economic advantages of utilizing autonomous over conventional ships. We consider a shipping network composed of conventional mother ships and autonomous daughter ships that perform cargo transshipment at specific ports. The mother ships sail between Europe and the Norwegian coastline and are conventional due to international regulations. The daughter ships serve small ports located along the Norwegian coastline and are autonomous. We apply this concept of mother and daughter routes to a Norwegian shipping company that transports containers between a continental European port and 21 ports scattered along the Norwegian coastline. Furthermore, we extend this case to a shipping network of 42 ports to study a possible increase in the activity of the company. For solving the corresponding optimization problem, we present a path-flow-based model formulation and a heuristic route generation method. We carry out extensive computational experiments that consider differently sized problems, various demand scenarios, advanced routes structures, and sensitivity analyses for cost rates and the degree of automation of the maritime transport system. The results provide evidence that autonomous ships might contribute to considerable cost savings.

*Keywords:* autonomous ships; liner shipping network design; hub-and-spoke network; advanced route structures

### 1. Introduction

The next generation of ships in the maritime shipping industry will likely be characterized by full autonomy where ships operate without any crew on board. In Norway, several projects on

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autonomous ships are already taking place, making Norway a leading country in this field. The two Norwegian companies Kongsberg Maritime and Yara International are developing the world's first commercial autonomous ship, Yara Birkeland, with a capacity of 120 TEU (YARA, 2018). Another example is NTNU's autonomous passenger ferry to transport people in urban water channels (NTNU, 2019). The motivation behind these projects is not just about developing the technology, but also about bringing up new economic, social, and environmental advantages. For example, due to the removal of the deckhouse and accommodation structure and because of a reduction of weight and air resistance, autonomous ships can achieve a 6% reduction in fuel consumption compared with conventional ships (Kretschmann et al., 2017). This reduction has not only economic benefits but also an environmental impact on reducing  $\text{NO}_x$  and  $\text{CO}_2$  emissions. If the ships are fully electrified, like the Yara Birkeland, there will be even zero-emissions at sea. A further positive environmental effect takes place if autonomous ships contribute to replacing truck traffic. For instance, Yara Birkeland will replace more than 100 daily diesel truck journeys, which will further contribute to reducing emissions (YARA, 2018). Next to this, autonomous ships might also be safer as nowadays 58% of accidental events in the shipping industry are attributed to human factors (EMSA, 2018).

Although autonomous ship projects are at an advanced phase, international regulations are still conservative against their introduction in international waters. Traditionally, maritime law assigns responsibility to the captain in ensuring safe operations of the ship at sea. Autonomous ships must be shown stable enough over time so regulations can be adapted to make sure that safety is ensured for both autonomous and conventional ships (Ellingsen & Tøndel, 2017). However, it is believed that the regulations in national waters will be adapted more quickly to accommodate the use of autonomous ships.

In this paper, we do not aim at investigating the technical and design aspects of autonomous ships, but rather on analyzing the economic consequences of utilizing autonomous over conventional ships in future maritime logistics systems. We consider a real short-sea shipping network for the transportation of containers between Europe and ports along the Norwegian coastline. Assuming that regulations in national waters can be adapted more quickly, we assume that autonomous ships can serve local ports in Norway and, thus, will be locally deployed on domestic routes, which we call *daughter routes*. Conversely, larger and conventional ships sail international waters and transport cargo from the European continent to main Norwegian ports on so-called *mother routes*. The economic analysis is performed based on data from a Norwegian liner shipping company, for which we investigate new network designs based on both conventional mother and autonomous daughter ships.

Our work belongs to the area of liner shipping network design (LSND). Most existing LSND studies focus on deep-sea shipping using conventional ships. For example, Agarwal and Ergun (2008) introduce an LSND that serves a weekly demand ensured by a heterogeneous fleet. This study is the first in the literature to consider cargo transshipment, where ships are synchronized to meet at a same port. The problem is modeled with an arc-flow formulation and solved with a time-space graph and column generation-based algorithm. This work is extended by Álvarez (2009) to include transshipment costs in the network design. The problem is solved using a combination of tabu search and column generation. Reinhardt and Pisinger (2012) present a branch-and-cut algorithm for the LSND problem with transshipment costs. The model allows for simple (one loop) and butterfly (two loops) routes with a heterogeneous fleet of ships. Thun et al. (2017) study the

LSND problem with advanced route structures, from one to many loops. The authors develop a branch-and-price algorithm. Unfortunately, the problem turns out to be very complicated such that instances are tested with at most two loops per route. Brouer et al. (2013) develop a benchmark suite for the LSND problem, where transshipment can be performed at any port and as many times as necessary, and it is also possible to split pickups and deliveries for the same demand. The problem is heuristically solved using tabu search and column generation. This problem has been further extended to include transit time restrictions (Karsten et al., 2017a) and speed optimization on each sailing leg (Karsten et al., 2017b).

Typically, transshipments in LSND problems are only allowed at specific ports, called hubs, whereas all other ports act as spoke ports. Such configuration of an LSND is referred to as hub-and-spoke networks. Typically, larger ships are deployed on routes visiting the hubs, whereas smaller ships are deployed on feeder routes visiting spoke ports (Zheng et al., 2015). In Meng and Wang (2011), only a limited set of ports act as hubs. Zheng et al. (2015) limit the number of transshipments to at most two hubs and also consider transit time restrictions. Holm et al. (2019) address a specific case for the liner hub-and-spoke shipping problem. The network consists of mother and daughter ships, where the mother ships serve main (hub) ports. In particular, the transshipment is not performed at regular ports, but instead at suitable locations at sea. Synchronization of mother and daughter ships is required in this system so that both mother and daughter ships meet at the same location at the same time for the transshipment.

A feeder network design problem is a particular version of the LSND problem that typically consists of a single hub port and many feeder ports (Meng et al., 2013). The containers are transported between hub and feeder ports, and transshipment is allowed. Fagerholt (1999) introduces a pioneering study in feeder network design, where the objective is to find the weekly routes of ships in order to minimize costs. Fagerholt (2004) extends the model to incorporate a heterogeneous fleet regarding speed and capacity. Wang and Meng (2014) consider direct connections between all ports, meaning that the shipping system runs without transshipment. Such a configuration results in short transit time, however, at the expense of higher operational costs. Santini et al. (2018) focus on the in-depth modeling of a feeder network itself. They combine strategic decisions, such as fleet utilization and port selection, with tactical decisions, such as speed optimization, in a single framework.

The contribution of this paper is to study an LSND with autonomous ships (LSND-A) applied to the current activity of a Norwegian shipping company. The network is, as previously mentioned, composed of mother routes and daughter routes sailed by conventional and autonomous ships, respectively. We analyze the economic impact of introducing autonomous ships by comparing it with a fully conventional system. We also consider how the optimal fleet size and mix differ between the system with autonomous and conventional ships. Furthermore, we study the inclusion of advanced route structures like butterfly routes and clover routes into the LSND-A in order to increase ship utilization and network efficiency. Finally, we test whether autonomous ships are also beneficial if their construction cost are higher than those of conventional ships and we analyze a fully autonomous system assuming that in the future autonomous ships can also sail international waters.

The remainder of this paper is organized as follows. In Section 2, we provide more explanation on the LSND-A problem. In Section 3, we propose the solution methodology for solving this network design problem. We first present a mathematical model based on a path-flow formulation and then provide a heuristic to solve large problems. We conduct detailed economic analyses of the introduction of autonomous ships in Section 4. Finally, Section 5 gives concluding remarks.

## 2. Liner network design for autonomous shipping in the Norwegian maritime industry

We consider a real case of a Norwegian shipping company that transports containerized goods between Europe and several ports along the Norwegian coast. The shipping follows a liner basis mode, which is distinguished by a *regular weekly service* for all served ports. This mode has the advantage of having fixed schedules that make the planning easier for the shippers. Currently, the operations of this company follow a feeder network design. Three lines are operated from a hub port in Rotterdam to serve the Norwegian ports. One of the routes is sailed by only one ship. This route has a duration of one week. Each of the other two routes are about 10 days in duration. They are served by two ships each to guarantee the weekly visiting frequency.

We investigate how this shipping company can run its current operations using autonomous ships. For this purpose, we develop an LSND-A system based on a combination of conventional and autonomous ships. We establish a so-called hub-and-spoke network, where larger conventional ships sail long routes between hubs ports, whereas smaller autonomous ships are deployed on feeder routes visiting spoke ports. Alumur and Kara (2008) point out that such networks concentrate flows in order to benefit from economies of scale. The LSND-A is thus to establish a liner shipping network design using both conventional mother ships that serve *main ports* (hubs) to ensure all cargo flows between Europe and Norway and smaller autonomous daughter ships that serve *small ports* along the Norwegian coast or inside fjords. We consider only the cargo flows to and from each Norwegian port and the continental port because cargo flows among Norwegian ports are negligible. To transport cargo from the continental hub port (Rotterdam) to a minor Norwegian port, the cargo is first loaded onto a mother ship at the continental port, then unloaded at a Norwegian main port, transshipped onto a daughter ship, and transported to its destination. The reverse routing is applied for bringing export cargo from small Norwegian ports to the continental port. The cargo flows between Norwegian main ports (hubs) and the continental port are conducted by mother ships or by a combination of a mother and daughter ship. In the latter case, there is an intermediate Norwegian port involved for transshipping the cargo. The classification of ports into main ports and small ports is according to their location and their capacity to dock a mother ship. Therefore, the network requires that (i) mother ships serve all or a subset of the main ports, and (ii) daughter ships visit small ports and those main ports that are not served by mother ships.

All mother ships sail a unique *mother route* that starts from the continental port, then serves the northern-most main Norwegian port belonging to its route before visiting other main ports located further in the south. Thus, the cargo deliveries and pickups are performed during southbound journeys. Furthermore, the number of mother ships to be deployed on a mother route is determined so that a weekly frequency is ensured. For example, a mother route with a total duration of 21 days requires three mother ships to ensure a weekly service at each port. On the other hand, as the *daughter routes* are much shorter, it is assumed that the total duration of each such route is at most one week and operated by only one daughter ship. A daughter route starts at the transshipment (main) port and serves a set of other (small and/or main) ports. The fleet of daughter ships is heterogeneous with respect to their capacity and cost structure, which means that each daughter route of the system can deploy a different daughter ship depending on how much cargo to carry for the designed route. In contrast, the fleet of mother ships is homogeneous where the overall capacity of the fleet is sufficiently high to transport all cargoes occurring in the system.

The LND-A problem consists of determining the composition of main and daughter routes to fulfill all cargo flows. Furthermore, it needs to be decided on which type and number of autonomous ships to use for the daughter routes. The objective is to minimize the total costs of operating the fleet of ships. It should be noted that the problem considered in this study is at a tactical level. That is, operational decisions, such as adjusting sailing speed or arriving at operating time at small ports, are made at a later stage and, therefore, out of scope of our study.

### 3. Model and solution methodology

In this section, we present a path-flow model for the LSND-A. We first provide the notation and the mathematical model of the problem. We then briefly describe an algorithm to generate the set of feasible and nondominated routes that are given as input to the path-flow model. We also present a heuristic version of this algorithm, which restricts the route generation in order to solve large problems.

#### 3.1. Mathematical model

We use the following notation for modeling the problem under investigation:

##### Sets

$\mathcal{V}$	set of daughter ship types,
$\mathcal{P}^{\mathcal{D}}$	set of small ports that only daughter ships can visit,
$\mathcal{P}^{\mathcal{M}}$	set of main ports,
$\mathcal{R}^{\mathcal{D}}$	set of daughter routes with a weekly service frequency; a daughter route $d$ is served by one daughter ship $v \in \mathcal{V}$ ,
$\mathcal{R}^{\mathcal{M}}$	set of mother routes; the ports visited by a mother route must be served with a weekly service and, thus, a mother route $m$ is to be served by one or more mother ships,
$\mathcal{R}_p^{\mathcal{D}}$	set of daughter routes that include port $p$ , $\mathcal{R}_p^{\mathcal{D}} \subseteq \mathcal{R}^{\mathcal{D}}$ ,
$\mathcal{R}_p^{\mathcal{M}}$	set of mother routes that include main port $p$ , $\mathcal{R}_p^{\mathcal{M}} \subseteq \mathcal{R}^{\mathcal{M}}$ .

##### Parameters

$C_m^{\mathcal{M}}$	weekly operational costs of using a fleet of mother ships to serve the mother route $m$ ,
$C_d^{\mathcal{D}}$	weekly operational costs of using a daughter ship to serve daughter route $d$ ,
$A_{mp}^{\mathcal{M}}$	is equal to 1 if mother route $m$ visits main port $p$ , and 0 otherwise,
$A_{dp}^{\mathcal{D}}$	is equal to 1 if daughter route $d$ does the transshipment in main port $p$ , and 0 otherwise,
$K$	Big-M value that represents the maximum number of daughter routes that can use main port $p$ for transshipment; an upper bound can be set to $K =  \mathcal{P}^{\mathcal{D}}  +  \mathcal{P}^{\mathcal{M}}  - 2$ .

A mother route  $m \in \mathcal{R}^{\mathcal{M}}$  specifies a set of main ports to be visited. The total duration of  $m$  for sailing between the different ports and for loading and unloading cargo at each visited port is precalculated. This is possible as we allow only one mother route from set  $\mathcal{R}^{\mathcal{M}}$  to be operated, and this route is therefore responsible for transporting the total weekly demand of all ports. The total duration of route  $m$  prescribes the number of mother ships that must be deployed so that a

weekly service is ensured. The cost  $C_m^M$  of a mother route  $m$  then comprises the weekly time charter costs for the required number of mother ships, the corresponding bunker costs, port fees, and cargo handling costs.

A daughter route  $d \in \mathcal{R}^D$  specifies a set of small (and/or main) ports to be visited by a daughter ship. The total duration of route  $d$  for sailing and handling containers must not exceed one week, and thus one daughter ship can be deployed to any given daughter route. The maximum number of containers being transported along route  $d$  determines the ship type  $v \in \mathcal{V}$  to deploy for this route. The corresponding cost  $C_d^D$  of a daughter route  $d$  includes the weekly time charter cost of the selected ship of type  $v$ , the bunker costs, port fees, and cargo handling costs.

### Decision variables

$x_m$  a binary decision variable that is equal to 1 if mother route  $m \in \mathcal{R}^M$  is part of the solution, and 0 otherwise,  
 $z_d$  a binary decision variable that is equal to 1 if daughter route  $d \in \mathcal{R}^D$  is part of the solution, and 0 otherwise.

The optimization problem is modeled as follows:

$$(F1) : \min = \sum_{m \in \mathcal{R}^M} C_m^M x_m + \sum_{d \in \mathcal{R}^D} C_d^D z_d \quad (1)$$

subject to:

$$\sum_{m \in \mathcal{R}_p^M} x_m + \sum_{d \in \mathcal{R}_p^D} z_d \geq 1, \quad p \in \mathcal{P}^M, \quad (2)$$

$$\sum_{d \in \mathcal{R}_p^D} z_d = 1, \quad p \in \mathcal{P}^D, \quad (3)$$

$$\sum_{m \in \mathcal{R}^M} x_m = 1, \quad (4)$$

$$K \sum_{m \in \mathcal{R}_p^M} A_{mp}^M x_m \geq \sum_{d \in \mathcal{R}_p^D} A_{dp}^D z_d, \quad p \in \mathcal{P}^M, \quad (5)$$

$$x_m \in \{0, 1\}, \quad m \in \mathcal{R}^M, \quad (6)$$

$$z_d \in \{0, 1\}, \quad d \in \mathcal{R}^D. \quad (7)$$

The objective function (1) minimizes the total weekly operational costs of the fleet of mother and daughter ships that operates the network. Constraints (2) state that each main port must be served by either a mother route or a daughter route. Constraints (3) ensure that each small port is visited exactly by one daughter route. Constraint (4) enforces only one mother route to be selected in the whole system. Constraints (5) establish the following transshipment relation: A daughter route  $d$  can be selected only if it performs transshipment at a main port  $p$  that is visited by a mother route  $m$ . Finally, the binary requirements for the decision variables are given in Constraints (6) and (7).

### 3.2. Creating the set of candidate routes

The mathematical model requires as input a set of mother and daughter routes, respectively. Clearly, creating all possible routes is computationally intractable for relevant numbers of ports, like, for example, the more than 20 ports being considered in our case. To create a subset of feasible and nondominated routes, we provide a label-setting dynamic programming algorithm as is widely used in the literature, for example, Holm et al. (2019), and combine this with a heuristic scheme for further reducing the number of generated routes.

Mother routes are created as follows: A mother route starts at the continental port and serves main Norwegian ports. The port visits are performed during the southbound journey meaning that, once a mother route serves a main port, it is only allowed to sail further south. This route fashion makes it easy to generate all feasible mother routes if the number of main ports is not too large. Indeed, a partial mother route, which is a sequence of visited ports, is extended to (i) any main port located further south than the last visited port, which yields a new partial mother route, or (ii) goes back to the continental port, which completes a mother route. Each completed mother route  $m$  gets assigned a weekly operational cost  $C_m^M$  as defined before.

Daughter routes are created as follows: A daughter route begins its voyage at a main port, where the daughter ship does the transshipment with the mother route. During its voyage, a daughter route can visit both main and small ports. At each served port, the ship unloads the containers to deliver and then loads the containers to pick up. While generating this set of routes, a partial daughter route can be extended to any main or small port as long as the route duration limit of one week is not violated. Furthermore, a dominance between two partial routes may occur if (i) they include the same visited ports but in a different order, and (ii) have the same last visited port. Among two such routes, the partial route with lower cost and lower maximum number of containers on board (at any visited port) dominates the other partial route. A partial route is completed by letting the daughter ship return to the main port where the route started. Finally, a completed daughter route gets assigned a ship of adequate capacity from the fleet of daughter ships. For example, if a route has 131 TEUs as a maximum number of containers on board, and the available set of daughter ships has capacities of 86, 158, and 190 TEUs, a ship of size 158 TEU is assigned. As described before, a weekly cost  $C_d^D$  is associated with each complete daughter route  $d$ .

### 3.3. Heuristic based on limiting the number of candidate routes

Although the label-setting algorithm is capable of generating all nondominated daughter routes, preliminary experiments showed that the computational time increases exponentially as the number of ports increases. It is, therefore, necessary to develop a heuristic, so that large-sized problems can be solved. We propose a simple heuristic that limits the number of candidate routes during the route generation step by exploiting specific features of the problem. Indeed, many daughter routes are unlikely to be included in the optimal solution, for example, if they sail long distances to serve a few ports that are far away from the transshipment port. Furthermore, Norway has a particular geographical shape where the ports lie more or less on a south–north line along the coast. Therefore, most cost-efficient routes go in one direction (southbound or northbound) from the main port, rather than zigzagging. Our idea is therefore to forbid daughter routes that perform zigzagging.

To do this, we first order the ports according to their latitude. The heuristic then starts extending partial daughter routes from the southernmost port. Extension of a partial route is only allowed toward the next  $e$  ports in northbound direction, where  $e$  is a preset parameter value that controls the heuristic. Then, the heuristic starts the extension from the second port, and so on. Furthermore, the heuristic duplicates any partial sequence that is extended to a main port. The latter is considered as the transshipment port in the duplicated route. By reducing the number of candidate routes, the number of decision variables considered by the mathematical model  $F1$  is significantly reduced, which effects a substantial reduction of the computational time. The parameter  $e$  is used to control the number of routes generated and, thus, the heuristic reduction of the optimization problem.

It should be emphasized that the procedure described above creates so-called *simple daughter routes* that consist of a single loop where a ship starts at a transshipment port, serves some ports, and then goes back to the initial port. If such a loop is sufficiently short, a daughter ship might sail another loop within the time limit of one week, to serve further ports. We call the resulting routes *advanced route structures*. More precisely, a *butterfly route* involves two loops, a *clover route* combines three loops, and a *flower route* includes four loops. The generation of advanced routes can be easily done by combining simple routes that have the same transshipment port  $p$  and are served by the same ship type  $v$ . If the total duration of the combined loops is within one week, a new advanced route is obtained.

#### 4. Computational study

Our computational study aims to provide an economic analysis of integrating autonomous ships into the studied maritime transportation system. First, we describe the data and parameters that were chosen such as to make the experiments as realistic as possible. Then, we measure the performance of the heuristic in regards to solution quality and computational time. Finally, we carry out extensive experiments to study the economic impacts of using autonomous ships.

The route generation procedures were implemented using MATLAB version R2018a, 64-bit. The mathematical model was implemented in Xpress-IVE Version 1.24.24 64-bit with Xpress Model Version 4.8.3 and solved by the Xpress Optimizer Version 33.01.02.

##### 4.1. Data collection

Currently, the liner shipping company is serving 22 ports. The continental port is at Rotterdam at the Netherlands, and the 21 Norwegian ports are located from the southwestern coastline of Norway to the very north, see Fig. 1. Furthermore, the study includes an examination of growth in demand and the possibility to integrate the transportation of farmed fish transported in specialized containers within the activity of the shipping company. Today, most farmed fish are transported to the European market by trucks, although all the existing fish farms are located along the Norwegian coast. Besides, according to the national transportation plan 2018–2029 of Norway, there is a political focus on shifting freight from road transportation to maritime transportation (Norwegian Ministry of Transport and Communications, 2017). Therefore, using autonomous ships for the farmed fish industry offers significant potential to fulfill this political requirement of reducing road traffic. The





Fig. 1. Map showing all the ports considered in the case study where 22 ports are served today by the case study company and 20 ports might be used for farmed fish transportation in the future.

focus on the farmed fish industry is justified by its importance in Norway. The Norwegian Sea Food Federation has set a goal for the Norwegian fish industry to increase the production of farmed fish to 5 million tonnes per year within 2050 (Sjømat Norge, 2018). Consequently, sustainable logistics solutions are needed in order to follow this growth. An efficient logistics system can potentially be obtained by utilizing autonomous ships. There are 20 fish ports with nearby slaughterhouses for farmed fish. We assume that these ports can be served by autonomous ships in the future too. Therefore, in our experiments, we consider the existing container ports and the additional fish ports too.

The computational study then considers three main instances with 22, 32, and 42 ports, respectively. The instance with 22 ports represents the container ports currently served by the shipping company, including seven main ports. The instance with 32 ports is composed of 22 ports served by the company plus 10 fish ports. This instance involves 10 main ports. The largest instance includes all the ports of which 12 are classified as main ports. The classification of main and small ports depends on the importance of a port in terms of demand and its geographical location. We assume that approximately 30% of ports with largest demand are classified as main ports.

Representative demand data for the currently served ports have been provided by the shipping company. This demand corresponds to the weekly volume of containers transported to/from Rotterdam. Conversely, the demand for fish ports is only related to containers exported to Rotterdam and is based on the slaughtered fish volumes in 2015. To study the impact of changes in demand, we consider three different scenarios: normal, high, and very high demand. The normal demand scenario uses the given demand data. The high demand scenario represents a 40% increase over normal demand, which reflects the growth forecasted for 2040 in the Norwegian national transport plan 2014–2023 (Regjeringen, 2013). The very high demand scenario envisages a positive growth of 100% increase in demand, considering that the national transport plan 2018–2029 estimates a 70% increase in demand for 2050 (Regjeringen, 2018). Furthermore, to have a broader testbed for the heuristic, we generate five additional test instances with 22, 32, and 42 ports for both normal and high demand scenarios, where demand is created randomly following similar demand ranges as in the original data provided by the shipping company and the slaughtered fish volumes.

To investigate the economic effect of introducing autonomous daughter ships, the LSND-A is solved for both conventional and autonomous daughter ships. The fleet of daughter ships can be composed of ships of three types that differ by capacity, fuel consumption rate, and time charter cost. We refer to these ships as “small” (S), “medium” (M), and “large” (L). The design and costs of the autonomous ships are based on estimations provided by a naval architect, as well as from the literature. The fuel consumption will be lower for an autonomous ship compared to a conventional with the same cargo capacity (Kretschmann et al., 2017). This is mainly because the autonomous ships can have somewhat smaller dimensions (or be more slender) as they have more space for carrying containers due to the removal of the superstructure, but also because of a reduced hotel load. The effects on building costs from going from conventional to autonomous ships is harder to estimate. We have followed the estimates provided by Kretschmann et al. (2017) and Willumsen (2018), which have also been verified by the naval architect. They estimate a net increase in building costs of 5%, based on that the removal of the deck house will reduce the costs by 5%, whereas the more complex redundancy systems and ship-shore communication result in an increase of 10%. As the case shipping company charters their vessels on time charter, we have embedded both the payment of the ship and the crew in a time charter rate. Despite that the building cost for

Table 1  
Parameters for conventional and autonomous daughter ships according to ship size

Conventional daughter ships	S	M	L
Capacity (TEU)	86	158	190
Fuel consumption (tonnes/hour)	0.101	0.114	0.123
Weekly time charter cost (kUSD)	25.0	30.0	35.0
Autonomous daughter ships	S	M	L
Capacity (TEU)	86	158	190
Fuel consumption (tonnes/hour)	0.085	0.097	0.107
Weekly time charter cost (kUSD)	9.7	15.0	20.2

Table 2  
Parameters for conventional and autonomous mother ships according to ship size

Conventional mother ships	I	II	III	IV	V
Capacity (TEU)	1000	1350	2000	2550	3500
Fuel consumption (tonnes/hour)	0.61	0.69	0.75	0.80	0.85
Weekly time charter cost (kUSD)	53.0	54.0	56.0	58.0	64.0
Autonomous mother ships	I	II	III	IV	V
Capacity (TEU)	1000	1350	2000	2550	3500
Fuel consumption (tonnes/hour)	0.55	0.62	0.68	0.72	0.77
Weekly time charter cost (kUSD)	32.5	33.5	35.6	37.7	44.0

autonomous ships are expected to increase compared to conventional ones, this time charter cost is significantly reduced in the fully autonomous case because we can remove the crew costs, which constitute a very high share of the time charter costs for such small ships. The (reduced) crew costs have been estimated using numbers from Utdanning.no (2019) and verified by the shipping company. Tables 1 and 2 show the different technical characteristics and the estimated costs for the daughter and mother ships, respectively, that are used in this case study.

As previously mentioned, as we assume that only one mother route is deployed, the sufficient capacity for mother ship(s) can easily be determined *a priori* by taking the maximum between the total number of containers going from and to Rotterdam. By doing so, we can assign for each instance a suitable mother ship type among the following capacities: 1000-TEU, 1350-TEU, 2000-TEU, 2550-TEU, and 3500-TEU, referred to as I, II, III, IV, and V, respectively. For any mother ship size, the fuel consumption is based on a standard sailing speed set equal to 12 knots, and the time charter costs are based on data for similar container ships that are taken from Hamburg Index (2019). The characteristics of different mother ship types are summarized in Table 2. Although the LSND-A is based on conventional mother ships, we consider autonomous mother ships in a later experiment to study the economics of a fully autonomous system, see Section 4.3.4. The fuel consumption and weekly time charter costs for these are estimated in the same way as for the autonomous daughter ships.

The remaining input data are estimated as follows. The bunker price is roughly based on the average market price in Rotterdam over one year and set to 600 USD per tonne for low sulfur

marine gas oil. Fees for port calls are based on average fees faced in Norwegian ports. For the autonomous ships, we follow Kretschmann et al. (2017), who estimate an increase of 20% in port cost as it will be necessary for extra assistance of these ships at ports. As for the cargo handling, the continental main port is assumed to have a higher handling rate (20 TEU/hour) compared to Norwegian ports (15 TEU/hour). The cargo handling cost is the same for all ports and is set to 30 USD/TEU.

It should be noted that the introduction of autonomous ships most likely will bring new additional cost components, such as the cost of a shore control center (Kretschmann et al., 2017). However, it is very hard to estimate this added cost today. Nevertheless, a shore control center might be able to monitor quite a large number of ships and fleets in parallel. Therefore, we assume that the cost per ship is negligible and ignore this cost in our evaluation. Additionally, we also perform sensitivity experiments regarding the increased costs of autonomous ships in Section 4.3.3, where the cost increase could include the cost of a shore control center.

#### 4.2. Performance of the heuristic

The performance of the heuristic is tested on the randomized test instances for normal and high demand scenarios. For each of these instances, we solve the LSND-A with autonomous daughter ships and simple daughter route structures. We tested the performance of the heuristic for values of the parameter  $e$  ranging from 1 to 5. We compare the gap of the obtained solutions to the exact solution found by Xpress (when optimality can be proven) or to the best among all solutions that can be found by the heuristic for the different values of  $e$ .

Tables 3 and 4 present the results for the random instances with normal and high demand scenarios, respectively. The first column gives the size of the problem in terms of the number of ports. The second column reports the solution method applied to the problem. The next three columns “Mother,” “Daughter,” and “CPU (s)” report the average number of mother and daughter routes generated for the problem and the average computational time (in seconds) that the route generation took for the five test instances. For the route generation, we have set a time limit of three hours. Entry “NA” in the corresponding columns indicates that this time limit was exceeded. Column “Optimization” provides the average CPU time required for solving the resulting optimization model for the five instances. “Gap” computes the deviation of the obtained solutions from optimal or best-known solutions. Here, the values “Avg.,” “Min,” and “Max” indicate the average, minimum, and maximum gap over the five test instances, respectively.

We can see from Tables 3 and 4 that the performance of the route generation and the solution of the optimization problem depend on two parameters: the number of ports and the demand scenario. For the normal demand scenario, generating all relevant routes within the time limit is only possible for the instances with 22 ports. Here, 127 mother routes and 26,572 daughter routes are obtained in 1501 seconds. This shows that the generation of daughter routes is by far the biggest challenge. The number of mother routes is strongly limited and depends only on the number of ports visited because all routes are strictly southbound directed. Therefore, the time for generating all mother routes is merely 11 seconds, even for the largest instances with 42 ports.

For the high-demand scenario, the generation of all relevant routes within the time limit is possible for 22 and 32 ports. In this scenario, port demands are higher, and fewer daughter routes

Table 3

Performance of the heuristic for random instances with normal demand. For each row, the reported results represent the average of five random instances. The italic row is related to the exact solution

No. of ports	Method	Route generation			Optimization	Gap (%)		
		Mother	Daughter	CPU (s)	CPU (s)	Avg.	Min	Max
22 ports	<i>Exact (Xpress)</i>	<i>127</i>	<i>26,572</i>	<i>1501</i>	<i>32</i>	<i>0.00</i>	<i>0.00</i>	<i>0.00</i>
	Heuristic ( $e = 1$ )	127	114	1	<1	3.11	2.50	3.97
	Heuristic ( $e = 2$ )	127	475	2	1	1.00	0.00	1.73
	Heuristic ( $e = 3$ )	127	1227	3	3	0.55	0.00	1.00
	Heuristic ( $e = 4$ )	127	2485	5	4	0.19	0.00	0.60
	Heuristic ( $e = 5$ )	127	4062	9	8	0.18	0.00	0.60
32 ports	<i>Exact (Xpress)</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
	Heuristic ( $e = 1$ )	1023	197	4	2	6.86	3.43	7.64
	Heuristic ( $e = 2$ )	1023	1054	8	7	1.20	1.03	1.31
	Heuristic ( $e = 3$ )	1023	3406	40	73	0.41	0.14	0.67
	Heuristic ( $e = 4$ )	1023	9803	318	255	0.18	0.00	0.13
	Heuristic ( $e = 5$ )	1023	21,906	1706	1167	0.00	0.00	0.00
42 ports	<i>Exact (Xpress)</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
	Heuristic ( $e = 1$ )	4095	341	22	5	2.09	1.76	2.34
	Heuristic ( $e = 2$ )	4095	3645	70	21	0.59	0.43	0.81
	Heuristic ( $e = 3$ )	4095	17,782	6693	224	0.00	0.00	0.00
	Heuristic ( $e = 4$ )	NA	NA	NA	NA	NA	NA	NA
	Heuristic ( $e = 5$ )	NA	NA	NA	NA	NA	NA	NA

are generated as daughter ships reach their capacity limit quickly after visiting a few ports. As a result, all routes can be generated for the high-demand instances with 32 ports in on average 4807 seconds. Considering the heuristic route generation process, we can generate routes for all instances except for the largest one with 42 ports and  $e = 4$  or  $e = 5$ , see Tables 3 and 4.

In almost all considered cases, the CPU time for solving the optimization problem is lower compared to the time for generating the routes. As expected, solving the optimization problem takes longer when there are more routes generated for a problem, that is, the higher the value of parameter  $e$  is. Still, even in the worst solvable case with 32 ports, normal demand, and  $e = 5$ , solving the optimization problem takes only 1167 seconds, see Table 3.

We make the following observations regarding the quality of the heuristic solutions. For those instances where Xpress obtained optimal solutions, that is, instances with 22 ports for normal demand as well as instances with 22 and 32 ports for high demand, the heuristic with  $e = 5$  provides good solutions with very low average gaps of 0.18%, 0.49%, and 0.94%, respectively. For lower values of  $e$ , gaps are higher at the benefit of a reduced runtime. Especially with  $e = 1$ , we observe relatively high average gaps of up to 8.1%. For those instances where Xpress did not solve the problem, gaps refer to the the best solution found by the heuristic. Clearly, this best solution is always determined by the heuristic solution with the highest value of parameter  $e$  that can be solved for an instance. For those cases, the gaps are 0.0%, see, for example,  $e = 4$  for the instances with 42 ports and high demand. Anyhow, even if  $e$  is slightly lower, the gaps do not worsen much. This indicates that the

Table 4

Performance of the heuristic for random instances with high demand. For each row, the reported results represent the average of five random instances. The italic row is related to the exact solution

No. of ports	Method	Route generation			Optimization	Gap (%)		
		Mother	Daughter	CPU (s)	CPU (s)	Avg.	Min	Max
22 ports	<i>Exact (Xpress)</i>	<i>127</i>	<i>4400</i>	<i>34</i>	<i>6</i>	<i>0.00</i>	<i>0.00</i>	<i>0.00</i>
	Heuristic ( $e = 1$ )	127	71	6	NA	NA	NA	NA
	Heuristic ( $e = 2$ )	127	195	6	< 1	1.32	1.12	1.61
	Heuristic ( $e = 3$ )	127	406	6	< 1	0.55	0.03	0.77
	Heuristic ( $e = 4$ )	127	647	7	1	0.52	0.03	1.07
	Heuristic ( $e = 5$ )	127	988	8	1	0.49	0.03	0.91
32 ports	<i>Exact (Xpress)</i>	<i>1023</i>	<i>53,558</i>	<i>4807</i>	<i>142</i>	<i>0.00</i>	<i>0.00</i>	<i>0.00</i>
	Heuristic ( $e = 1$ )	1023	120	10	< 1	8.10	7.07	9.12
	Heuristic ( $e = 2$ )	1023	401	11	2	6.43	6.23	6.76
	Heuristic ( $e = 3$ )	1023	851	25	4	1.66	0.84	2.09
	Heuristic ( $e = 4$ )	1023	1785	47	30	1.13	0.70	1.98
	Heuristic ( $e = 5$ )	1023	2898	350	12	0.94	0.55	1.67
42 ports	<i>Exact (Xpress)</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
	Heuristic ( $e = 1$ )	4095	193	22	2	2.70	1.48	3.37
	Heuristic ( $e = 2$ )	4095	977	37	7	1.07	0.89	1.15
	Heuristic ( $e = 3$ )	4095	2912	341	14	0.38	0.11	0.72
	Heuristic ( $e = 4$ )	4095	7716	5906	42	0.00	0.00	0.00
	Heuristic ( $e = 5$ )	NA	NA	NA	NA	NA	NA	NA

solution converges to near optimal quality with settings  $e = 4$  or  $e = 5$ . As a conclusion, the heuristic generates very good solution quality for higher values of  $e$  within reasonable computation times.

### 4.3. Economic analysis

In this section, different analyses are conducted to investigate the economic effects of incorporating autonomous ships into liner shipping. The analyses are performed on nine different test instances with 22, 32, and 42 ports under normal, high, and very high demand scenarios. These instances use the realistic demand data that are described in Section 4.1. We use the heuristic to generate the candidate routes for the daughter ships. For each instance, we select the highest value of  $e$  for which the route generation is completed within a three-hour time limit.

#### 4.3.1. Conventional and autonomous daughter ships with simple routes

This experiment compares the LSND-A with conventional and autonomous daughter ships using only simple routes. The objective is to study (i) the impact of introducing autonomous ships on the operational costs and (ii) the fleet composition of the obtained solution. The gained results for instances with 22, 32, and 42 ports are presented in Tables 5–7, respectively. In each table, we report results for the three demand scenarios (“Normal,” “High,” and “Very high”). The total operational costs are given together with their composition into fuel cost, time charter cost, cargo handling, and

Table 5

The results of the LSND-A with conventional and autonomous daughter ships for simple daughter routes for instances with 22 ports

Results (22 ports)	Normal ( $e = 5$ )		High ( $e = 5$ )		Very high ( $e = 5$ )	
	Conv.	Aut.	Conv.	Aut.	Conv.	Aut.
No. of main ports = 7						
Total op. costs (kUSD)	522	474	649	585	900	800
Fuel cost (kUSD)	76	74	85	71	90	85
Time charter costs (kUSD)	258	211	298	243	437	342
Cargo handl. costs (kUSD)	185	185	263	267	369	369
Port costs (kUSD)	3	4	3	4	4	4
Fleet of daughter ships	2 M, 1 L	2 S, 2 M	2 M, 2 L	5 M	1 M, 5 L	6 M, 1 L
Fleet of mother ships	3 II	3 II	3 III	3 III	4 IV	4 IV
No. of mother routes	127	127	127	127	127	127
No. of daughter routes	14,871	14,871	4456	4456	1384	1384
Total solution time (s)	72	73	26	27	12	13
Route generation (s)	62	58	20	21	11	11
Optimization problem (s)	15	15	6	6	1	2

Table 6

The results of the LSND-A with conventional and autonomous daughter ships for simple daughter routes for instances with 32 ports

Results (32 ports)	Normal ( $e = 4$ )		High ( $e = 5$ )		Very high ( $e = 5$ )	
	Conv.	Aut.	Conv.	Aut.	Conv.	Aut.
No. of main ports = 10						
Total op. costs (kUSD)	620	551	836	742	1151	1022
Fuel cost (kUSD)	83	79	92	87	105	94
Time charter costs (kUSD)	308	243	427	337	595	476
Cargo handl. costs (kUSD)	224	224	312	312	446	446
Port costs (kUSD)	5	5	5	6	5	6
Fleet of daughter ships	4 L	1 S, 3 M, 1 L	3 M, 3 L	7 M	1 M, 7 L	5 M, 4 L
Fleet of mother ships	3 III	3 III	4 IV	4 IV	5 V	5 V
No. of mother routes	1023	1023	1023	1023	1023	1023
No. of daughter routes	50,658	50,658	17,882	17,882	3219	3219
Total solution time (s)	10,478	10,874	4563	4020	257	254
Route generation (s)	10,461	10,561	3567	3549	250	245
Optimization problem (s)	17	112	996	474	7	9

port calls in thousand USD (kUSD). The fleet composition of each solution is also provided, where letters “S,” “M,” and “L” are used to indicate the daughter ship size, and roman numbers are used for mother ship sizes (see Tables 1 and 2). The further rows of each table mention the number of mother and daughter routes generated and the overall CPU time required as well the time needed for generating the routes and for solving the optimization problem.

A central observation from the results of Tables 5–7 is that the introduction of autonomous ships reduces total operational cost by on average 11% over all the considered instances. Note that 94% of these savings come from the reduced time charter costs and 6% of the savings stem from fuel cost

Table 7

The results of the LSND-A with conventional and autonomous daughter ships for simple daughter routes for instances with 42 ports

Results (42 ports)	Normal ( $e = 2$ )		High ( $e = 3$ )		Very high ( $e = 4$ )	
	Conv.	Aut.	Conv.	Aut.	Conv.	Aut.
No. of main ports = 12						
Total op. costs (kUSD)	661	582	883	783	1219	1073
Fuel cost (kUSD)	87	82	116	103	113	108
Time charter costs (kUSD)	328	253	432	341	625	485
Cargo handl. costs (kUSD)	240	240	329	332	473	473
Port costs (kUSD)	6	7	6	7	6	7
Fleet of daughter ships	3 M, 2 L	1 S, 5 M	2 M, 4 L	2 S, 6 M	2 M, 7 L	1 S, 9 M, 1 L
Fleet of mother ships	3 III	3 III	4 IV	4 IV	5 V	5 V
No. of mother routes	4095	4095	4095	4095	4095	4095
No. of daughter routes	10,442	10,442	14,934	14,934	8300	8300
Total solution time (s)	414	373	6766	7320	10,418	10,548
Route generation (s)	205	197	6610	7275	10,354	10,412
Optimization problem (s)	209	176	156	45	64	136

reduction. The costs of cargo handling and port calls are almost the same for the conventional and the autonomous system.

The significant savings in time charter cost stem from differing fleet compositions and ship routes between the conventional system and the autonomous system. For any instance and demand scenario, the fleet of autonomous daughter ships is larger but consists of smaller ships than in the conventional system. The lower cost components of autonomous ships, especially for the time charter, allows the use of more, but smaller, daughter ships while reducing overall costs. In contrast, the fleet of mother ships is the same for both solutions with conventional and autonomous daughter ships in each of the instances. This means that the observed cost reduction is indeed due to changes in the daughter ship operations. For more details on the role of daughter ships, we consider the instance with 42 ports and normal demand (see Table 7), which has the same mother route in both configurations. For this instance, the operational cost of mother ships is 404 kUSD in both configurations. Total operational costs amount to 257 kUSD for the conventional daughter ships and to 178 kUSD for the autonomous ships, which yields a saving of 79 kUSD (30.8%) per week. The majority of this saving (75 kUSD) is due to the lower time charter cost.

Table 8 shows the average utilization of transport capacities and operation times of daughter and mother ships. The time utilization relates the total route duration of a ship to the one-week time interval that is available in a weekly service system. It can be observed that the average time utilization for the mother ships is very high for all instances and demand scenarios, that is, between 80% and 99%. This shows that this resource is well exploited in the LSND-A solutions. For the daughter ships, we observe a very high capacity utilization of more than 90% for all test instances, whereas the average time utilization is quite low. Especially for autonomous ships, time utilization is only between 32% and 56%. This is explained by two factors: (1) the type of daughter ships used, conventional or autonomous, and (2) the demand scenario. Regarding the first factor, the number of conventional daughter ships deployed in the LSND-A is less than in the autonomous system.



Table 8

Average capacity and time utilization for the LSND-A with conventional daughter ships and autonomous daughter ships

Demand	No. of ports	LSND-A with conv. daughter ships			LSND-A with aut. daughter ships		
		Daughter ships		Mother ships	Daughter ships		Mother ships
		Avg. util. capacity (%)	Avg. util. time (%)	Avg. util. time (%)	Avg. util. capacity (%)	Avg. util. time (%)	Avg. util. time (%)
Normal	22	92	73	80	97	56	80
	32	96	59	90	97	46	90
	42	97	57	94	94	46	94
High	22	94	71	99	94	56	96
	32	97	51	85	92	44	85
	42	98	46	98	98	40	94
Very high	22	96	53	98	92	44	98
	32	97	53	90	94	41	90
	42	96	42	99	93	32	99

Thus, daughter routes with conventional ships are on average longer. The second factor indicates that the average utilized time decreases with higher demand for both types of daughter ships. This is because for high demand, daughter ships reach their capacity limit rapidly already from serving a few ports in a short route. After completing their routes, daughter ships remain idle. As the average utilized capacity is high, but the time utilization is low, it might be worth considering more advanced route structures, which motivates the next experiment.

#### 4.3.2. Autonomous daughter ships with advanced route structures

In order to achieve a better time utilization of daughter ships, one might consider butterfly routes, clover routes, and flower routes as introduced in Section 3.2. Tables 9–11 report the obtained results if such advanced daughter route structures are incorporated into the LSND-A. The three tables cover instances with 22, 32, and 42 ports and all demand scenarios. They present the same information as tables in the previous section. Additionally, they report the relative savings (in %) in total operational costs compared to using only simple daughter routes. For the fleet of daughter ships, the letters S, M, and L are used for the ship sizes and the route types are denoted by “Si” (simple route), “B” (butterfly route), “C” (clover route) and “F” (flower route).

From Tables 9–11, we can see that the number of generated daughter routes significantly increases when advanced daughter route structures are considered too. For example, the number of daughter routes for the instance with 42 ports and normal demand increases from 10,442 (simple routes only) to 221,620 (simple and advanced routes). Even for instances where advanced routes are generated with a lower value of  $e$ , the number of daughter routes remains very high. For example, the instance with 42 ports and very high demand has 8300 simple daughter routes generated with  $e = 4$  and 316,498 advanced daughter routes generated with  $e = 3$ . However, the computational time for the route generation does not increase exponentially as the advanced routes are not generated from scratch but just combined from simple daughter routes.

Table 9

The results of the LSND-A with autonomous daughter ships and advanced daughter route structures for instances with 22 ports

Results (22 ports)	Normal ( $e = 5$ )	High ( $e = 5$ )	Very high ( $e = 5$ )
Total operating costs (kUSD)	455	555	749
Savings (%)	3.9	5.2	6.4
Fuel cost (kUSD)	75	71	89
Time charter costs (kUSD)	191	213	287
Cargo handling costs (kUSD)	185	267	369
Port costs (kUSD)	4	4	4
Fleet of daughter ships	1 S Si, 2 S C	1 M Si, 1 M B, 1 M C	1 S B, 1 S C, 1 M B, 1 L C
Fleet of mother ships	3 II	3 III	4 IV
No. of mother routes	127	127	127
No. of daughter routes	415,984	91,380	16,525
Total solution time (s)	7227	436	44
Route generation (s)	6778	385	39
Optimization problem (s)	449	51	5

Table 10

The results of the LSND-A with autonomous daughter ships and advanced daughter route structures for instances with 32 ports

Results (32 ports)	Normal ( $e = 3$ )	High ( $e = 4$ )	Very high ( $e = 5$ )
Total operating costs (kUSD)	519	693	932
Savings (%)	5.8	6.7	8.8
Fuel cost (kUSD)	81	88	95
Time charter costs (kUSD)	208	287	385
Cargo handling costs (kUSD)	224	312	446
Port costs (kUSD)	6	6	6
Fleet of daughter ships	1 S C, 1 M B, 1 M C	1 S C, 2 M B, 1 M C	1 M B, 2 M C, 1 L F
Fleet of mother ships	3 III	4 IV	5 V
No. of mother routes	1023	1023	1023
No. of daughter routes	531,794	439,755	132,979
Total solution time (s)	9967	6115	1086
Route generation (s)	5377	5010	558
Optimization problem (s)	4590	1105	528

The results from Tables 9–11 show that advanced daughter route structures lower cost significantly. The average saving over all instances is 6.0%. Such savings are achieved even if daughter routes are generated with a low value of  $e$  to limit the growth of routes. For example, the instance with 42 ports and very high demand has a saving of 9.1%, although incorporating advanced daughter routes requires to set  $e = 3$  in the heuristic, compared to  $e = 4$  when considering simple daughter routes only. The cost savings follow from a much better usage of ship resources where fewer daughter ships are required to serve all ports. For example, in total six daughter ships are needed for the instance with 42 ports and normal demand when only simple routes are allowed, whereas four daughter

Table 11

The results of the LSND-A with autonomous daughter ships and advanced daughter route structures for instances with 42 ports

Results (42 ports)	Normal ( $e = 2$ )	High ( $e = 2$ )	Very high ( $e = 3$ )
Total operating costs (kUSD)	548	732	976
Savings (%)	5.8	6.5	9.1
Fuel cost (kUSD)	84	101	110
Time charter costs (kUSD)	217	287	385
Cargo handling costs (kUSD)	240	337	474
Port costs (kUSD)	7	7	7
Fleet of daughter ships	2 S C, 1 M Si, 1 M B	1 S F, 1 M B, 2 M C	1 M B, 1 M C, 1 M F, 1 L C
Fleet of mother ships	3 III	4 IV	5 V
No. of mother routes	4095	4095	4095
No. of daughter routes	221,620	55,774	316,498
Total solution time (s)	5476	392	3669
Route generation (s)	1956	211	3514
Optimization problem (s)	3520	181	155

Table 12

Average capacity and time utilization for the LSND-A with advanced daughter routes

Demand	No. of ports	Autonomous daughter ships		Mother ships
		Avg. util. capacity (%)	Avg. util. time (%)	Avg. util. time (%)
Normal	22	95	85	80
	32	88	90	90
	42	92	73	94
High	22	91	91	96
	32	88	80	85
	42	91	82	94
Very high	22	95	90	98
	32	92	96	90
	42	95	94	99

ships are sufficient if advanced route structures are allowed. In the latter case, two ships perform a clover route, one ship performs a single route, and one more ship performs a butterfly route, see Table 11. Moreover, advanced route structures are used increasingly as the demand increases. For example, the instance with 42 ports and very high demand deploys butterfly, clover, and flower daughter routes. This is because daughter ships quickly reach their capacity limit in this demand scenario although the time limit of one week is not exploited in a single loop. Therefore, a ship can conduct up to four loops in a week, which reduces the fleet size from nine ships (see Table 7) to four ships (see Table 11), yielding substantial savings in time charter cost.

Table 12 shows the average capacity and time utilization of the ship fleet for the solutions with advanced daughter routes. It shows that advanced daughter routes contribute substantially to a more efficient utilization of the daughter ship resource. In particular, the average utilization time

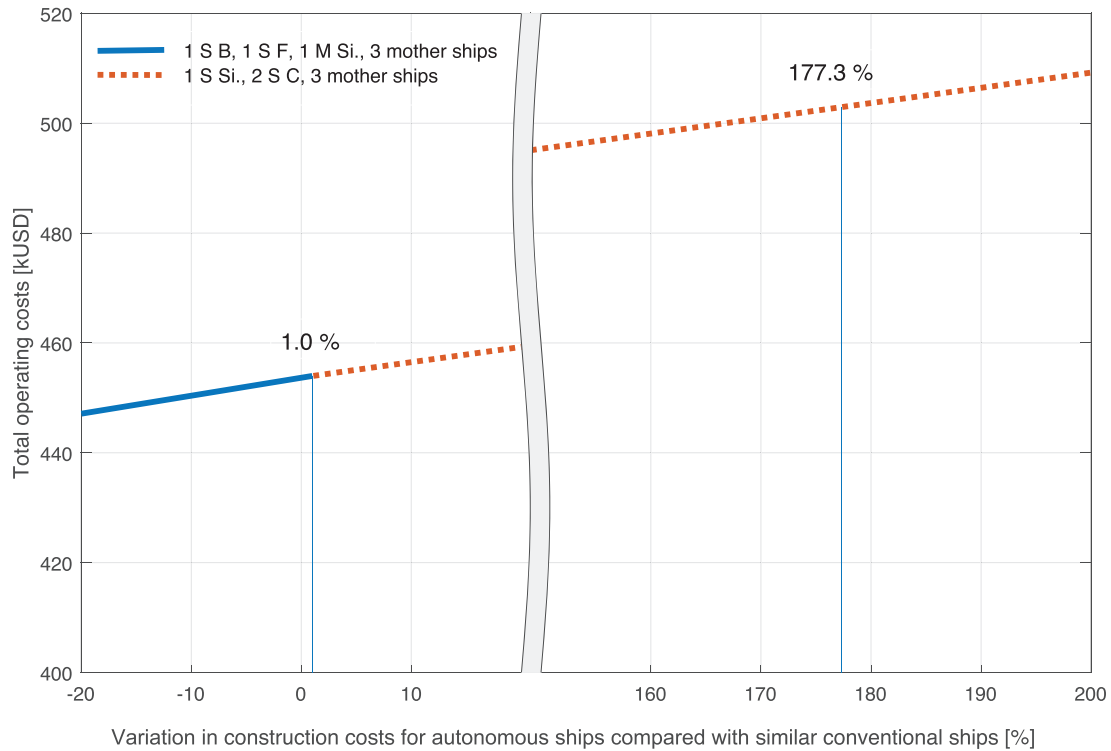


Fig. 2. Sensitivity analysis on construction costs for autonomous daughter ships, 22 ports, normal demand. Optimal solutions are obtained with autonomous daughter ships for construction costs up to 177.3%, and with conventional daughter ships for a rate more than 177.3%.

improved very much. It now ranges from 73% to 96%, whereas it was in the range of 32–56% for the same instances but with simple daughter routes only, compare Tables 8 and 12.

#### 4.3.3. Sensitivity analysis on the construction cost for autonomous daughter ships

The results obtained so far show that the most substantial portion of savings in operational costs is due to time charter costs, which cover both the payment of the ships (construction costs) and the crew. However, it is clear that our estimations of the construction costs of the autonomous ships are uncertain. Thus, we perform a sensitivity analysis for the construction costs using the instances with 22 and 42 ports under normal demand. These instances represent the current operations of the shipping company and the possible future extension toward fresh fish transportation, respectively.

Figure 2 shows the total operating costs when the construction cost for autonomous ships varies from  $-20\%$  to  $200\%$  compared with the cost for conventional ships of same size. Figure 2 excludes the interval between  $20\%$  and  $150\%$  as this region only continues the linear behaviour. When varying the *construction* cost for the instance with 22 ports and normal demand, two optimal solutions are obtained in terms of fleet composition. The first solution is represented by a thick line and is composed of three autonomous daughter ships (1 S B, 1 S F, and 1 M Si) and three mother ships of

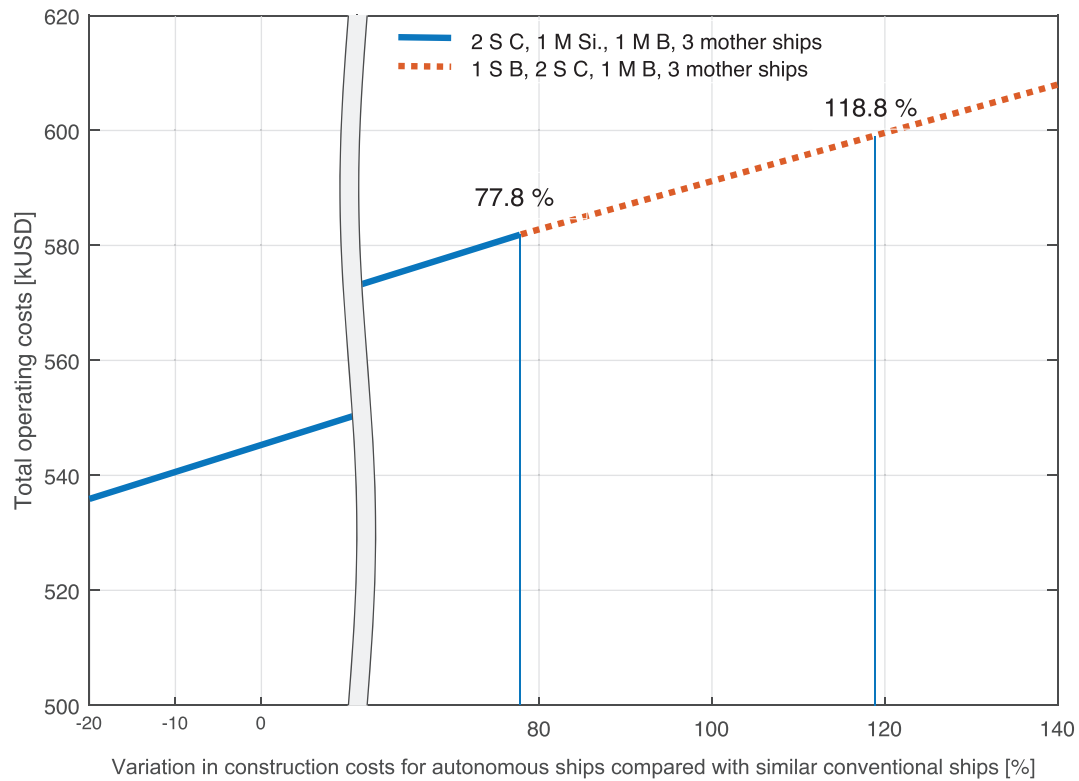


Fig. 3. Sensitivity analysis of construction costs for autonomous daughter ships, 42 ports, normal demand. Optimal solutions are obtained with autonomous daughter ships for construction costs up to 118.8%, and with conventional daughter ships for a rate more than 118.8%.

type II. This solution is obtained in the range  $-20\%$  to  $+1\%$  for the difference in construction costs. If this measure increases beyond  $+1\%$ , the routes corresponding to the best-found solution change for the daughter ships (1 S Si and 2 S C), represented by the dashed line in the figure. The fleet of daughter ships is autonomous up to an increase of construction costs of 177.3%. If the construction cost of autonomous ships is even higher, an entirely conventional system becomes more beneficial.

The results of the sensitivity analysis for the instance with 42 ports and normal demand are shown in Fig. 3. Here, a first fleet composition is observed in the range from  $-20\%$  to  $+77.8\%$  in construction cost. This fleet consists of four daughter routes (2 S C, 1 M Si, and 1 M B) and three mother ships of type III. A second fleet composition is observed in the range  $+77.8\%$  to  $+118.8\%$ , represented with a dashed line. This fleet is composed of four autonomous daughter ships (1 S B, 2 S C, and 1 M B) and the same mother ships as before. If the additional construction cost of autonomous ships exceeds 118.8%, it becomes economical to use conventional daughter ships again. Both solutions confirm that it is more cost-efficient to introduce autonomous daughter ships unless the construction costs are very much higher compared to conventional ships. The identified boundary of 118.8% exceeds by far any existing estimates. The results of this sensitivity analysis again support the introduction of autonomous ships in maritime transportation systems.

Table 13

The results of the LSND-A with autonomous daughter ships and autonomous mother ships for instances with 22 ports

Results (22 ports)	Normal ( $e = 5$ )	High ( $e = 5$ )	Very high ( $e = 5$ )
Total operating costs (kUSD)	388	489	662
Savings 1 (%)	14.8	11.9	11.7
Savings 2 (%)	22.9	18.9	18.6
Fuel cost (kUSD)	69	66	83
Time charter costs (kUSD)	130	152	205
Cargo handling costs (kUSD)	185	267	369
Port costs (kUSD)	4	4	5
Fleet of daughter ships	1 S Si., 2 S C	1 M Si, 1 M B, 1 M C	1 S B, 1 S C, 1 M B, 1 L C
Fleet of mother ships	3 II	3 III	4 IV
No. of mother routes	127	127	127
No. of daughter routes	415,984	91,380	16,525
Total solution time (s)	2712	434	49
Route generation (s)	1977	373	40
Optimization problem (s)	735	61	9

Table 14

The results of the LSND-A with autonomous daughter ships and autonomous mother ships for instances with 42 ports

Results (42 ports)	Normal ( $e = 2$ )	High ( $e = 2$ )	Very high ( $e = 3$ )
Total operating costs (kUSD)	481	643	868
Savings 1 (%)	12.2	12.2	11.1
Savings 2 (%)	19.8	19.1	16.5
Fuel cost (kUSD)	78	92	102
Time charter costs (kUSD)	156	206	285
Cargo handling costs (kUSD)	240	337	473
Port costs (kUSD)	7	8	8
Fleet of daughter ships	2 S C, 1 M Si, 1 M B	1 S F, 1 M B, 2 M C	1 M B, 1 M C, 1 M F, 1 L C
Fleet of mother ships	3 III	4 IV	5 V
No. of mother routes	4095	4095	4095
No. of daughter routes	221,620	55,774	316,498
Total solution time (s)	2706	573	4023
Route generation (s)	1757	202	3171
Optimization problem (s)	949	371	852

#### 4.3.4. Autonomous mother ships

If or when, in the future, the international regulations by the International Maritime Organization (IMO) allow operating autonomous ships in international waters, the mother routes in the LSND-A can also be sailed by autonomous mother ships. This experiment tests the LSND-A with a fully autonomous fleet for both daughter and mother ships. The analysis is conducted on the test instances with 22 and 42 ports. The results are presented in Tables 13 and 14, respectively. Next to measures that were introduced for previous tables, Tables 13 and 14 also report two types of relative savings. “Savings 1” is the saving of the fully autonomous system over a partial autonomous

fleet with conventional mother ships and autonomous daughter ships as was investigated before. “Savings 2” is the saving of the fully autonomous fleet over a fully conventional fleet of mother and daughter ships. For all configurations, daughter ships can sail advanced route structures.

According to the two tables, the total operating costs decrease between 11.1% and 14.8% compared with a partial autonomous fleet with conventional mother ships and autonomous daughter ships (see Savings 1). Compared with an entirely conventional fleet, savings of 16.5–22.9% are observed (see Savings 2). In all these solutions, cargo handling costs are almost the same for the fully autonomous system and the partially autonomous system as the same number of containers is transported. Fuel costs decrease by 10% when utilizing a fully autonomous configuration, whereas the port costs increase by 22% compared to an entirely conventional fleet. However, these two cost components make up a relatively small share of the total operating cost. The biggest share is again the time charter cost. The reduction of this cost component due to autonomous mother ships explains 94% of the cost savings observed in this experiment. It can be concluded that both, autonomous daughter ships and autonomous mother ships, have to potential of significantly lowering the operational cost in maritime freight transportation.

## 5. Conclusion

This paper studies LSND-A. We consider a real short-sea shipping network for the transportation of containers between Europe and ports along the Norwegian coastline. Assuming that regulations in national waters can be adapted more quickly, autonomous daughter ships are used to only serve local ports in Norway. Conversely, larger and conventional mother ships sail international waters and transport cargo to/from the European continent to be transshipped from/to autonomous daughter ships to reach their destinations. For solving the resulting optimization problem, we use a combination of a path-flow-based optimization model and a (heuristic) label-setting algorithm that generates candidate routes.

Extensive computational experiments were carried out using realistic case data. A more technical experiment shows that the developed heuristic generates a high solution quality within reasonable computational time. The results of our manifold economic analyses indicate that introducing autonomous daughter ships reduces operating costs by 11% on average, where reduced time charter cost contribute to most of the cost saving. Cost reductions in fuel consumption and time charter motivate the use of more daughter ships with less capacity each compared to a similar system with conventional daughter ships. The adaption of advanced daughter route structures, that is, butterfly, clover, and flower routes, saves another 6% of operational cost. The additional introduction of autonomous mother ships yields further benefits such that the operational cost of a fully autonomous system with advanced daughter routes are about 20% below the cost of a conventional fleet that uses simple daughter routes only.

As much of the benefits from introducing autonomous ships come from the reduction/removal of crew costs, it is likely that such solutions will take hold first in high-cost countries like Norway. For future research, it would be interesting to improve the service degree of the network to make the LND-A more competitive to trucks. One way to improve the service degree is to increase the service frequency of the entire network, for example, by visiting ports twice per week. It would also be useful to study the introduction of autonomous ships in an on-demand service system.

Autonomous ships offer a better flexibility with regards to crew working restrictions and thus can be exploited to increase the service of short sea shipping.

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