# Evaluating Port Development Strategies for a Modal Shift: a Norwegian Case Study

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**Abstract.** We study the design of a multi-modal distribution network for the transportation of incoming containers from a container terminal to nearby customer regions. The motivation for the study has been the relocation of the existing cargo terminal in the Port of Bergen, which is expected to increase the road transportation need in the region. To mitigate the consequences of increased driving distances, maritime solutions have been suggested as replacements for truck transportation, but as no such concepts currently exists, more knowledge and insight is needed. Therefore, in this paper we propose a Mixed Integer Programming (MIP) model for optimizing and evaluating strategies for a modal shift in the final stage of the supply chain, i.e. the short distance final distribution from the main terminal to the customer regions. We use it on the case study for the Port of Bergen to analyze whether it is possible to come up with solutions where a significant share of the distribution is done by small electric (and possibly autonomous) container ships instead of trucks. The analyses indicate that a multi-modal distribution network can be a cost-effective option for this particular case.

**Keywords:** Maritime transportation · Modal shift · Mixed integer programming.

## 1 Introduction

More than 90% of the global trade is performed by ships (IMO 2019). Container shipping, which has more than doubled in the last 15 years, is a substantial part of this. Among the busiest routes for containerized cargo is the route from East Asia to Northern Europe , with the ports in Rotterdam, Antwerp and Hamburg being the three largest. From these ports, several optional transportation modes for further distributions exist, including truck or rail transportation, as well as further distribution by smaller ships to different end customer regions all across Europe.

In Norway, the total volume of distributed cargo is expected to increase by approximately 70% towards 2050, where truck transportation is expected to have the largest share (The Ministry of Transport 2017). Trucks are often the preferred transportation mode due to lower costs and a higher flexibility through more frequent deliveries than ship transportation can offer. Despite being a flexible and cost-efficient way of distributing cargo, an increase in road-based transportation using current technologies might contribute to amplify some of the challenges that hinders a sustainable development. This is seen in several Norwegian (and European) cities, where road transport is a significant source to air pollution and noise. Some ports, such as the Port of Bergen on the west coast of Norway, shown in Figure 1, is today located near the city center, which generates large amounts of traffic through urban areas. The port also restricts the access to the sea and occupies large land areas suited for urban development (Gulbrandsen et al. 2018). To overcome these challenges, it has been decided to move the cargo terminal of the Port of Bergen from the city center to one of the surrounding regions in 2025 (Bergen Havn 2018). However, this will induce a larger transportation need as the distance to the main customer regions increases. One of the suggested solutions to mitigate the increase in road traffic, has been to strengthen the maritime transportation in the region, also for shorter distances from the main terminal to surrounding end customer regions (Berg and Haram 2018). This will be consistent with both national and international goals and visions for future transportation systems.

The European Union has set a goal of shifting 30% of the road transportation to other transportation modes such as rail or maritime transport by year 2030, and a similar benchmark of at least 50% by year 2050 (European Commision 2011). The largest container port in Europe, the port of Rotterdam, has formulated an even more ambitious vision for inland transportation of cargo handled in the port - at most 35% of the further distribution should take place by trucks, 45% transported on inland waterways (barges) and the remaining 20% should be distributed by rail transport (OECD 2010). Also in Norway there is a national interest beyond the port of Bergen of working towards a modal shift in the domestic cargo transportation, with a goal of shifting 30% of the current road transportation to alternative transportation modes within 2030 (The Ministry of Transport, 2017).

It should be noted that the above mentioned visions mostly apply for larger transportation distances, defined as more than 300 kilometers. Less attention has been given to the final stages of the supply chain over shorter distances, where requirements to delivery frequencies can, in many cases, still be satisfied by ships. However, as the sailing distances get shorter, port fees, cargo handling activities and manning costs contribute to a larger portion of the total ship transportation cost. It has traditionally been hard to reduce the impact of these cost drivers, which will be a necessity to increase the share of maritime transportation. The introduction of new ship concepts, such as autonomous (and unmanned) ships, may facilitate such a change.

In the Norwegian shipping segment, several new concepts have been developed in recent years aiming to replace significant amounts of the current road-based transportation. In collaboration with the Kongsberg group, the Norwe-

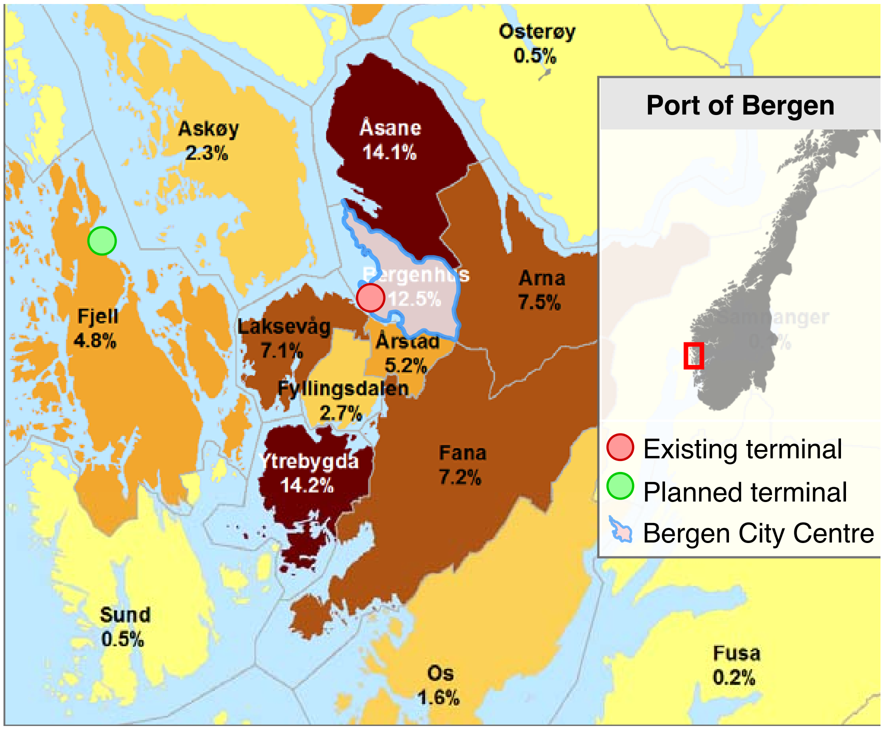


**Fig. 1.** Geographical distribution of cargo to different geographic locations in the Bergen region (Sundfjord 2015).

gian fertilizer company Yara has developed the world's first fully electric and autonomous container ship, Yara Birkeland. The vessel will have a capacity of 120 TEUs (Twenty-foot Equivalent Units), and is estimated to reduce the annual emissions of $NO_x$ and $CO_2$ corresponding to 40 000 journeys by trucks between the facilities at Herøya, Brevik and Larvik (Kongsberg 2017). The Norwegian grocery wholesaler ASKO has also developed a similar concept for reducing the need for truck transportation, by using an electric and autonomous ro-ro vessel with a capacity of 16 trucks. The concept will replace two million ton-kilometers per year, and cut the $CO_2$ emissions by 5000 tons (ASKO 2019). The logistics company North Sea Container Line developed a concept for transshipment of containers at sea, using smaller feeder vessels to serve ports along the Norwegian coast and synchronize the routes with the route of the main vessel distributing cargo from the European ports. This concept has been further studied with respect to optimizing its performance (Holm et al. 2019).

A transportation system including both road-based and maritime transportation, with time window requirements for multiple commodities, is studied in (Ayar and Yaman 2012). A MIP model is formulated, aiming to minimize the transportation costs. A similar multi-modal distribution network is studied in

(Chandra, Christiansen, and Fagerholt 2020), where the potential for a growth in the modal shift is being analyzed for a coastal shipping case for distribution of cars in India. A MIP model is formulated and used to determine the fleet size and mix as well as the number of voyages performed on a set of feasible routes generated a priori, in order to minimize the overall costs.

While a large number of the reviewed articles focus on minimizing cost, there are also some studies considering mitigation of $CO_2$-emissions. (Zhou et al. 2018) point out the lack of multi-objective studies in the existing literature, and present network flow models aiming to optimize a multi-modal transportation network with respect to both total costs and emissions of $CO_2$ equivalents ($CO_2$e). Five different scenarios of supply chain design in the UK, each with a different level of investments in port infrastructures and expansion projects, are analyzed by (Rodrigues et al. 2015). The five scenarios are analysed with respect to both costs and $CO_2$e emissions, aiming to motivate a modal shift in the UK.

The motivation for studying multi-modal transportation networks in this paper has been the relocation of the existing cargo terminal in the Port of Bergen, which is expected to increase the road transportation need in the region. In order to mitigate the consequences of increased driving distances, maritime solutions have been suggested as replacements for truck transportation, but as no such concepts currently exists, more knowledge and insight is needed. Therefore, in this paper we propose a Mixed Integer Programming (MIP) model for optimizing and evaluating strategies for a modal shift in the final stage of the supply chain, i.e. the short distance final distribution from the main terminal to the customers. Furthermore, we use it on the case study for the Port of Bergen to see whether it is possible to come up with solutions where a significant share of the distribution is done by small electric (and possibly autonomous) container ships instead of trucks. In this MIP model, we take as input an estimated cargo demand from the Port of Bergen to the different customer regions surrounding Bergen, as well as cost data for a few alternative small-sized container ships that can potentially be used in this distribution. The model will then, for a given number of different input scenarios, determine the share of truck vs. ship transportation for the final distribution and the optimal fleet of small-sized container ships, and as such provide valuable decision support for analyzing the effects from a modal shift after the relocation of the Port of Bergen. Bergen and its surroundings consists of numerous fjords and islands, which makes the topography especially interesting for this, see Figure 1.

Section 2 provides a problem definition and presents a MIP model for analyzing it. Section 3 presents the computational results from the case study for the Port of Bergen, while concluding remarks are provided in Section 4.

## 2 Problem Definition and Mathematical Formulation

In the following we provide a problem definition in Section 2.1 together with the mathematical notation, while the MIP model is presented in Section 2.2.

### 2.1 Problem Definition and Notation

The planning problem deals with designing a distribution network for the transportation of containers from a main terminal to a given set of customer regions (as illustrated in Figure 1). There are two possible alternatives for transportation available: 1) Direct truck transportation from the main terminal to the customer regions, and 2) Multi-modal transportation with ships to unloading port(s) in or close to the customer regions, and then truck transportation from the unloading port(s) to the customers. The problem can be defined as to determine:

- which ships to use, i.e. the optimal fleet size and mix,
- the deployment of the ships, i.e. the ship routes,
- which unloading ports to use, and
- the cargo flow through the network, including mode of transportation.

To define this problem mathematically, we need the following notation. There is a set of customer regions, $\mathcal{K}$, where region $k$ has a given monthly demand from the main terminal given by $D_k$. We assume there is a set of available ship types, $\mathcal{V}$, to choose from, each with a given capacity, $\overline{Q}_v$. There is also a set of candidate unloading ports, $\mathcal{P}$, that can be used in the distribution of containers from the main terminal to the customer regions. Furthermore, we define $\mathcal{R}_v$ as the set of candidate routes that can be used by ships of type $v$, while $\mathcal{P}_r$ is the set of unloading ports along route $r$. The parameter $T_{vr}$ is the time it takes for a vessel of type $v$ to perform route $r$ (including the loading and unloading time, assuming that the ship is fully loaded).

We need to define the following cost parameters: $C_v^F$ represents the fixed costs per vessel of type $v$, i.e. it represents the time charter rate that is also supposed to cover the building costs. $C_{vr}^{VS}$ is the variable sailing cost for a vessel of type $v$ to operate route $r$. $C^{VM}$ is the unit cost (per container) for loading the vessels in the main terminal, while $C_i^{VH}$ is the unit handling cost at unloading port $i$. $C_k^{DT}$ and $C_{ik}^{FT}$ represent the unit cost for direct truck distribution from the main terminal and the final truck distribution from unloading port $i$ to customer region $k$, respectively. In this particular case study, the candidate unloading ports either do not exist or need to be upgraded. It will therefore be a decision regarding which unloading ports to open (i.e. build or upgrade), and we assume that the fixed cost for opening port $i$ is given by $C_i^F$. The fixed costs for investing in ships, $C_v^F$, and ports, $C_i^F$, have been translated into equivalent periodic costs for the planning horizon, $\overline{T}$ (set to 30 days), based on an expected lifetime (chosen as 20 years for the ships and 40 years for the ports) and a given discount rate (set to 5%).

The decision variables are as follows: The integer variable $u_v$ represents the number of ships of type $v$ to be used, while $y_{vr}$ is the total number of voyages on route $r$ performed by vessels of type $v$ over the planning horizon. $q_{vr}^L$ represent the total quantity transported along route $r$ by all vessels of type $v$, while $q_{ivr}^U$ is the total quantity unloaded in port $i$ by vessels of type $v$ sailing route $r$. The total quantity transported directly by truck from the main terminal to customer $k$ is given by $l_k^{DT}$, while the total quantity transported by trucks as final distribution from port $i$ to customer region $k$ is given by $l_{ik}^{FT}$. Finally, we let the binary variable $\delta_i$ be equal to 1 if unloading port $i$ is opened, and 0 otherwise.

### 2.2 Model

By using the notation introduced in the previous section, we can formulate our planning problem with the following MIP model.

$$\begin{aligned}\text{minimize}\quad z = &\sum_{k\in\mathcal{K}} C_k^{DT} l_k^{DT} + \sum_{v\in\mathcal{V}} C_v^F u_v + \sum_{i\in\mathcal{P}} C_i^F \delta_i \\ &+ \sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} C^{VM} q_{vr}^L + \sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} C_{vr}^{VS} y_{vr} \\ &+ \sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v}\sum_{i\in\mathcal{P}_r} C_i^{VH} q_{ivr}^U + \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{P}} C_{ik}^{FT} l_{ik}^{FT}\end{aligned} \tag{1}$$

subject to

$$q_{vr}^L - \sum_{i\in\mathcal{P}_r} q_{ivr}^U = 0, \quad v\in\mathcal{V}, r\in\mathcal{R}_v \tag{2}$$

$$\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} q_{ivr}^U - \sum_{k\in\mathcal{K}} l_{ik}^{FT} = 0, \quad i\in\mathcal{P} \tag{3}$$

$$l_k^{DT} + \sum_{i\in\mathcal{P}} l_{ik}^{FT} \geq D_k, \quad k\in\mathcal{K} \tag{4}$$

$$q_{vr}^L - \overline{Q}_v y_{vr} \leq 0, \quad v\in\mathcal{V}, r\in\mathcal{R}_v \tag{5}$$

$$u_v \geq \frac{1}{\overline{\overline{T}}} \sum_{r\in\mathcal{R}_v} T_{vr} y_{vr}, \quad v\in\mathcal{V} \tag{6}$$

$$\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} q_{ivr}^U \leq \sum_{k\in\mathcal{K}} D_k \delta_i, \quad i\in\mathcal{P} \tag{7}$$

Non-negativity requirements are imposed for the load variables, i.e. all variables $q_{ivr}^U$, $q_{vr}^L$, $l_k^{DT}$, and $l_{ik}^{FT}$, while we make sure that the fleet selection and deployment variables, $u_v$ and $y_{vr}$ take non-negative integer values. Finally, we impose binary requirements on the port selection variables, $\delta_i$.

The objective function (1) minimizes the total cost over the planning horizon, which consists of the following cost components: a) costs for the direct truck distribution from the terminal to the customer regions, b) fixed cost for the selected ships, c) fixed costs for the selected unloading ports, d) variable loading costs at the main terminal, e) variable sailing costs, f) variable handling costs at the unloading ports, and g) the costs for the final truck distribution from the unloading ports to the customer regions.

Constraints (2) ensure that the load balance for all vessel types is maintained, i.e. the total cargo quantity loaded on board the vessels of each type that sail a given route must equal the sum of the cargo quantity unloaded to all ports along the given route. Constraints (3) express the cargo flow balance between unloaded and further distributed cargo in each port, i.e. the total quantity unloaded in a given port $i$ must equal the cargo quantity distributed by final truck transportation to all customer regions from that port. Constraints (4) ensure that the demand in each customer region is satisfied, while constraints (5) make sure that the ship capacity is respected for each ship type and route. Constraints (6) are time constraints that make sure that the number of vessels is sufficiently large to perform the selected routes for each ship type. Finally, constraints (7) ensure that cargo can be unloaded at a given port only if the port is in use.

The MIP model presented above requires a set of candidate routes for each vessel type as input. Each route will start at the main terminal and visit at least one unloading port before returning to the main terminal. Since the number of ports for this case study is rather small, it is easy to generate all feasible route combinations. For routes only visiting one or two unloading ports, the sequence of the port calls does not affect the total sailing distance of the route. However, for the routes including three or more unloading ports, the visiting sequence affects the sailing distance. We therefore solve a Traveling Salesman Problem for each subset of ports with three or more unloading ports, so as to only include the non-dominated routes for each subset.

## 3 Computational Study

In the following, Section 3.1 provides the input data for our case study, while computational results are presented and discussed in Section 3.2.

### 3.1 Input Data for the Case Study

The estimated distribution of the cargo flow to the different regions in and around the city of Bergen is shown in Figure 1 presented in Section 1. Based on this, we exclude the regions with very small demands from our analyses. We also remove the region Fjell, as this coincides with the location of the new container terminal, meaning that all cargo from the container terminal to this region will most likely in any case go by truck. We are then left with the following nine demand or customer regions: 1) Askøy, 2) Ytrebygda, 3) Laksevåg, 4) Bergenhus, 5) Åsane, 6) Fyllingsdalen, 7) Årstad, 8) Arna, and 9) Fana. Based on interviews with representatives of the Port of Bergen, the total monthly demand to these nine regions is approximately 2000 TEUs, which we distribute among the nine regions according to the distribution in (Sundfjord 2015), and as shown in Figure 1.

Based on this cargo flow distribution, as well as what are suitable locations based on existing infrastructure, we have selected five candidate port locations. Figure 2 shows the port locations and the sailing paths between them, which are used to calculate the sailing distances. From each of these six port locations,

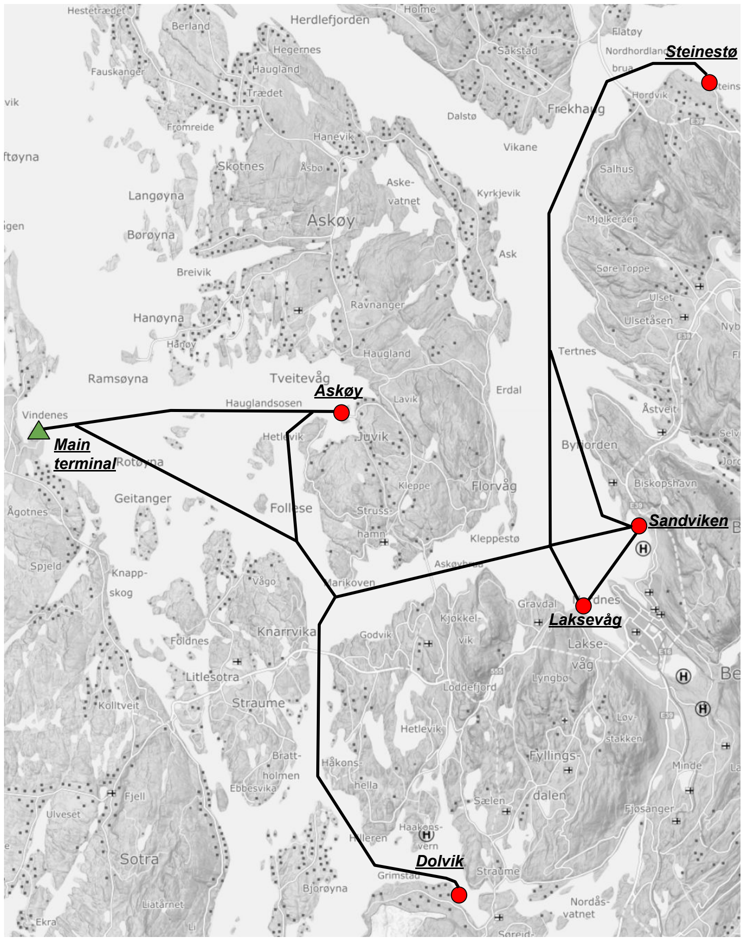


**Fig. 2.** Proposed port network with feasible sailing routes between the selected ports. Background map is retrieved from (The Norwegian Mapping Authority 2019).

including the new main terminal, we have calculated the driving distances on road to the geographical centre of each of the nine demand regions. However, some restrictions are imposed on the final distribution from an unloading port to a customer region:

- Region 1, which covers the island of Askøy, can only be served from the unloading port that is located on the island or by direct distribution from the main terminal.
- To avoid unnecessary transport through the city centre, no cargo distribution is allowed from the unloading ports north of the city center (i.e. Sandviken and Steinestø) to customer regions south of the city center, and vice versa.

According to (Berg and Haram 2018), the costs for truck transportation in the Bergen region, in Norwegian Kroner (NOK), can be found as $1500 + 31d$, where $d$ is the driving distance (in km).

Few existing container vessels exist with a loading capacity in the range of 10 – 30 TEUs, which is the capacity considered to be most relevant for this case study. Inspired by the existing projects of Yara Birkeland and the maritime supply chain project at ASKO briefly discussed in Section 1, a set of vessel characteristics as presented in Table 1 has been obtained. The vessels involved in the projects mentioned above are fully electric, and we assume that the infrastructure in the relocated port of Bergen will be able to accommodate electric vessels as well. As the vessels are assumed to be electric, the maximum sailing range will strongly depend on the battery capacity and energy consumption during a voyage, as shown in Table 1. A consumption equal to 15% of the vessel's installed power is assumed to be used during cargo handling activities in port.

**Table 1.** Vessel characteristics used to calculate both investment costs and feasible routes for each vessel type.

| **Vessel Type** | | **1** | **2** | **3** |
|---|---|---|---|---|
| Loading Capacity | TEUs | 10 | 20 | 30 |
| Engine Power | kW | 150 | 250 | 300 |
| Sailing Speed | kts | 12 | 10 | 10 |
| Battery Capacity | kWh | 1200 | 1500 | 1800 |
| Energy Consumption | kWh/km | 6.7 | 13.5 | 16.2 |
| Building Costs | MNOK | 20 | 25 | 35 |
| Annual Maintenance Costs | MNOK | 0.3 | 0.6 | 1.0 |

With an energy consumption as shown in Table 1, and by assuming a cost of energy of 2 NOK/kWh, the cost for operating the vessels can be found. Whether the vessels are manned or autonomous is not explicitly considered in this study. However, an additional unit cost of 50 NOK per km sailed is included to capture additional variable costs that is not related to the usage of energy.

There are three cost components associated with the activities in the selected ports: 1) Investment cost for upgrading an existing port to become an operative unloading port in the distribution network, 2) unit costs (per container) for loading of the vessels in the main terminal, and 3) unit costs (per container) for unloading the containers in the unloading ports, from the vessel to a truck ready for final distribution to the end customer. We have used cost figures for the ports which are based on existing port charges (Dale et al. 2018) and similar port infrastructure upgrades (Amundsen 2019).

### 3.2 Computational Results

When minimizing costs, as in objective function (1), the optimal distribution network design has a total cost of 5.22 MNOK. In this solution, 940 TEUs are distributed at sea by one vessel of type 2 before being further distributed by trucks to its final destination. The remaining 1,060 TEUs (of the total monthly demand of 2,000 TEUs), which are destined to customer regions 1, 2, 3, 6, 7 and 9, are transported by trucks directly from the main terminal. The total truck transportation for this solution, including the final distribution from the unloading ports, is approximately 79,010 kilometers (km).

By fixing the ship variable $u_v$ to zero, we obtain a solution where only direct truck transportation takes place. This solution has a cost of 5.24 MNOK, which is only slightly higher than the cost-minimizing solution. However, the total road transportation increases to 131,950 km.

Since one aims at reducing the road traffic, as discussed in Section 1, another interesting objective would be to minimize the total truck transportation. This solution gives a total cost of 5.74 MNOK and there is no direct truck distribution to any customer region. In this solution, all available unloading ports are used, except for Sandviken (see Figure 2). The final distribution from the unloading ports requires 26,780 km of truck transportation, which is a significant reduction compared to both the cost-minimizing solution with 79,010 km, and even more so compared with the pure truck solution with 131,950 km. Two vessels of type 2 are used in this solution.

**Table 2.** Costs and truck driving distance for three solutions based on minimizing total costs, minimizing total truck transportation, and pure trucks, respectively.

| | **Cost-minimizing** | **Truck-minimizing** | **Pure truck** |
|---|---|---|---|
| Total cost [MNOK] | 5.22 | 5.74 | 5.24 |
| Total truck transportation [km] | 79,010 | 26,780 | 131,950 |

Table 2 summarizes the total cost and the total truck transportation for the solutions based on minimizing costs, minimizing total truck transportation and pure truck distribution, respectively.

To examine more closely the trade-off between costs and the amount of truck transportation, we can solve the problem as a bi-objective optimization problem by the epsilon-constrained method. We keep the cost in the objective function, and add a constraint to restrict the amount of truck transportation. By solving the model for different values of the maximum amount of truck transportation, we obtain the Pareto frontier between costs and truck transportation as shown in Figure 3.

As seen from Figure 3, the maximum reduction of road transport will equal more than 50,000 kilometers per month. However, this will increase the total operational costs by nearly 10%. If the goal is to obtain a modal shift of at least 30% of the total truck transportation to a maritime alternative, in accordance with the goals set by EU and the Norwegian government, this can be done at a rather moderate cost increase.

Several input parameters used in this computational study are uncertain. In order to evaluate the robustness of the solutions, a sensitivity analysis is

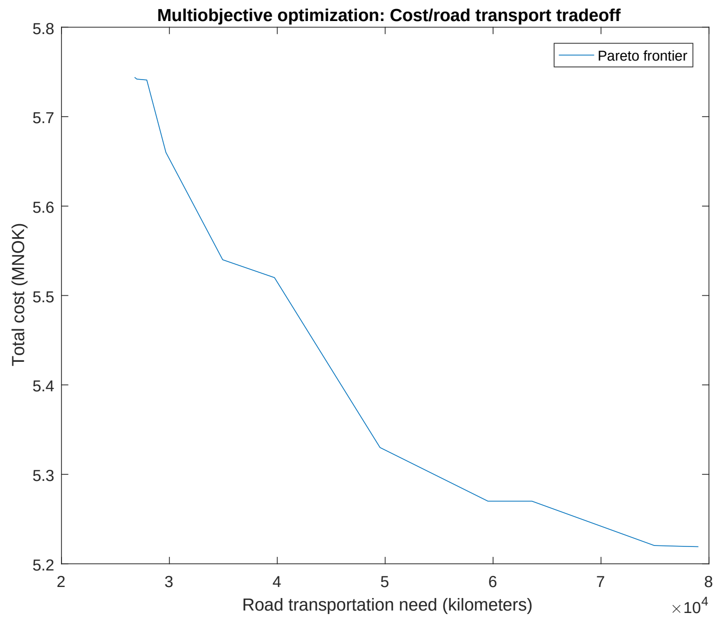


**Fig. 3.** Illustration of the trade-off between minimizing the truck transportation and minimizing the total cost for the distribution network. The solutions along the Pareto frontier can be seen as "equally good".

performed, where we run the model with different values for certain input parameters. The sensitivity analysis is performed with respect to two groups of uncertain data, demand and costs, which will be evaluated further in the following.

The customer demands were established based on port statistics and existing studies of the cargo flows from the port of Bergen. From (Berg and Haram 2018), the incoming cargo through the port of Bergen represents approximately 20% of the total market share of goods to the region. In other words, the total demand for cargo in the region equals 10,000 TEUs per month. Table 3 shows the optimal solutions with respect to costs, as well as other key performance parameters, for different shares of cargo through the port of Bergen, while assuming the same distribution among the customer regions.

As seen in Table 3, for small cargo flows through the port, a unimodal distribution network including only truck transportation is found to be the most cost-efficient. As the total cargo flow increases, the unit cost decreases. It should be noted that for the case of 4,000 TEUs, a decrease in the share of maritime transportation is observed. In this particular solution, a vessel of type 3 is selected to perform voyages on the same route as in the original solution. As seen in Table 1, this vessel has a 50% larger loading capacity than a vessel of type 2. However, as more cargo is handled the route duration increases, and the number

**Table 3.** Sensitivity analysis with respect to uncertainty in customer demands. The solution for the current situation, based on existing cargo flows, is marked in bold text.

| Incoming Supply | Total cost | Unit cost | Maritime transportation |
|---|---|---|---|
| 1000 TEUs | 2.62 MNOK | 2620 NOK/TEU | 0 units (0 %) |
| **2000 TEUs** | **5.22 MNOK** | **2610 NOK/TEU** | **940 units (47 %)** |
| 4000 TEUs | 10.21 MNOK | 2550 NOK/TEU | 1530 units (38 %) |
| 6000 TEUs | 15.25 MNOK | 2540 NOK/TEU | 3090 units (52 %) |

of voyages are limited by the time constraints given in Section 2.2. Thus, the remaining demand increase has to be satisfied by truck transportation. In the case of an increase of the total cargo demand to 6000 TEUs, two vessels of type 3 are selected.

The largest uncertainties for the system studied in this computation study, are probably related to some of the costs. We have therefore run the MIP model for the following five different scenarios, varying one cost component at the time.

- Scenario 1: Increased acquisition costs for all vessel types, $C_v^F$, tested for an increase of both 10% (1a) and 20% (1b)
- Scenario 2: Increased port investment costs. Tested for an increase of both 20% (2a) and 40% (2b).
- Scenario 3: A 20% increase of the maintenance costs, for both the vessels of all types and the suggested unloading ports.
- Scenario 4: Increased (a) and reduced (b) variable sailing costs, $C_{vr}^{VS}$, of 20%, where the reduced sailing costs can be relevant in the autonomous (unmanned) case.
- Scenario 5: A 20% increase of the truck transportation costs, which could for example represent toll charges, which have not been included originally.

**Table 4.** Sensitivity analysis with respect to uncertainty in cost components. The initial cost-minimizing solution is defined as scenario 0.

| Scenario | Total cost | Vessel distribution | Road transportation |
|---|---|---|---|
| 0 | 5.219 MNOK | 940 TEUs | 79,010 km |
| 1a | 5.236 MNOK | 940 TEUs | 79,010 km |
| 1b | 5.241 MNOK | 0 TEUs | 131,950 km |
| 2a | 5.239 MNOK | 940 TEUs | 79,010 km |
| 2b | 5.241 MNOK | 0 TEUs | 131,950 km |
| 3 | 5.236 MNOK | 940 TEUs | 79,010 km |
| 4a | 5.241 MNOK | 0 TEUs | 131,950 km |
| 4b | 5.188 MNOK | 1100 TEUs | 72,190 km |
| 5 | 6.052 MNOK | 1100 TEUs | 72,204 km |

The optimal solutions for each of these scenarios are presented in Table 4. It can be noted that all scenarios from 1a to 4a equal either the cost-minimizing solution or the only truck-solution (see Table 2). Further, this sensitivity analysis shows that an increase in the port investment costs only leads to minor increases in the total operating monthly costs. The main reason for this is that in all solutions, only one unloading port is chosen (Sandviken, ref. Figure 2). Lastly, the results illustrate an ”instability” in the solutions. By introducing vessels for maritime transportation, several additional investments such as vessel acquisition, port investments and annual maintenance costs need to be taken into account, each with an uncertainty in the specified input value. Due to the relatively low cost reduction this will induce, too large changes in one of the cost parameters will cancel out the cost reduction obtained by taking the vessels in use. Instead, a solution where only trucks perform cargo distribution is selected.

On the other hand, the results presented show that if the truck costs increase as in scenario 5, this will strengthen the competitiveness of maritime transportation and lead to a further increase in the share of cargo distributed by vessels.

Despite the dramatic changes in the structure of the obtained solutions in Table 4 due to modest changes in cost parameters, the total costs seem to be relatively stable or robust with respect to these cost changes. Thus, the obtained results indicate a relatively “flat” objective function, where a large number of different solutions yield almost the same costs. This finding is also illustrated through the solutions along the Pareto frontier in Figure 3, and can actually be seen as beneficial in the case of redeveloping the Port of Bergen. The political goals of moving significant amount of cargo from road to sea can be achieved at relatively little cost increases and through several combinations of strategic investment decisions.

## 4 Concluding Remarks

The performed analyses indicate that a multi-modal distribution network can be a viable option for the case of Bergen after relocating the main cargo terminal. For a given set of parameters and assumptions used as model input, the most cost-efficient solution proved to contribute to satisfy nearly 50% of the total cargo demand by multi-modal transportation. This share can be further increased at a relatively low increase of the overall costs. If the social costs of road congestion, air pollution and accidents induced by road transport are included, this finding will strengthen the competitiveness of a multi-modal distribution network.

With the significant uncertainties related to cost components and customer demands, together with the assumptions made throughout the study, the exact values obtained from the results are not of great importance in this project. Instead, the results indicate that given the topography of Bergen and its surrounding, with many fjords and islands, establishing a multi-modal network may provide cost-savings and a significant reduction of the increased road transportation need initiated by the relocation of the port.

Despite being a study of the specific case for the Port of Bergen, the proposed model and findings can be applicable to other ports and cargo distribution networks. There are several other cities in Norway, as well as in other countries, experiencing similar challenges regarding road congestion and where the topography creates maritime "shortcuts" which currently are utilized to a low extent. However, it is reasonable to expect that major changes of the distribution network design will be easier to implement through a port redevelopment process, for instance through the relocation of a port terminal, such as in Bergen.

In this study we have only considered the distribution from the main terminal to the different customer regions. However, in reality there is also a flow of containers in the opposite direction. It would therefore be of interest to extend our model to include this flow, which is likely to make the multi-modal distribution even more competitive compared to only using trucks.

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