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Design of a sustainable maritime multi-modal distribution network – Case study from automotive logistics

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ABSTRACT

Multi-modal transportation takes advantage of multiple transport modes and can be an effective way to ease the negative environmental effects of freight transportation. This paper addresses a multi-modal distribution network design problem with the aim of balancing the trade-off between economic and environmental benefits. The distribution network that we consider includes both transportation with trucks and ships. We propose a new mixed integer programming (MIP) model which decides the optimal design of the system, i.e. how many ships of each type to use, their corresponding routes and sailing speeds. It also suggests an optimal cargo flow through the maritime and road-based network. We show how the MIP model can be used to provide decision support through a case study from the distribution of automobiles in India, which has a vast coastline that can be used for maritime transportation. Environmental emissions from automobile transportation in India have been rapidly increasing in recent years with the fast economic development, and it has become a major contributor to regional air pollution and road congestion. One possible way to ease these negative environmental consequences is to consider a modal shift where some of the automobile transportation from the production facilities located close to the coastline is replaced by roll-on roll-off (RoRo) ships. Our study shows that multi-modal distribution is both environmentally friendly and economically beneficial, especially if more industrial players can collaborate to create economies of scale.

1. Introduction

Freight transportation, as one of the most crucial elements of a supply chain, plays a key role in economic growth. According to Crippa et al. (2019), approximately 15.5% of worldwide CO_2 equivalent greenhouse gas (GHG) emissions (53.7 billion tons) are generated by transportation in 2017. Road transportation by trucks is the leading transportation mode, and accounts for 72.9% of the total CO_2 emissions generated by the transportation sector, as shown in Fig. 1.

Road transportation by trucks is widely used in freight transportation due to its flexibility for transporting small volumes and for providing door-to-door services. However, it is generally considered to be less environmentally friendly and have higher CO_2 emissions per ton-mile compared to for example rail or maritime transportation, see for example Wang and Lutsey (2013) and Heinold and Meisel (2018). Transportation by trucks also comes with challenges related to road congestion and local emissions of NO_x and particulate

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matters (PM) in urban areas. Therefore, it has been an increased interest on developing solutions for multi-modal transportation that entail a modal shift towards rail or maritime transportation. This is especially the case for countries with navigable waterways, including coastal shipping and inland waterways, which are focusing on decongesting existing road and rail infrastructures through the use of coastal and short sea shipping.

The focus of this paper is to present a new mixed integer programming (MIP) model for the design of multi-modal distribution networks that includes maritime transportation. Furthermore, we show how the MIP model can be used for analyses and to provide decision support through a case study from the distribution of automobiles in India, which has a vast coastline that can be used for maritime transportation. The automotive industry in India is one of the largest automobile markets in the world and among the fastest growing industries in the country. Several automotive brands have production facilities in India, and the country's total production of vehicles exceeded four million units in 2018 (Wagner, 2019). Several of these production facilities are located relatively close to the coastline. From the different production facilities, there is an extensive distribution across the country, most of which today is done by trucks. Environmental emissions from automobile transportation in India have been rapidly increasing in recent years with the fast economic development, and it has become a major contributor to regional air pollution and road congestion. One possible way to ease these negative environmental consequences is to consider a modal shift where some of the automobile transportation from the production facilities located close to the coastline is replaced by roll-on roll-off (RoRo) ships. As shown by Chandra et al. (2020), this is most likely economically viable.

There is a large volume of published studies on multi- and inter-modal freight transportation, e.g. Crainic et al. (2007), Kubanova and Schmidt (2016) and SteadieSeifi et al. (2014). Multi-modal transport usually refers to freight transportation with more than one alternative transport mode available for the transportation between a given origin and destination, e.g. transportation by trucks and ships. On the other hand, inter-modal transportation, which can be considered as a special subset of multi-modal transportation, is normally used when a sequence of more than one transport mode are used for a particular cargo, e.g. trucks for the first-mile and last-mile transportation and transportation by ships in between (but when there is still only one transportation alternative between a given origin and destination).

Ayar and Yaman (2012) study a multi-commodity multi-modal transportation system involving land and sea-based transportation. Two MIP models are formulated with the aim of minimizing the total transportation costs and the inventory cost at sea ports. In contrast to our study, they assumed predefined maritime services in terms of capacity and time. Fazi (2014) divide the supply chain of container cargo transportation into three subsystems: ocean transport, sea terminals and inland transport. The inland transport from the sea terminals to the end customers is their main focus, and this is analyzed by allocating cargo flows to either road or river in the hinterland container supply chain. They demonstrate that the transport mode with larger capacity, such as barges, can produce economies of scale when the capacity utilization is high compared with the transport mode with smaller capacity, such as trucks. Ghaderi and Burdett (2019) consider the transportation of hazardous materials more economically and safely in a multi-modal network consisting of road and rail, with the aim of minimizing costs and risk using a two-stage stochastic programming model.

In a recent paper, Chandra et al. (2020) study a similar problem as the one that we are studying in this paper. They develop a MIP model for the problem and discuss the potential effects for encouraging the modal shift from land-based to maritime transportation for a case study on Indian outbound automotive logistics. Based on analyses with the MIP model, they find it beneficial for the current business to make almost one-third shift from road to inter-modal coastal shipping.

A large number of the reviewed articles, like the above mentioned articles, focus on economic aspects, and the mathematical models of multi-modal network design have been formulated with the objective of cost minimization. As the environmental concern has become an increasingly important issue in identifying environmentally sustainable ways to develop transportation industries, there is a growing requirement to incorporate the planning of carbon footprint in the design of multi-modal distribution network (Comer et al., 2010). Since sea transportation usually results in lower carbon emissions than transportation by trucks, introducing this mode of transportation as an alternative in a multi-modal network system provides extensive possibilities to improve environmental sustainability (Lam and Gu, 2016).

Environmental issues, especially the mitigation of CO_2 emissions, have been addressed in a growing number of studies. Zhou et al. (2018) study a "complex network" with regard to multiple transport modes (highway, ordinary road, railway, and waterway) and multiple vehicle types, which have impacts on both economics and environments. The two objectives are integrated through a multi-objective optimization framework to identify the best set of solutions that achieve the trade-off between the two objectives. Comer

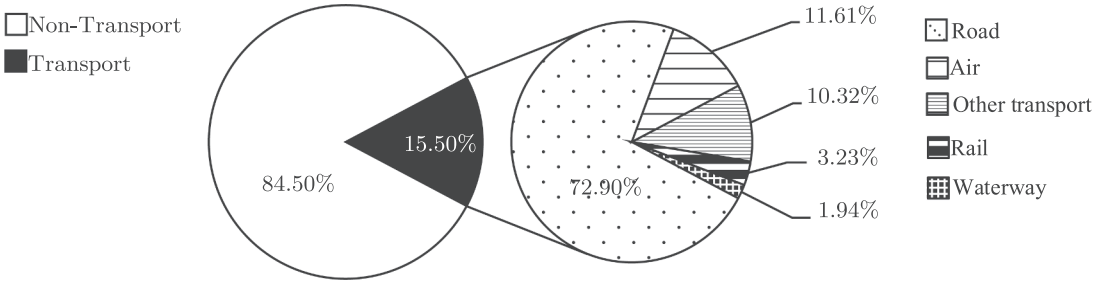

Fig. 1. The CO_2 emissions by sources from the transport and non-transport sector around the world. Information extracted from Crippa et al. (2019).

et al. (2010) examine the potential for freight emissions reduction through a modal shift from trucks to marine vessels in the Great Lakes region. They develop a geospatial inter-modal freight transport model consisting of a multi-modal (rail, highway, and waterway) network that is featured by time of delivery, operating costs and emissions. Rodrigues et al. (2015) formulate a transport distance model at a strategic level and study the effects of re-routing containers on both cost and CO_2 emissions. In addition, some tactical level factors are incorporated into the model, such as the average number of vehicles on the relevant roads. Five candidate CO_2 mitigation strategies for UK multi-modal distribution network design with different expansion projects regarding port infrastructure investments are compared aiming to motivate modal shift in the UK. Guo et al. (2018) solve a green transportation scheduling problem to reduce the total costs and carbon emissions. They formulate a bi-objective mixed integer nonlinear program which is then solved by a metaheuristic-based Pareto optimization approach.

Maiyar and Thakkar (2019) study a bi-objective transportation problem minimizing the total costs and GHG emissions. The proposed model decides optimal shipment quantities, modal choice, route selection, hub location, and vehicle velocities, and is used to provide managerial insights with respect to the trade-offs between costs and emissions. Fattahi and Govindan (2018) study the design of a biofuel supply chain from biomass to demand centers, where the biomass supply is stochastic and seasonal, and facilities' capacity varies randomly because of possible disruptions. They propose a multi-stage stochastic program in which the greenhouse gas emissions and the social impact of the supply chain are considered. A rolling horizon procedure is used on a real case study to evaluate the stochastic model solution.

The overall aim of this paper is to gain insights in multi-modal transportation and investigate how multi-modal distribution networks can be designed and used to initiate a modal shift. We use the automobile industry in India as a case study for computational tests to address cost analyses, in addition to mitigation of CO_2 emissions. The paper makes the following contributions to the literature: It extends the work of Chandra et al. (2020) by handling a more general version of the problem where we consider more than one production facility and loading port. We have therefore extended the model to include more general route structures which becomes relevant when there is more than one loading port. In addition, we take into consideration speed choice in the maritime transportation, as this heavily influences the fuel consumption of the ships. Finally, the model developed in this paper balances the trade-offs between the effects of multi-modal distribution network on CO_2 emissions and costs. The case study investigates the effects associated with a modal shift from carbon-intensive modes of transportation (land-based automobile-carrier trucks) to a less carbon-intensive mode (short sea RoRo ships) for automobile transport in India. The aim of the modeling process is to gain an overview of how a potential modal shift from land to sea can lead to a reduction in either costs or CO_2 emissions, or both.

The rest of the paper is organized as follows: Section 2 introduces the detailed problem description followed by a model formulation in Section 3. Section 4 presents a case study with respect to India and discusses the computational results and their managerial implications. Concluding remarks are given in Section 5.

2. Problem definition and case study description

Here, we start with a description of a general sustainable multi-modal distribution network design problem in Section 2.1. In addition, some assumptions are presented. Then, we give an example to ease the understanding of the problem. Furthermore, in Section 2.2 the problem is illustrated with a case study on the distribution of automobiles in India. The goal is to study the costs and environmental effects of using a maritime distribution network in addition to the current land-based network.

2.1. General problem description and assumptions

There exists a set of *production facilities* where a given type of cargo is produced. Customers located in the same geographical area are aggregated and are treated as one single customer group. The demand of such a customer group equals the aggregated demand of all the included customers, while the location of the group is at the center of gravity of the locations of the included customers and named *customer locations*. Each customer location has a given demand for the products from a particular production facility within the planning horizon.

There are two modal options available for transportation of the cargo between production facilities and customer locations. Direct transportation can be made by truck. We assume that the truck capacity (i.e. the number of trucks available within the planning horizon) is unlimited. Based on the truck speed and distance between the production facilities and customer locations, the trucking costs and emission cost can be calculated for each pair of facilities and locations. In addition to truck transportation, it might be beneficial to transport some of the cargo by ships between *ports* close to the production facilities and customer locations. The trucks are in such cases used for first mile delivery between the production facility and the loading port and for last mile delivery from the unloading port to the customer location. The trucking costs and emissions for these distances are calculated in the same way as for the distances between production facilities and customer locations.

There exists a set of *ship types* available for chartering with various speed options, capacities, cost structures and fuel consumption profiles. For each ship type there exists a set of pregenerated candidate *routes* consisting of several ports where a particular ship loads in one or several ports and unloads in one or several ports along the route. Based on the distance of the route and the speed chosen for a particular ship type, the sailing time of the route is calculated as well as the costs and emissions. These costs include the variable shipping costs (i.e. fuel costs) and the fixed charter cost of hiring the ships in the planning horizon. A ship's fuel consumption, and hence cost, depends on the chosen sailing speed. In addition, there are port costs, which consist of both fixed costs for visiting the port (depending on the size of the ships) and variable handling costs per unit of cargo that is loaded and unloaded.

Finally, this strategic problem consists of designing a distribution network between the production facilities and the customer

locations, while ensuring that the customer demands are fulfilled and ship capacities are not exceeded. The objective is to minimize either the total distribution costs or the total environmental emissions from the trucks and ships. The decisions include:

- the optimal fleet size and mix of ships,
- the ship routes, including the number of times each ship performs each route at a certain sailing speed over the planning horizon,
- the distribution pattern of direct truck delivery and multi-modal transportation between production facilities and customer locations.

Fig. 2 shows a simplified example of the problem with two production facilities, seven ports and nine customer locations. Production facility 1 serves customer locations 1 and 2 with direct truck deliveries, while serving customers locations 6 to 9 with multi-modal transportation. The first mile truck delivery from production facility 1 ends at port 1 where the cargo is loaded. For simplicity, just one route is given in the figure from port 1 to port 7, where port 5 is visited on the way. A ship sailing the route loads in port 1 and unloads in ports 5 and 7. From port 5 there is a last mile truck delivery to customer locations 6 and 7, while the transportation from port 7 to customers 8 and 9 is performed by trucks. All the truck transportation from production facility 1 is shown by use of solid lines. From production facility 2, trucks are responsible for direct delivery to customer locations 7 and 9. In addition, production facility 2 serves customer locations with multi-modal transportation. The first mile truck delivery is made between production facility 2 and port 7. Then a ship is sailing a route from port 7 to port 1 via port 5. The ship unloads in ports 5 and 1. The last mile truck delivery from port 5 ends at customer location 5, while the last mile truck delivery from port 1 ends at customer locations 3 and 4. All truck transportation from production facility 2 are shown with stippled lines.

2.2. Case study: automotive logistics in India

The motivation for studying the multi-modal distribution network design problem is a real problem in India concerning transportation of automobiles from manufacturers where the automobiles are made (production facilities) to auto dealers (customer locations) where the automobiles are sold. For this case, our aim is to study the cost and environmental effects of moving some of the transportation of automobiles by trucks to RoRo ships. Details related to the case study is illustrated in Fig. 3.

There exist several auto-manufacturers and production facilities located close to the coastline of India. These auto-manufacturers can be grouped into two main groups of production facilities that are located close to the cities of Chennai and Sanand, respectively. They are marked with black triangles in the figure. Each auto-manufacturer produces its own automobile make.

There is a large number of auto dealers with a given demand spread all over India in different layers. Since we do not have detailed information of each separate auto dealer, we aggregate these into customer groups or customer locations, as explained in the general description of the problem. For each customer location, an annual demand from each production facility must be fulfilled. These customer locations are shown by black dots in the figure.

Seven important ports are located along the Indian coastline; namely Chennai, Vishakhapatnam, Kolkata, Cochin, Mangalore, Mumbai and Pipavav. These are shown by black squares in the figure. The ports closest to the auto-manufacturers are Chennai port for the auto-manufacturers in Chennai and Pipavav port for the auto-manufacturers in Sanand. Therefore, Chennai port is regarded as the potential loading port for automobiles from Chennai, while Pipavav port is responsible for loading automobiles from Sanand. However, Chennai port might unload automobiles coming from auto-manufacturers from Sanand. The rest of the ports are entirely

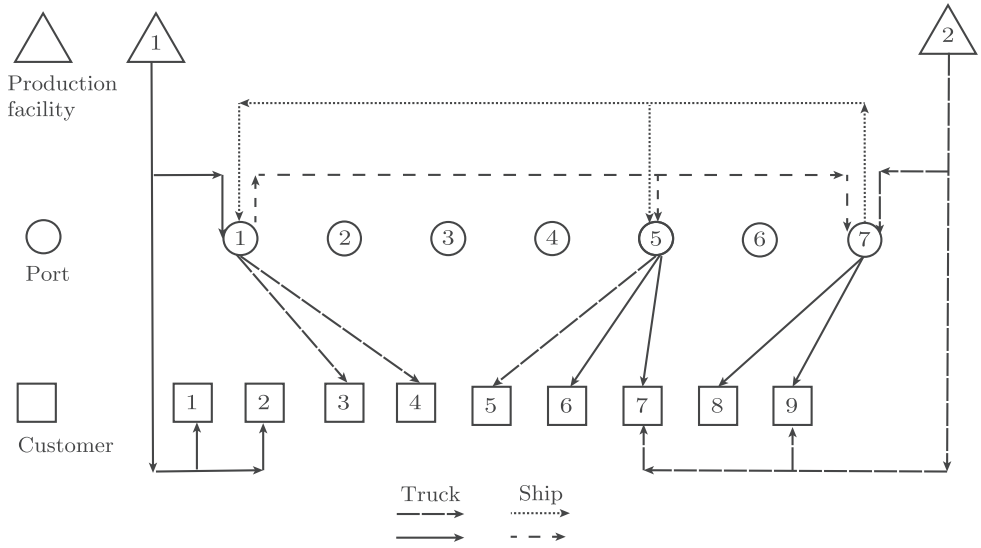

Fig. 2. Multi-modal shipping from production facilities to customer locations.

Fig. 3. Map of India with two production facilities, seven ports along the Indian coastline and 261 customer locations.

unloading ports for automobiles from the auto-manufacturers.

The available inland transportation mode is automobile-carrier trucks. It is possible to hire a RoRo shipping company to manage the coastal shipping. A heterogeneous fleet of ships with various speed options, capacities, cost structures and fuel consumption profiles are owned by the shipping company.

Fig. 2 shows two alternatives for transportation of automobiles to the city of Hosapete, i.e. one from the auto-manufacturers in Chennai and one from Sanand. Automobiles are delivered by truck only between auto-manufacturers in Chennai to auto dealers in Hosapete, while intermodal delivery is used to transport automobiles from Sanand to Hosapete. First, the automobiles are transported by trucks from Sanand to Pipavav port. Then, a RoRo ship loads the automobiles at Pipavav port before sailing to Mangalore port for unloading. Finally, the automobiles are transported by trucks from Mangalore port to auto dealers in Hosapete.

3. Model formulation

This section describes the proposed mixed integer programming (MIP) model for the multi-modal distribution network design problem. Section 3.1 discusses the modeling approach, while Section 3.2 provides a description of the notation, before presenting the mathematical model in Section 3.3.

3.1. Modeling approach

The model we propose for the multi-modal distribution network design problem is based on the model proposed by Chandra et al. (2020). The model relies on the pregeneration of all (or a subset of all) feasible sailing routes, which is used as input to the model. However, the model proposed here includes two important extensions compared to Chandra et al. (2020). The first extension, described in Section 3.1.1, is related to the modeling of the routes. In the second extension, described in Section 3.1.2, we also introduce the possibility to choose sailing speeds for the ships used in the multi-modal distribution network.

3.1.1. Modeling with partial routes

A route is defined as a sequence of ports visited by a ship. In Chandra et al. (2020), they consider the distribution only from one production facility (and hence only one loading port). Therefore, they included only routes that are simple cycles where each port can be visited only once. However, when there are more than one production facility, it can be beneficial to have more advanced route structures where some ports can be visited twice. If we, as an example, refer to our case study, illustrated in Fig. 3, it might be beneficial

to have the following route: start at Chennai port, where cargo originating from the production facility in Chennai is loaded – sail to the ports Cochin and Mangalore to unload the cargo from Chennai – continue to Pipavav, where the ship both unloads cargo from Chennai to customers located in the vicinity of the port and loads cargo originating from the production facility in Sanand – sail back to Mangalore and Cochin ports to unload cargo units from Sanand, before it finally comes back to Chennai where it unloads cargo units from Sanand. With such a route, which is sometimes referred to as a *conveyor belt route*, the ship capacity can be fully utilized on both the outbound and inbound sailing from/to Chennai. If we only allow simple cycles, where each port is visited once, it will be hard to achieve such good ship capacity utilization.

We therefore could, in theory, pregenerate all such conveyor belt routes. However, even the number of simple cyclic routes, where each port is visited at most once, increases exponentially with the number of ports. Including the possibility to visit each port twice would further increase this number with an exponential factor. Therefore, in this paper, we introduce so-called *partial routes* to efficiently model very general route structures. A partial route is a route that is not a cycle, i.e. it starts in one (loading) port and ends in another (unloading) port. By combining such partial routes in clever ways, we can model conveyor belt routes without a dramatic increase in the number of feasible pregenerated routes. Since we generate a variable in the MIP model for each combination of route and ship type, this significantly reduces the number of variables compared to generating all conveyor belt routes.

Fig. 4 illustrates three different route types, where Fig. 4(a) illustrates a simple cyclic route where each port is only visited once. Fig. 4(b) shows an example of a conveyor belt route that consists of two partial routes in sequence. In this case, the starting port of one of the partial routes must be the same as the ending port of the other, and vice versa. In this illustration, port 1 (which for example could refer to Chennai in Fig. 3) is both the start (loading) port of partial route 1 and the end (unloading) port of partial route 2, while port 3 (which could refer to Pipavav) is both the end (unloading) port of partial route 1 and the start (loading) port of partial route 2. In Fig. 4(b), port 2 is an intermediate port in both partial routes 1 and 2, and could for example refer to port 4 (Cochin) in Fig. 3. Fig. 4(c) shows yet another conveyor belt route that is made up of three partial routes.

It should be noted that there is one limitation with modeling conveyor belt routes using partial routes. We will, in Section 3.3, model the flow of cargo along ports within each (partial) route. This means that we do not allow cargo flow between two partial routes, even though they together create a conveyor belt route. If we refer to the example in Fig. 4(b), it means that we cannot model flow of cargo for example from port 1 to port 4. This is because the route between these ports goes between two different partial routes. However, by carefully choosing the starting ports of the partial routes based on what are natural loading ports (e.g. Chennai and Pipavav in Fig. 3), this will not be a major limitation for this multi-modal distribution network design problem.

When generating both the cyclic and partial routes, we only need the non-dominated ones. This means that for a given subset of ports, we only generate the cyclic routes which has the shortest sailing distance/time. The same principle applies for the partial routes: for a given subset of ports, and with a given start and end port, we only generate the route with shortest sailing distance/time.

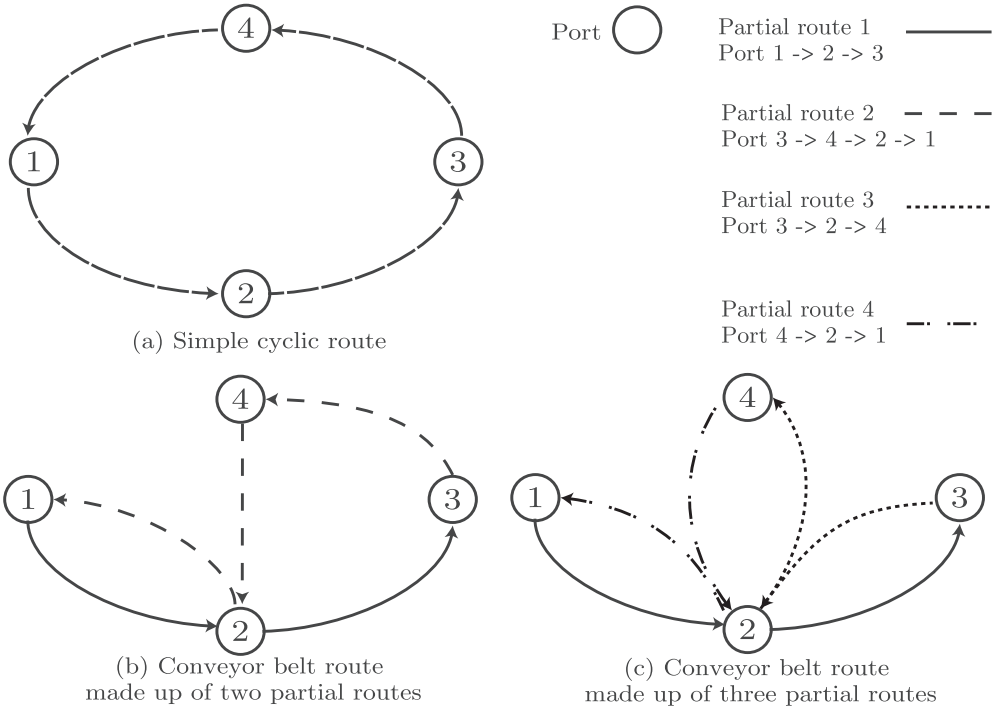

Fig. 4. Different route types. The nodes denote ports and the arcs are sailing legs.

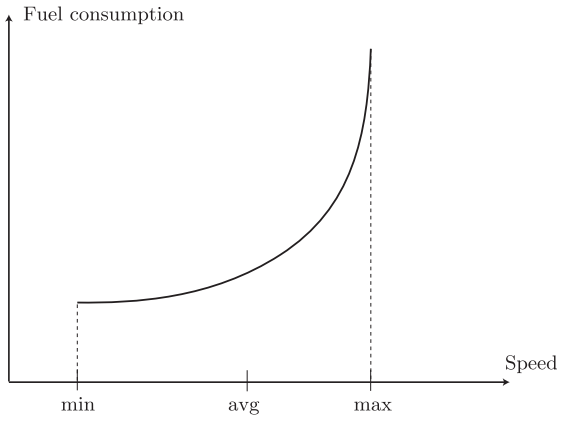

Fig. 5. Fuel consumption function and the three chosen speed points for each ship type.

3.1.2. Modeling of sailing speed

The fuel consumption of a ship is typically a non-linear convex function of the ship's sailing speed, as illustrated in Fig. 5. The chosen sailing speed therefore heavily influences the fuel consumption of the ships, and hence the fuel costs. Incorporating speed as a decision variable might therefore affect the optimal design and cost of the multi-modal distribution network.

We will not handle this non-linearity in detail in this model. However, we have for simplicity chosen to approximate the non-linear fuel consumption function by selecting a set of discrete speed options between the minimum and maximum operating speed to estimate the ship fuel consumption. It is assumed that a ship sails at a constant speed on all sailing legs along a voyage. A voyage is here defined as one occurrence or sailing of a route (partial or cyclic).

3.2. Notation

In this section, the indices, sets, parameters and variables used in the MIP model are defined. In the end, we illustrate the relation between some of the variables in Fig. 6.

Indices

i	Port
k	Customer location
o	Production facility
r	Shipping route, can be either simple route or partial route
s	Speed option
v	Ship type

Sets

$\mathcal{K}$	Set of customer locations
$\mathcal{N}$	Set of ports or sea nodes
$\mathcal{N}_r$	Set of ports along route r
$\mathcal{N}_v^B$	Set of first (beginning) ports in partial routes served by a ship of ship type v
$\mathcal{O}$	Set of production facilities
$\mathcal{R}_v$	Set of simple and partial shipping routes that can be served by ships of type v
$\mathcal{R}_v^P$	Set of partial routes served by ships of type v
$\mathcal{S}_v$	Set of speed options for a ship of type v
$\mathcal{V}$	Set of available ship types

Parameters

C_v^{FS}	Fixed cost of hiring a ship of ship type v in the planning horizon [million USD]
C_{vrs}^{S}	Cost of sailing route r once by a ship of type v at speed option s. It includes the daily shipping cost charged by the shipping company and the fixed port costs for visiting the ports in the route [million USD]
C_{ok}^{TA}	Trucking cost from production facility o to customer k [million USD]
C_{oi}^{TB}	Trucking cost from production facility o to port i [million USD]
C_{ik}^{TC}	Trucking cost from port i to customer k [million USD]
C_i^{VN}	Cost per unit for loading and unloading cargo at port i [million USD]
E_{vrs}^{S}	Emission cost by using a ship of ship type v on route r at speed option s [million kg]
E_{ok}^{TA}	Emission cost per unit by using truck from production facility o to customer location k [million kg]

E^{TB}_{oi} Emission cost per unit by using truck from production facility o to port i [million kg]
E^{TC}_{ik} Emission cost per unit by using truck from port i to customer location k [million kg]
I^{B}_{r} First (beginning) port in route r [–]
I^{E}_{r} Last (ending) port in route r [–]
K_v Maximum carrying capacity of a ship of ship type v [units]
Q_{ok} Estimated demand from production facility o to customer location k [units]
T_{vrs} Time to complete route r once by a ship of ship type v at speed option s [days]
$\overline{T}$ Length of the planning horizon [days]

Decision variables

f^{TA}_{ok} Amount of direct truck delivery from production facility o to customer location k [units]
f^{TB}_{oik} Amount of first mile truck delivery made from production facility o to port i for the cargo that is finally delivered to customer location k [units]
f^{TC}_{oik} Amount of last mile truck delivery made from port i to customer location k for the cargo that produced in the production facility o [units]
q^{L}_{oikvr} Quantity loaded at port i on board a ship of ship type v sailing route r; originating in production facility o and ending in customer location k [units]
q^{U}_{oikvr} Quantity unloaded at port i from a ship of ship type v sailing route r; originating in production facility o and ending in customer location k [units]
u_v Number of ships of ship type v used in the planning horizon [ships]
x_{vrs} Number of times a ship of ship type v sails route r at speed option s

The ship variables u_v and x_{vrs} are integer variables. The fleet sizing is represented by u_v, while the liner route design and fleet deployment part of the problem are given by x_{vrs}. The options available for ship types and routes are given apriori. The fleet deployment along the different selected routes provides the necessary capacity for the coastal shipping between the loading ports and the different unloading ports.

The remaining variables represent the quantity transported by ships (q-variables) and trucks (f-variables). These are considered continuous due to their considerable size. Fig. 6 illustrates the relationship between the quantity variables for the same example as in Fig. 2. Two partial routes shown in the figure, $r = 6$ and $r = 8$, are serviced by ships of type 1, i.e. $v = 1$. These two routes make a conveyor belt route. An example of a simple cycle route could have started in port 7 and visited port 5 before returning to port 7 again.

3.3. Mixed integer linear programming model

First the objectives are presented and described before the all the constraints for the model are given and discussed.

3.3.1. Objective functions

Here we are presenting two types of objective functions. In the first function we are minimizing the total costs for the transportation from the production facilities to the customer locations by trucks and ships, while in the other we are minimizing the environmental emissions from the transportation. In the computational study, we are discussing the results of using the different objective functions.

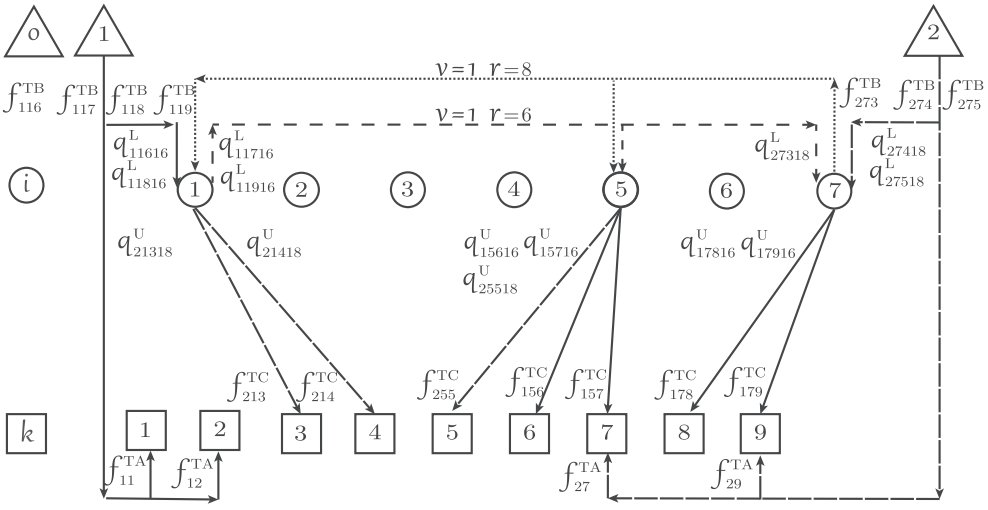

Fig. 6. Illustration of variables corresponding to Fig. 2.

Objective 1 - Minimizing costs

$$\begin{aligned} minimize\ z_1 = & \sum_{o\in\mathcal{O}}\sum_{k\in\mathcal{K}} C^{TA}_{ok} f^{TA}_{ok} + \\ & \sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}}\sum_{k\in\mathcal{K}} C^{TB}_{oi} f^{TB}_{oik} + \sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}}\sum_{k\in\mathcal{K}} C^{TC}_{ik} f^{TC}_{oik} + \\ & \sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v}\sum_{s\in\mathcal{S}_v} C^{S}_{vrs} x_{vrs} + \sum_{v\in\mathcal{V}} C^{FS}_{v} u_v + \\ & \sum_{o\in\mathcal{O}}\sum_{k\in\mathcal{K}}\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v}\sum_{i\in\mathcal{N}_r} C^{VN}_{i} q^{L}_{oikvr} + \sum_{o\in\mathcal{O}}\sum_{k\in\mathcal{K}}\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v}\sum_{i\in\mathcal{N}_r} C^{VN}_{i} q^{U}_{oikvr} \end{aligned} \tag{1}$$

The objective function (1) minimizes the total cost of transportation from the production facility to all customer locations in the planning horizon. The cost terms are: (1) direct truck deliveries made from the production facilities to the customer locations, (2) first mile transportation by trucks from the production facilities to the ports, (3) last mile trucking from ports to respective customer locations, (4) variable costs of operating ships along the selected routes together with the fixed cost of visiting the ports along each served route, (5) fixed cost of chartering ships over the planning horizon, (6) variable loading costs at the ports, and (7) variable unloading costs at the ports.

Objective 2 - Minimizing environmental emissions

$$\begin{aligned} minimize\ z_2 = & \sum_{o\in\mathcal{O}}\sum_{k\in\mathcal{K}} E^{TA}_{ok} f^{TA}_{ok} + \\ & \sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}}\sum_{k\in\mathcal{K}} E^{TB}_{oi} f^{TB}_{oik} + \sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{P}}\sum_{k\in\mathcal{K}} E^{TC}_{ik} f^{TC}_{oik} + \\ & \sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v}\sum_{s\in\mathcal{S}_v} E^{S}_{vrs} x_{vrs} \end{aligned} \tag{2}$$

The objective function (2) minimizes the total environmental emissions of transportation from the production facility to all customer locations in the planning horizon. The emission terms are: (1) direct truck deliveries made from the production facilities to the customer locations, (2) first mile transportation by trucks from the production facilities to the ports, (3) last mile trucking from ports to respective customer locations, and (4) operating ships along the selected routes.

3.3.2. Constraints

$$\sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}_r}\sum_{k\in\mathcal{K}} q^{L}_{oikvr} - \sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}_r}\sum_{k\in\mathcal{K}} q^{U}_{oikvr} = 0, \quad v\in\mathcal{V}, r\in\mathcal{R}_v, \tag{3}$$

$$\sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{N}_r}\sum_{k\in\mathcal{K}} q^{L}_{oikvr} - K_v \sum_{s\in\mathcal{S}_v} x_{vrs} \leqslant 0, \quad v\in\mathcal{V}, r\in\mathcal{R}_v, \tag{4}$$

$$\sum_{r\in\mathcal{R}_v}\sum_{s\in\mathcal{S}_v} T_{vrs} x_{vrs} - \overline{T} u_v \leqslant 0, \quad v\in\mathcal{V}, \tag{5}$$

$$\sum_{r\in\mathcal{R}^P_v \mid l^B_r = i}\sum_{s\in\mathcal{S}_v} x_{vrs} - \sum_{r\in\mathcal{R}^P_v \mid l^E_r = i}\sum_{s\in\mathcal{S}_v} x_{vrs} = 0, \quad v\in\mathcal{V}, i\in\mathcal{N}^B_v, \tag{6}$$

$$\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} q^{L}_{oikvr} - f^{TB}_{oik} = 0, \quad o\in\mathcal{O}, i\in\mathcal{N}, k\in\mathcal{K}, \tag{7}$$

$$\sum_{v\in\mathcal{V}}\sum_{r\in\mathcal{R}_v} q^{U}_{oikvr} - f^{TC}_{oik} = 0, \quad o\in\mathcal{O}, i\in\mathcal{N}, k\in\mathcal{K}, \tag{8}$$

$$f^{T}_{ok} + \sum_{i\in\mathcal{N}} f^{TC}_{oik} \geqslant Q_{ok}, \quad o\in\mathcal{O}, k\in\mathcal{K}, \tag{9}$$

$$f^{TA}_{ok} \geqslant 0, \quad o\in\mathcal{O}, k\in\mathcal{K}, \tag{10}$$

$$f^{TB}_{oik}, f^{TC}_{oik} \geqslant 0, \quad o\in\mathcal{O}, i\in\mathcal{N}, k\in\mathcal{K}, \tag{11}$$

$$q^{L}_{oikvr}, q^{U}_{oikvr} \geqslant 0, \quad o\in\mathcal{O}, k\in\mathcal{K}, v\in\mathcal{V}, r\in\mathcal{R}_v, i\in\mathcal{N}_r, \tag{12}$$

$$u_v \in Z^{+}, \quad v\in\mathcal{V}, \tag{13}$$

$$x_{vrs} \in Z^{+}, \quad v\in\mathcal{V}, r\in\mathcal{R}_v, s\in\mathcal{S}_v. \tag{14}$$

Constraints (3) ensure that the quantity loaded is equal to the quantity unloaded at the ports in each route. The quantity carried by ships of ship type v on route r cannot exceed the capacity of a ship of this type multiplied by the number of times the route is performed during the planning horizon, and these constraints are given by (4). Constraints (5) make sure that there are a sufficient number of ships of each ship type available to perform the various routes an optimal number of times. Constraints (6) link the partial routes together. The constraints make sure that if a partial route that starts in a given port is chosen, then we also need to choose another partial route that ends in the same port, and vice versa. Constraints (7) ensure that the quantity loaded at each port is equal to the quantity transported by truck from the production facility to the port. Similarly, the quantity unloaded in a port is equal to the quantity transported by truck from this port to the customer location given by constraints (8). Furthermore, constraints (9) are the demand fulfillment constraints at each customer location, and indicate that the sum of truck and ship delivery to each customer location should satisfy its demand.

Constraints (10)–(12) impose non-negativity conditions on five sets of decision variables, while conditions for the integer decision variables are given in constraints (13) and (14).

4. Computational study

This section presents the computational study, where Section 4.1 describes the case study of the automobile distribution in India in more detail, as well as how the input data has been estimated, while the computational results are presented and discussed in Section 4.2. The proposed model was implemented in Python 2.7, using CPLEX version 12.9 as the MIP solver. All computational tests were performed on a computer with an Intel Core(TM) i5-5200, 2.20 GHz processor and 8.00 GB RAM, and an operating system of Microsoft Windows 10. When running the model for the case study described in the following, around 169 thousand variables (of which 1155 were integer) and 9126 constraints were generated, and the model was solved in a matter of seconds.

4.1. Case study and data estimation

We consider a similar case study for the distribution of automobiles as Chandra et al. (2020), with a few exceptions. Chandra et al. (2020) consider the distribution only for auto-manufacturers located close to the port in Chennai, from where automobiles are distributed to dealers all over India, as illustrated in Fig. 3. Here, we include several additional auto-manufacturers located close to the ports both in Chennai and Sanand. The distribution can be done either by direct distribution with automobile-carrier trucks or by intermodal distribution by ship and trucks. We represent the automobile dealers by customer regions, and to estimate annual demand per region, we have used the same source data as Chandra et al. (2020), which relied on detailed data sources for automotive sales in India. In total, we consider 11 auto-manufacturers with an estimated total distribution of 1.56 million cars per year. All road distances from auto-manufacturers and possible unloading ports to customers are obtained from Chandra et al. (2020).

Each automobile-carrier truck has a capacity of eight automobiles. The truck rates in USD is calculated based on the formula $185.69 + 1.46*Distance$ (km), which was found by Chandra et al. (2020) from regression analysis after obtaining truck freight rates from trucking companies for 200 location pairs in India. To estimate the truck emissions, the round trip distances need be considered, as it is not likely that trucks can be filled with return cargo. We use emission factors of trucks together with the distance traversed between different pairs of locations, adjusted by the truck capacity, to estimate the truck emissions. The CO_2 truck emission factor, E^T, is estimated to 1.254 kg/km (StatisticsNorway, 2016b). The ship emission parameters can be obtained by the ship fuel consumption times the emission factor of sea transport mode.

As illustrated in Fig. 3, we consider seven candidate ports along the coastline of India to be used in the multi-modal distribution of automobiles. The distances between all port pairs are obtained from Ports.com (2018). When generating all non-dominated ship routes, as described in Section 3.1, we end up with 64 simple cyclic routes and 64 partial routes (which can be combined into conveyor belt routes).

Based on data from a RoRo shipping company, we have defined three available ship types. Table 1 shows the capacities given in CEUs (car equivalent units) and the three speed options for each of the three ship types. For each speed option, we have calculated the fuel consumption per day, which for cargo ships is typically a cubic function of speed. This means that the fuel consumption increases rapidly when the speed approaches the maximum speed of the ships.

We have used a fuel cost of 700 USD per ton fuel. The CO_2 emission rate for the ships is 3.17 ton per ton fuel (StatisticsNorway (2016a)). Furthermore, each ship type also has a given time charter rate per year. The port call costs depend on the size of the ships, and have been estimated like in Chandra et al. (2020) as 0.82 GRT, where GRT is the gross register ton, which is a volume measure for the ship. Cargo handling costs are set to 2.00 USD per automobile handling (i.e. for loading or unloading one automobile).

Table 1
Available ship types with capacities and the three speed options.

ShipType	Capacity(CEU)	Speed Option(knot)		
		Min Speed	Service Speed	Max Speed
1	3000	14.2	16.0	17.5
2	5250	15.2	17.0	18.5
3	7194	15.2	17.0	19.0

4.2. Computational results

In the following, we present and discuss the results from the computational study. We begin by comparing the results from using the different planning objectives (i.e. minimizing costs vs. emissions). Then we compare the results with pure truck delivery, before we test the effect from introducing speed optimization. Finally, we test the effect from introducing partial routes that can be combined into conveyor belt routes, before we study the effect of collaboration between the auto-manufacturers at the two different origins.

4.2.1. Comparing the results from minimizing costs vs. minimizing emissions

Fig. 7 shows the comparison of cost and emission components when minimizing costs (Objective 1) and emissions (Objective 2) for the multi-modal distribution network in India, respectively. When minimizing emissions, we also include the cost in the objective function multiplied by a very small constant, so as to ensure that among all solutions that are optimal with respect to emissions, we choose the one with lowest cost.

As shown in Fig. 7 (a), the total cost of the solution when we minimize costs is 310.71 million USD, while the cost is around 5% higher when we minimize emissions. If we look at the emissions of the solutions when using the two different objectives, shown in Fig. 7 (b), we notice that the CO_2 emissions are reduced by only around 2.6% when minimizing emissions compared to minimizing costs (i.e. 412.98 million kg vs. 423.80 million kg). This shows that the two objectives are not conflicting to a large extent and that the cost-optimal solution is also very good with respect to minimizing emissions.

The main difference between the two solutions is that when minimizing emissions, an even higher share of multi-modal distribution (coastal shipping) is selected, i.e. 72.2% vs. 65.4%. This is made possible through a larger fleet of ships in this solution, where all ship types are chosen, while the cost-minimal solution only includes two ships of the largest type. Another important difference between the two solutions is, not surprisingly, that in the emission-optimal solution, almost all selected voyages (98%) are sailed at the lowest speed available in order to reduce fuel consumption, and hence emissions. The highest speed is not chosen at all in this solution, while in the cost-optimal solution, all speed options are used. However, still as many as 69% of the voyages are sailed at the lowest speed, so it seems beneficial also from a cost-perspective to sail at low speeds.

4.2.2. Comparing with distribution by trucks only

Fig. 8 shows the effects of introducing multi-modal shipping compared with pure truck delivery. Here, we have used Objective 1, i.e. we are minimizing costs. The figure clearly shows that the multi-modal distribution is significantly more cost-efficient than the pure truck delivery, with approximately 25.9% reduction in costs. When considering emissions, the difference is even higher at around 35.8%. This shows that significant gains, both in costs and emissions, can be achieved from a modal shift from direct truck delivery to multi-modal distribution.

The cost reduction obtained from introducing multi-modal distribution is much higher than in Chandra et al. (2020), which only showed cost reductions of around 10%. The main reason for this is that Chandra et al. (2020) consider one auto-manufacturer that distributes only around 430,000 cars per year from Chennai, while we in this analysis consider several auto-manufacturers, located close to the ports both in Chennai and Sanand, which have an estimated combined volume of 1.56 million cars per year (i.e. 730,000 from Chennai and 830,000 from Sanand). This results in large economies-of-scale for the multi-modal distribution. In addition, several ports for loading cars results in a better capacity utilization of the ships. By allowing the partial routes, which is discussed later, the ships can have cargo in both directions of the voyages, which is very beneficial. We have also introduced the possibility to optimize the speeds here in contrast to Chandra et al. (2020), which may also have some impact (discussed in more detail in the following).

4.2.3. Effect from speed optimization

One of the extensions we consider in this paper compared to Chandra et al. (2020), is the possibility of optimizing the sailing speed

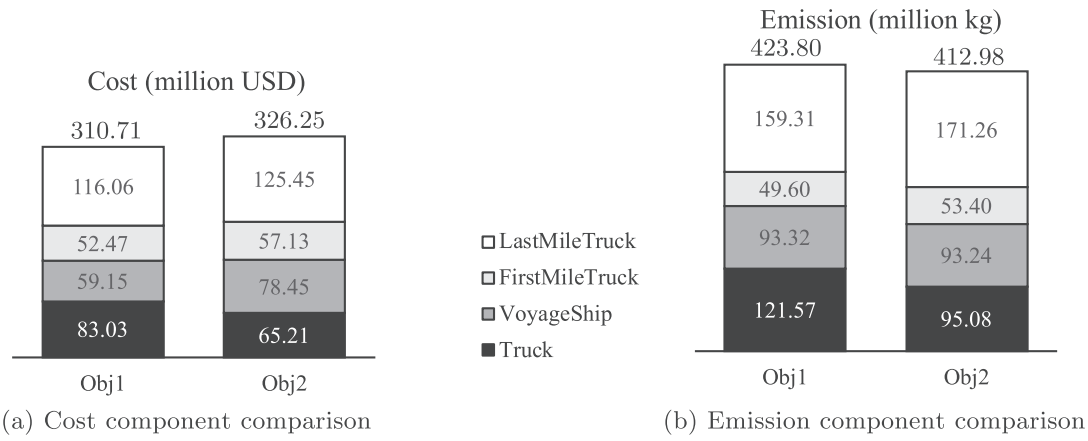

Fig. 7. Comparison of solutions from minimizing costs (Objective 1) and emissions (Objective 2).

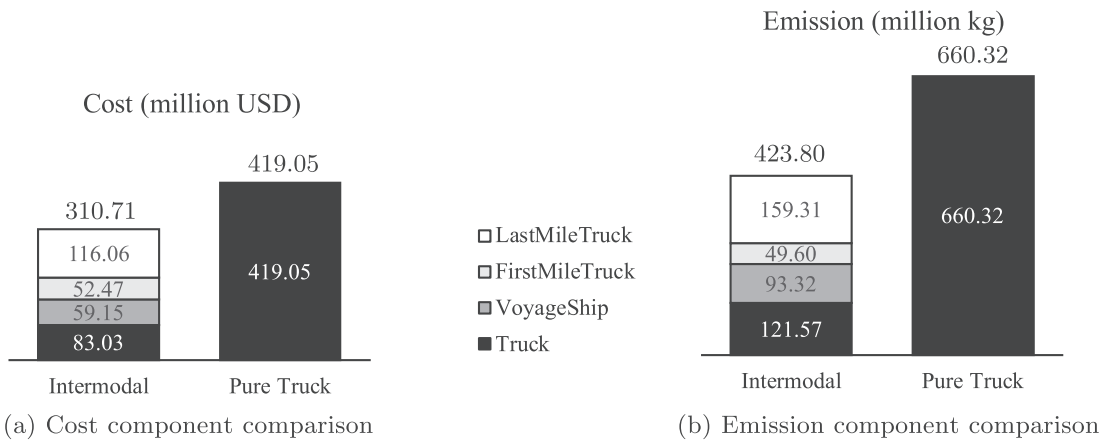

Fig. 8. Comparison with pure truck solution in terms of cost and emission.

of the ships, which might heavily influence the fuel consumption (and costs), and hence also the emissions. Fig. 9 shows the effect of introducing speed optimization. Here, we have used the service speed of the ships, which corresponds to the middle speed option for the different ships types, when not including speed optimization.

When minimizing costs (Objective 1), we can see that we gain only 0.80% in cost reduction from optimizing the sailing speeds (310.71 million USD vs. 313.22 million USD). However, the difference in emissions is much higher, i.e. 423.80 million kg vs. 436.41 million kg, which corresponds to a reduction of CO_2 emissions of around 2.9%. If we minimize emissions, the emission reduction from optimizing speeds is around 4.2% (412.98 million kg vs. 431.30 million kg), while we see an increase in the cost of around 3.9% (326.25 million USD vs. 314.14 million USD). The latter can be explained by the fact that the minimum emission solution has a larger share of multi-modal transport, which gives a total reduction in truck transportation. This actually increases the cost in this case even though it contributes to reduced emissions.

4.2.4. *Effect from introducing partial routes*

The other significant extension compared with Chandra et al. (2020) is that we consider the distribution from more than one auto-manufacturer. As a result of that, it my be beneficial to introduce conveyor belt routes in addition to the simple cyclic routes used in Chandra et al. (2020). As discussed in Section 3, we generate conveyor belt routes by combining partial routes. Here, we study the effect of introducing and combining partial routes. Fig. 10 shows the comparison of cost and emission components with or without partial routes when we are minimizing costs (Objective 1) and speed optimization is included.

It can be seen that we obtain reductions in both costs and emissions from introducing the partial routes. The cost reduction is 1.7% (i.e. 310.71 million USD vs. 316.09 million USD), while the emission reduction is around 5%. The main difference is again that multi-modal distribution takes a higher share of the total transportation when partial routes are included, i.e. 65.4% vs. 62.1%. All routes that are chosen in the optimal solution consist of either two or three port visits. When analyzing the results, we also see that the share of partial routes used in the optimal solution is as high as 35.2%. This clearly shows that including partial routes has a positive effect on the solution quality.

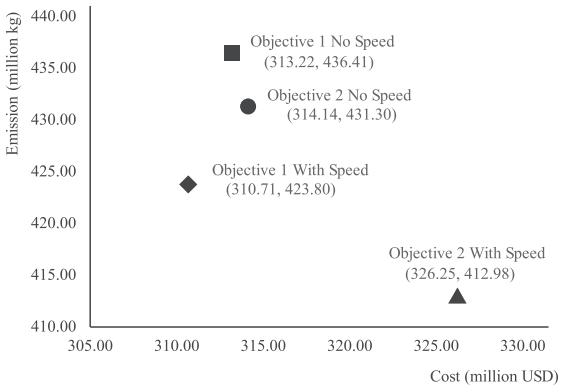

Fig. 9. Comparing costs and emissions with and without speed optimization when minimizing both costs (Objective 1) and emissions (Objective 2).

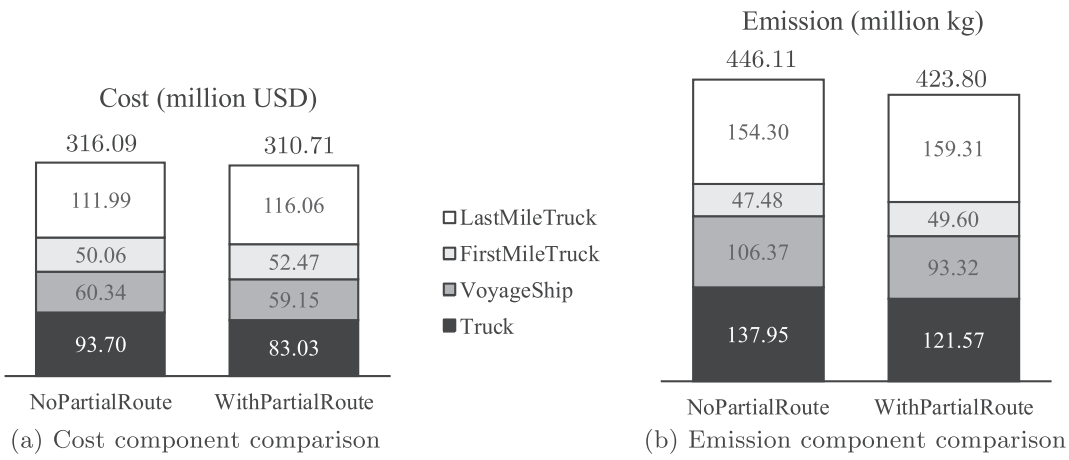

Fig. 10. Comparison with and without partial routes in terms of cost and emission when minimizing costs.

4.2.5. *Collaboration between auto-manufacturers*

In the analyses so far, we have assumed that the all auto-manufacturers located in the regions close to Chennai and Sanand have *full collaboration*. This means that they share their demand information to one logistics company which will use this collective information to manage the transportation. It also means they share the ship fleet and routes in the multi-modal distribution. In this section we compare this full collaboration with two other levels of collaboration. We consider the same 11 auto-manufacturers that have production facilities in the regions close to Chennai and Sanand, so that the total volumes and costs are comparable. Furthermore, we use cost as our objective in this analysis.

First, we consider each *auto-manufacturer separately* and optimize its distribution network, before we aggregate the results. It should be noted some of these have production facilities in both of the two regions (i.e. close to Chennai and Sanand), and it is assumed that two production facilities for the same auto-manufacturer can collaborate and share ship fleet and routes. Second, we assume *regional collaboration*, meaning that all the production facilities located in each of the two regions collaborate. However, this option does not include any collaboration between production facilities located in different regions.

Table 2 summarizes the solutions for the three levels of collaboration. As shown, the costs compared to full collaboration increase by 4.8% and 2.6% when each auto-manufacturer is considered separately and for regional collaboration, respectively. The emissions go up by around 5–6% if the auto-manufacturers do not fully collaborate. This shows that it is beneficial in terms of both cost and emission if the auto-manufacturers in the two regions can collaborate and have a common multi-modal distribution system.

There are some characteristics in the solutions in Table 2 that can be noted. Firstly, when each auto-manufacturer is considered separately, the proposed solution includes as many as six ships for the coastal shipping (i.e. one large ship of type 3 and five small of type 1). This is in contrast to the solutions for the full and regional collaboration, which both include only two large ships. The reason for this is that when each auto-manufacturer optimizes its distribution network separately, the volumes are not high enough to make it viable to use a large ship, except for one auto-manufacturer. This is also the reason why this solution is the one with the lowest share of coastal shipping.

Secondly, it can be observed that emissions are higher for the regional collaboration than when each auto-manufacturer is considered separately. This can be explained by that when each auto-manufacturer is considered separately, there can still be collaboration between two production facilities located in different regions as long as they belong to the same auto-manufacturer. This creates a possibility, through the use of partial routes, to let the ships transport cargo in both directions. This is in contrast to the regional collaboration, where there is no collaboration across the two regions. This gives no possibility of having return cargo for the coastal shipping and no partial routes are chosen and it results in more empty sailing.

As a final note, by studying Table 2 and Fig. 8, we see that both the costs and emissions are much lower than when using pure truck delivery even when the auto-manufacturers do not fully collaborate. This shows that the multi-modal distribution is beneficial even without a full collaboration among the auto-manufacturers.

5. Conclusions

Multi-modal transportation takes advantage of multiple transport modes and can be an effective way to ease the negative environmental effects of freight transportation. This paper addresses a multi-modal distribution network design problem with the aim of balancing the trade-off between economic and environmental benefits. The distribution network that we consider includes both transportation with trucks and ships. We proposed a new mixed integer programming (MIP) model which decides the optimal design of the system, i.e. how many ships of each type to use, their corresponding routes and sailing speeds. It also suggests an optimal cargo flow through the network. The MIP model extends the one from Chandra et al. (2020) by handling a more general version of the problem where we consider more than one production facility and loading port. We have therefore extended the model to include more general route structures which becomes relevant when there are more than one loading port. In addition, we take into consideration speed

Table 2
Comparison of cost-optimal solutions without and with collaboration among the auto-manufacturers.

	Auto-manufacturer separately	Δ(%)	Regional collaboration	Δ(%)	Full collaboration
Total Cost (million USD)	325.58	4.8 %	318.70	2.6 %	310.71
Unit Cost (USD)	208.54		203.93		198.82
Total Emission (million kg)	444.42	4.9 %	448.66	5.9 %	423.80
Unit Emission (kg)	284.65		287.08		271.18
Share of multi-modal	60.47 %	−7.5 %	63.46 %	−2.9 %	65.37 %
Ship type (No.)	3(1),1(5)	–	3(2)	–	3(2)

choice in the maritime transportation, as this heavily influences the fuel consumption of the ships.

We have shown how the MIP model can be used for analyses and to provide decision support through a case study from the distribution of automobiles in India, which has a vast coastline that can be used for maritime transportation. The automotive industry in India is one of the largest automobile markets in the world and among the fastest growing industries in the country. Several automotive brands have production facilities in India, and the country's total production of vehicles exceeded four million units in 2018. Several of these production facilities are located relatively close to the coastline. From the different production facilities, there is an extensive distribution across the country, most of which today is done by trucks. Environmental emissions from automobile transportation in India have been rapidly increasing in recent years with the fast economic development, and it has become a major contributor to regional air pollution and road congestion. One possible way to ease these negative environmental consequences is therefore to consider a modal shift where some of the automobile transportation from the production facilities located close to the coastline is replaced by RoRo ships. The proposed MIP model therefore includes both cost and environmental aspects, so as to analyze the trade-off between these two objectives.

Our study showed that multi-modal distribution is both environmentally friendly and economically beneficial, especially if more industrial players can collaborate to create economies of scale. The results showed that an estimated cost reduction of 25.9% can be obtained using multi-modal transportation compared to only direct truck delivery, which is mostly used today. The emission reduction was even higher at 35.8%. The cost-optimal solution suggested that as much as 65.4% of the automobiles should be transported using the coastal shipping transportation mode. When minimizing emissions, the cost reductions were still around 22% and the emissions were reduced by as much as 37.5% compared to only direct truck delivery. In this case, as much as 72.2% was transported using the coastal shipping mode.

For future research, it could be interesting to look at the results' sensitivity of changes in the ships' fuel price. Since changes in fuel price most likely also will result in changes in the fuel prices for the trucks, and hence the truck rates, one would need to have more precise data about how such changes in fuel price affect the truck rates. Another interesting direction for future research could be to introduce alternative and better ways of handling the non-linear relationship between ship speed and fuel consumption, for example following the ideas from Andersson et al. (2015) or Wang and Meng (2012). We also believe it would be interesting in the future to extend the model to overcome the limitation that we discussed in Section 3.1.1 regarding that we cannot have cargo flow between partial routes.

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