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Combined fleet deployment and inventory management in roll-on/roll-off shipping

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ABSTRACT

In maritime transportation of automobiles, roll-on/roll-off (ro–ro) shipping companies operate liner shipping services across major trade routes. Large ro–ro shipping companies are well placed to offer end-to-end integrated logistics services to auto manufacturers engaged in international trade of vehicles. Therefore, we present a new mixed integer programming model for fleet deployment including inventory management at the ports along each trade route. Due to the complexity of the problem, a rolling horizon heuristic (RHH) is proposed. The RHH solves the problem by iteratively solving sub-problems with shorter planning horizon. Computational results based on real instances are presented.

1. Introduction

Roll-on Roll-off (ro–ro) shipping deals with seaborne transportation of all types of rolling material; cars being the most dominant cargo type. In the international trade of automobiles most of the shipping routes originate from the Far East where Japan and South Korea are the major exporters. USA is the largest importer followed by continental Europe. A small but rising share of export volume originates from emerging economies like India and South Africa. According to a Mitsui O.S.K. Lines Ltd. report (MOL, 2013), the average monthly export volume of new vehicles from Japan stood at around 380,000 units from 2010 to 2012. The use of maritime transportation for this type of trade leads to the realization of economies of scale. Further, ro–ro shipping is promoted as a replacement for truck transport as an attempt to reduce environmental emissions, through programs like Marco Polo in Europe and similar initiatives in US and other parts of the world. Thus, this form of shipping is expected to play an even more dominant role in maritime logistics of automobiles in the coming future.

A ro–ro shipping company owns and operates a heterogeneous fleet of ships having different cargo capacities, sailing speed ranges, and bunker consumption profiles. These type of ships operate in liner mode, in which ships sail pre-defined trade routes, as per published itineraries and schedules. Increased logistics outsourcing by auto manufacturers and proliferation of manufacturing and demand locations worldwide has increased complexity of maritime logistics of automobiles. This has led to the emergence of strong logistics service providers (LSPs) offering integrated inter-modal transportation and cargo handling services. Following this trend, the major ro–ro shipping companies are broadening their scope as third party LSPs in finished automobile trade. In this scenario, a ro–ro shipping company in collaboration with other LSPs offers end-to-end integrated maritime logistics solutions to various automobile manufacturers. We refer to a ro–ro shipping company from now on as a *shipping company* or just *company*. Under such a contract, an automobile manufacturer outsources the complete

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maritime logistics of its finished vehicles to a shipping company for overseas distribution. We refer to such an auto manufacturer as a *client* of the shipping company. The shipping company undertakes the full responsibility of inland transportation between the factory and the sea port at both ends, inventory management and cargo handling at these ports, along with overseas maritime transportation. In practice many of these shipping companies operate a separate division for logistics management or may collaborate with a partner LSP to integrate planning of associated services along with maritime transportation. The client is expected to share the production and demand information with the shipping company on a regular basis. In turn the shipping company shares the ship arrival information with these clients to ensure smooth production plans for vehicles meant for export.

The shipping company services a given set of trade routes. A trade route is specified by two or more geographical regions between which goods are traded and consists of a given sequence of loading and discharge ports. The company plans a given number of repeated voyages on each trade route in a given planning horizon. Each such voyage follows the sequence of port calls and must start within a specified time window. The fleet deployment problem deals with finding an optimal assignment of available ships in the fleet to the predefined voyages in a given planning horizon to maximize profits or minimize costs. The shipping company offering integrated maritime logistics services first estimates the shipment sizes of the different cargoes traded in each route in collaboration with clients and partner LSPs. This is followed by fleet deployment in a given planning horizon. Shipment planning may be further refined based on the ship arrival information across each port of a route, based on the fleet deployment planning. This sequential approach to logistics planning is performed under restrictive constraints as fleet deployment planning is carried out under fixed transportation requirements.

Fig. 1 presents two trading routes served by a ro–ro shipping company. In Route-1, represented with solid arcs, cargoes are loaded from European and South African ports and discharged mid route and finally at four successive Australian ports. Two voyage starting dates with ship names are published for this route. Similarly, Route-2, connecting Far-East loading ports with European discharge ports, is represented by dotted arcs. Starting date and ship name for two successive voyages are given. In a fleet deployment planning problem, a ship may first serve a voyage in Route-1. This route will end at a port on the East coast of Australia. The ship may then continue to serve a voyage on Route-2. In this case there would be a ballast voyage from Australia to Far-East between the two voyages.

Container shipping is the major segment of liner shipping. Therefore, most of the literature on fleet deployment focuses on container shipping. Perakis and Jaramillo (1991) present a linear programming (LP) model for a container ship fleet deployment problem. The LP model is concerned with minimizing the annual operating costs for a fleet of liner ships. The model considers allocating owned ships to the trade routes, deciding number and types of ships and duration of chartering-in ships, and number, type and duration of owned ships that are laid-up during the planning horizon. Ships speeds are taken as fixed values and assumed to be the same in the ballast and loaded conditions. It is assumed that a fixed amount of cargo, evenly distributed throughout the year, will be carried between a given pair of ports belonging to a given route. Powell and Perkins (1997) present an integer programming (IP) formulation as an improvement to the existing model.

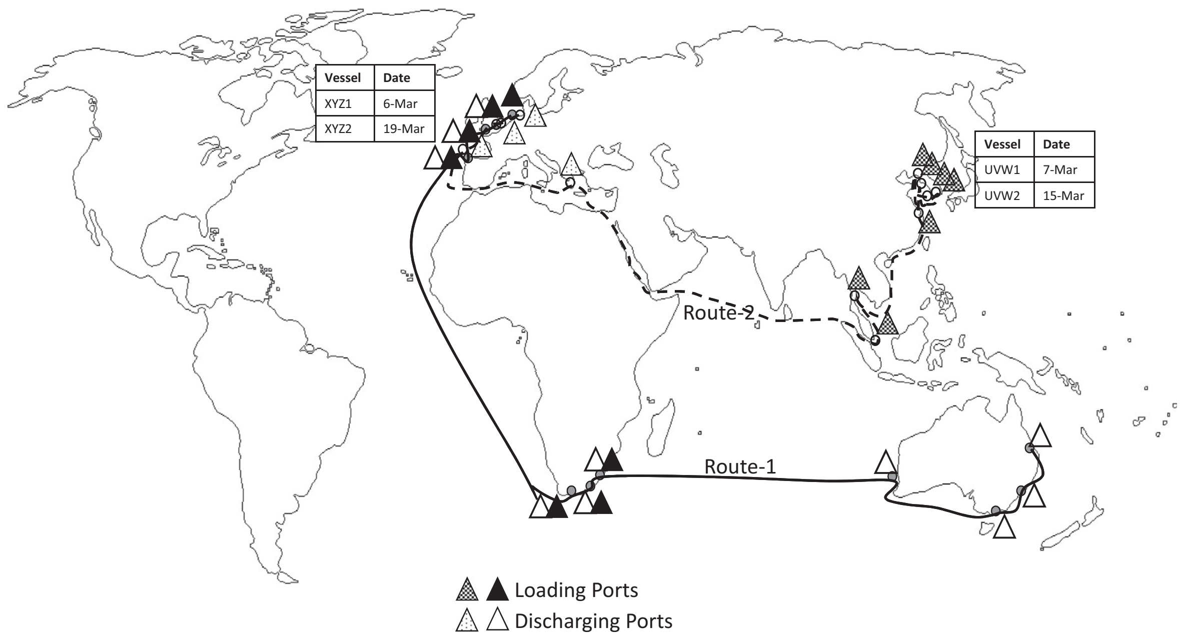

Fig. 1. Two trade routes and respective voyage calls.

Computational results are presented on real data from a container shipping company and substantial savings in costs are reported in comparison to the current manual planning.

Gelareh and Meng (2010) present a MIP formulation for a short-term fleet deployment problem, where sailing speed is considered as a decision variable. Improvements to the existing models and new formulations are suggested by Wang et al. (2011) and Zacharioudakis et al. (2011). Liu et al. (2011) present a container ship fleet deployment problem which considers additional discounts to customers on increasing shipment volumes for estimating revenues. Moura et al. (2001) present a fleet deployment problem with transshipment at a single hub port, while Wang and Meng (2012) present a MIP model for fleet deployment with the possibility of container transshipment at every port. Fagerholt et al. (2009) present an alternative MIP formulation for a fleet deployment problem considering routing and scheduling of individual ships, while Andersson et al. (2015) extend that model by integrating speed optimization.

When an actor is responsible for the ship routing and scheduling as well as the inventory management at the associated loading and discharge ports, the underlying planning problem is classified as a maritime inventory routing problem (MIRP) in the literature (Christiansen et al., 2013). Christiansen (1999) presents a single cargo MIRP in industrial shipping. Al-Khayyal and Hwang (2007) extend the model to include the planning of multiple cargoes. Grønhaug and Christiansen (2009) present a MIRP in the context of LNG transportation. Several other versions of MIRPs have been proposed in the industrial shipping segment, involving different products like crude oil, petroleum products, cement, bitumen, pulp, chemicals, wheat, calcium carbonate slurry, etc. Stålhane et al. (2014) present a planning problem that combines inventory routing for a selected group of clients in a traditional tramp ship routing and scheduling problem. In this problem the planner determines the routes and schedules of the ships in the fleet, while simultaneously taking care of the inventory management from a selected group of clients for which the shipping company offers vendor managed inventory (VMI) services.

As per our investigation, the literature on fleet deployment problem has not considered the shipment planning of cargoes at various loading and discharging ports across a trade route. The cargo volumes are taken as given data in the fleet deployment studies. Most of the papers consider cargo shipment in terms of aggregate volumes between the ports in a trade route, which are used to simply determine the ship-route compatibilities. This suggests that the inventory management and shipment planning of liner cargo are considered as input to the fleet deployment problem. The MIRP literature suggests great economic potential in combining inventory management and ship routing and scheduling planning in the context of industrial and tramp shipping. It can be inferred from the extant literature on fleet deployment problems and MIRP that the overall fleet deployment planning in ro–ro liner shipping can be improved by considering combined planning of inventory management of cargoes at various origin and destination ports. These combined planning tasks have just been studied in one other paper (Chandra et al., 2015) as far as we know.

This paper describes the continuation of the research relative to the results in Chandra et al. (2015). In this paper we propose an improved and new modelling approach for integrating shipment planning and inventory management for a group of car types from several auto manufacturers along with fleet deployment planning for a ro–ro shipping company. Under this combined planning approach, the daily production and consumption quantities of each group of car types at the respective origin and destination ports are known to the shipping company for the whole planning horizon. The shipping company has to make sure that the inventory of cars at each port stockyard remains within its limits. This problem is called a fleet deployment and inventory management problem (FDIMP). Our contribution is to present the FDIMP problem, propose a new and improved MIP model for the problem, and, finally, describe a rolling horizon heuristic (RHH) for the FDIMP that solves instances in reasonable time and with good solution quality.

The rest of the paper is organized as follows: Section 2 is devoted to a detailed description of the planning problem and the mathematical formulation. In Section 3, we present an illustrative example with its optimal solution. The RHH is described as a solution technique to the problem in Section 4. Section 5 provides computational experiments with test instances generated from realistic data. Finally, we discuss some concluding remarks and future research.

2. Problem description and formulation

This section presents a detailed description of the combined fleet deployment and inventory management (FDIMP) problem for a ro–ro shipping company which offers integrated logistics services to automobile manufacturers for overseas shipment of finished vehicles on a regular basis.

The shipping company serves a given set of pre-defined trade routes. A trade route consists of a given sequence of ports, which are assumed to remain fixed during the planning horizon. A certain number of voyages are pre-planned for each trade route in the planning horizon, e.g. on a weekly or biweekly basis. It is assumed that any ship that serves a voyage in a particular trade route follows the given sequence of ports. When serving a particular trade route, a ship starts its voyage at the first port of the trade route, travels to successive ports for loading/discharging cargo and finishes the voyage at its last port. Then the ship may serve another voyage in the same trade route, or another trade route, or end its service in the planning horizon. To serve another voyage it might need to sail in ballast (i.e. empty) to the first port of the next voyage. We consider deterministic sailing times for each ship between the destination of one route and the origin of another route and also along successive ports in a route. It is assumed that the loading/discharging times in case of a ro–ro ship are minor compared to the sailing times. Variable waiting times for starting voyages are allowed, but not between successive ports while serving a voyage in a trade route. For each voyage on a trade route, there exists a time window for the earliest and latest start of the voyage. We assume a given service speed for each ship between a pair of ports.

There are costs associated with performing the voyages. When a ship from the shipping company sails a voyage, variable costs including the ships fuel consumption costs, port, and canal costs are incurred. All costs depend on the ship characteristics such as size and fuel consumption. The shipping company has the option to charter available ships from the market to serve a voyage at a charter cost. These ships are referred to as spot ships. It is assumed that spot ships are readily available to serve any voyage during the planning period. It is common in this business that the shipper owns the cargo until the car is delivered to its customer. This means that the cargo is in the shippers inventory at the origin port, while in transport between the origin and destination ports, as well as at the destination port. Therefore, the inventory costs can be considered as a sunk cost (since we do not consider manufacturing and/or sales decisions), and can hence be disregarded. This is consistent with most of the literature on maritime inventory routing.

The shipping company offers integrated inventory management and maritime transportation services to its clients. We use the term cargo for a group of car types produced in the same origin port and consumed in the same destination port and transported on the same trade route on one or several voyages. Each cargo has a given production/consumption rate at the associated ports, which may vary by the day. A particular ro–ro ship has a fixed capacity in terms of the number of vehicles it can carry on-board at any time. Similarly, a particular port served by the company has a storage capacity in terms of maximum number of vehicles it can hold at any time. Although the storage spaces in the ports as well as on-board the ships are common for all cargoes, the problem represents a multiple product transportation planning problem. This is because each cargo needs to be considered as a separate product with paired origin–destination. Spot cargoes are disregarded, because we consider just the shipments and transportation of the cargoes for which the shipping company manages the complete maritime logistics. At each port the company manages a set of cargoes, some of which may be produced cargoes meant for export and others may be meant for consumption. Cars are very seldom transshipped in ro–ro shipping, so we disregard the possibility of transshipment.

When the shipping company serves a voyage under a given schedule with a ship from its fleet having a certain capacity, it may not be feasible to fulfill all the transportation demands during this period. To avoid the possibilities of inventory limit violations or demand backlogging in any port of the trade route, a part of cargo shipment may be fulfilled by using spot capacity available in the market. To ensure maximum utilization of the shipping companies own fleet, such shipments are penalized.

The objective of the problem is to find the optimal deployment of a fleet of ships to a given set of pre-defined trade route voyages along with inventory management of cargoes at production and consumption ports in their respective trade routes. In other words, an underlying mathematical model should determine the routes and schedules of each ship, i.e. which ships should perform which voyages and in which sequence, the start time of each voyage, which voyages should be served by spot ships, and the quantity of each cargo to be loaded/discharged at an associated port during a voyage, in order to minimize the costs of transportation and chartering of spot ships. The above objective has to be achieved keeping into consideration that all voyages are serviced within their given time windows, the aggregate inventory limit of all cargoes in a particular port should not exceed the maximum storage limit and there is no backlogging of demand for any commodity in any of the ports.

FDIMP is a tactical planning problem with a planning horizon from a few months to one year. The total time period in the planning horizon is divided into periods of equal length. Each period typically has a length of one day, which seems appropriate for the operations involved, although periods of smaller length can easily be considered. The notation used in the model is presented in the following subsection for easy reference.

2.1. Notations

2.1.1. Indices

v	ship operated by the shipping company
r,q	trade route served by the company
p	port
c	cargo (group of car types)
t,w	time period in the planning horizon
i, j	voyage number associated with a trade route
p_c^O	origin port of cargo c
p_c^D	destination port of cargo c
a	travel arc (sailing leg) connecting two voyages across two time periods, $((r,i,t), (q,j,w))$
o_v	origin location of ship v
d_v	artificial destination of ship v

2.1.2. Sets

$\mathcal{T}$	set of discrete time periods in the planning horizon, $\{0, 1, 2, 3, \ldots, \lvert\mathcal{T}\rvert\}$
$\mathcal{V}$	set of ships operated by the shipping company
$\mathcal{R}$	set of geographical trade routes served by the shipping company
$\mathcal{R}_v$	set of trade routes feasible for ship v
$\mathcal{R}_p$	set of trade routes in which port p is included
$\mathcal{I}_r$	set of voyages for trade route r
$\mathcal{P}$	set of ports across all the trade routes served by the shipping company
$\mathcal{P}_r$	set of all ports belonging to a trade route r
$\mathcal{P}_r^O$	set of loading ports in trade route r
$\mathcal{P}_r^D$	set of discharge ports in trade route r
$\mathcal{C}_r$	set of cargoes associated with trade route r
$\mathcal{C}_{rp}$	set of all cargoes associated with port p in trade route r
$\mathcal{C}_{rp}^O$	set of cargoes originating at port p of route r
$\mathcal{C}_{rp}^D$	set of cargoes destined for port p of route r
$\mathcal{N}$	set of all feasible nodes, defined as, $\mathcal{N} = \{(r, i, t) \mid r \in \mathcal{R},\ i \in \mathcal{I}_r,\ t \in \mathcal{T}\}$
$\mathcal{N}_v$	set of all nodes feasible to ship v
$\mathcal{A}_v$	set of feasible travel arcs for ship v, $\mathcal{A}_v = \{((r, i, t), (q, j, w)) \mid r, q \in \mathcal{R}_v,\ i \in \mathcal{I}_r, j \in \mathcal{I}_q;\ t, w \in \mathcal{T} : w \geqslant t + T_{vr} + T_{vrq}^B\}$

2.1.3. Parameters

$\overline{Q}_v$	maximum cargo carrying capacity of a ship v, in terms of number of vehicles it can carry
P_{rpct}	number of units of cargo c produced/consumed in port p of trade route r in time period t
$\bar{I}_p$	maximum storage capacity at port p
T_{vrp}	sailing time for ship v from first port of trade route r to port p in the same trade route
T_{vr}^O	sailing time for ship v from its origin to the first port of trade route r
T_{vr}	sailing time for ship v to complete trade route r
T_{vrq}^B	sailing time for ship v to complete the ballast leg between trade route r and trade route q
E_{ri}	start of time window of voyage i of trade route r
L_{ri}	end of time window of voyage i of trade route r
C_{vrq}	cost of performing a voyage on trade route r and sailing the ballast leg between route r and route q by ship v
C_{vr}^O	cost of sailing from ship v's initial position to the first port of trade route r
C_{vr}^E	cost of performing the last voyage for ship v on trade route r
C_{ri}^S	cost of assigning a spot ship to voyage i of trade route r
I_{rpc}^0	initial inventory of cargo c at port p of trade route r
C^P	penalty cost per unit of using spot service to transport a cargo

2.1.4. Decision variables

x_{va}	1, if ship v traverses an arc a, 0 otherwise
s_{ri}	1, if voyage i of route r is assigned to a spot ship, 0 otherwise
q_{vrpct}	quantity of cargo c loaded/discharged by ship v at port p on trade route r during time period t
i_{rpct}	inventory level of cargo c in port p belonging to trade route r at the end of time period t
l_{vt}	total load on-board ship v at the end of time period t
i_{rpct}^+	excess inventory of cargo c in port p belonging to trade route r, assigned for spot pick-up in time period t
i_{rpct}^-	shortfall inventory of cargo c in port p belonging to trade route r, assigned for spot delivery in time period t

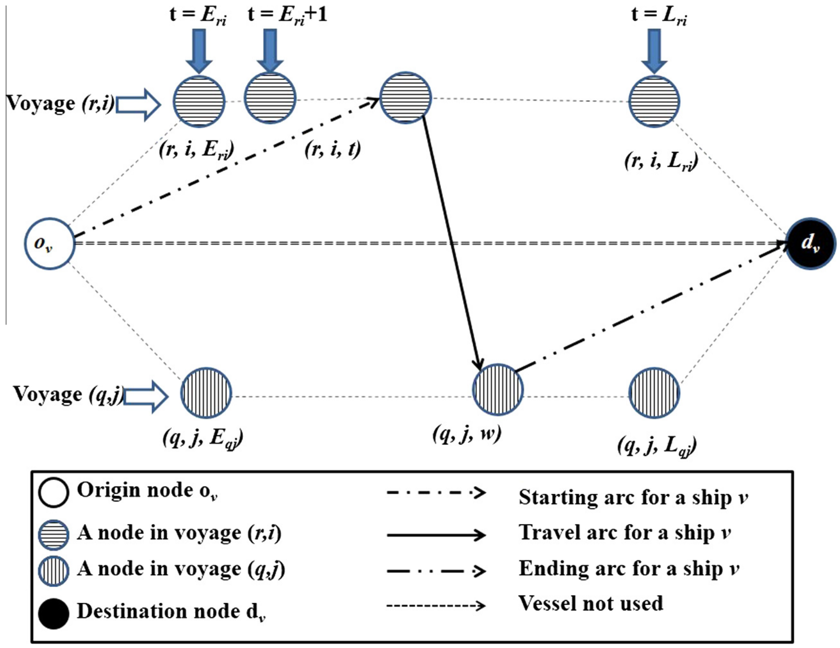

Fig. 2. Illustration of the discrete time–space network.

To model the FDIMP, we use a time expanded network consisting of arcs and nodes. A network is defined for each ship $v \in \mathcal{V}$. As illustrated in Fig. 2, a node in the network is defined as (r, i, t) and visiting the node denotes that voyage number i for trade route r starts at time t. Fig. 2 also illustrates the nodes o_v and d_v, where node o_v is the initial position, while d_v is the artificial destination of ship v. d_v corresponds to the last port of the last voyage performed by ship v. The interval $[E_{ri}, L_{ri}]$ represents the time window for the start of service of a particular voyage (r, i). A node, $n = (r, i, t)$, is defined for time periods within the given time window only, i.e. $t \in \{E_{ri}, E_{ri}+1, \ldots L_{ri}\}$. The arcs between the nodes, represented by a, denote the ballast sailing between the voyages. There are primarily four types of arcs for each ship $v \in \mathcal{V}$. The first type of arcs, defined as $a = (o_v, (r, i, t))$, links the origin o_v of ship v to node (r, i, t). These arcs will be feasible and defined only when t is greater than or equal to T^O_{vr}. Arcs of the second type connect two nodes corresponding to actual voyages, defined as $a = ((r, i, t), (q, j, w))$. This type of arc is feasible when the time period w is greater than or equal to $(t + T_{vr} + T^B_{vrq})$ and lies in the range $[E_{qj}, L_{qj}]$. The third type of arcs links a node corresponding to an actual voyage to the artificial destination node d_v, defined as $a = ((r, i, t), d_v)$. The last type of arcs links directly the origin node o_v to the artificial destination node d_v. It denotes the possibility that the ship v remains unused during the planning horizon. Although a network is defined for each ship v, most nodes and arcs are common for all the ships. Each ship has its own set of nodes and arcs owing to the different initial positions and sailing speeds of different ships.

Now the mathematical formulation for the FDIMP can be defined as follows.

2.2. Mathematical model

$$\begin{aligned} \textit{minimize} \quad z = & \sum_{v\in\mathcal{V}} \sum_{(r,i,t)\in\mathcal{N}_v} C^O_{vr} x_{v(o_v,(r,i,t))} + \sum_{v\in\mathcal{V}} \sum_{(r,i,t)\in\mathcal{N}_v} C^E_{vr} x_{v((r,i,t),d_v)} + \sum_{v\in\mathcal{V}} \sum_{((r,i,t),(q,j,w))\in A_v} C_{vrq} x_{v((r,i,t),(q,j,w))} + \sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{I}_r} C^S_{ri} s_{ri} \\ & + C^P \sum_{r\in\mathcal{R}} \sum_{p\in\mathcal{P}_r} \sum_{c\in C_{rp}} \sum_{t\in\mathcal{T}} (i^+_{rpct} + i^-_{rpct}) \end{aligned} \quad (1)$$

Subject to:

$$\sum_{(r,i,t)\in\mathcal{N}_v} x_{v(o_v,(r,i,t))} = 1, \quad \forall v \in \mathcal{V} \quad (2)$$

$$\sum_{(r,i,t)\in\mathcal{N}_v} x_{v((r,i,t),d_v)} = 1, \quad \forall v \in \mathcal{V} \quad (3)$$

$$\sum_{(q,j,w)\in\mathcal{N}_v} x_{v((q,j,w),(r,i,t))} - \sum_{(q,j,w)\in\mathcal{N}_v} x_{v((r,i,t),(q,j,w))} = 0, \quad \forall v \in \mathcal{V}, (r,i,t) \in \mathcal{N}_v \setminus \{o_v, d_v\} \quad (4)$$

$$\sum_{v\in\mathcal{V}}\sum_{(q,j,w)\in\mathcal{N}_v}\sum_{t\in\mathcal{T}} x_{v((r,i,t),(q,j,w))} + s_{ri} = 1, \quad \forall r\in\mathcal{R}, i\in\mathcal{I}_r \tag{5}$$

$$q_{vrpct} \leqslant \overline{Q}_v \sum_{i\in\mathcal{I}_r}\sum_{\substack{t'\in\mathcal{T}:\\ t=t'+T_{vrp}}}\sum_{(q,j,w)\in\mathcal{N}_v} x_{v((r,i,t'),(q,j,w))}, \quad \forall v\in\mathcal{V}, r\in\mathcal{R}_v, p\in\mathcal{P}_r, c\in C_{rp}, t\in\mathcal{T} \tag{6}$$

$$q_{vrp_c^O ct} = q_{vrp_c^D ct'}, \quad \forall v\in\mathcal{V}, r\in\mathcal{R}_v, c\in\mathcal{C}_r, t\in\mathcal{T} : t' = (t + T_{vrp_c^D} - T_{vrp_c^O}) \tag{7}$$

$$i_{rpc0} = \mathcal{I}^O_{rpc}, \quad \forall r\in\mathcal{R}, p\in\mathcal{P}_r, c\in\mathcal{C}_{rp} \tag{8}$$

$$i_{rpc(t-1)} - \sum_{v\in\mathcal{V}} q_{vrpct} + P_{rpct} - i_{rpct} - i^+_{rpct} + i^-_{rpct} = 0, \quad \forall r\in\mathcal{R}, p\in\mathcal{P}^O_r, c\in\mathcal{C}^O_{rp}, t\in\mathcal{T} \tag{9}$$

$$i_{rpc(t-1)} + \sum_{v\in\mathcal{V}} q_{vrpct} - P_{rpct} - i_{rpct} - i^+_{rpct} + i^-_{rpct} = 0, \quad \forall r\in\mathcal{R}, p\in\mathcal{P}^D_r, c\in\mathcal{C}^D_{rp}, t\in\mathcal{T} \tag{10}$$

$$l_{v0} = Q^O_v, \quad \forall v\in\mathcal{V} \tag{11}$$

$$l_{v(t-1)} + \sum_{r\in\mathcal{R}_v}\sum_{p\in\mathcal{P}^O_r}\sum_{c\in\mathcal{C}^O_{rp}} q_{vrpct} - \sum_{r\in\mathcal{R}_v}\sum_{p\in\mathcal{P}^D_r}\sum_{c\in\mathcal{C}^D_{rp}} q_{vrpct} - l_{vt} = 0, \quad \forall v\in\mathcal{V}, t\in\mathcal{T} \tag{12}$$

$$\sum_{r\in\mathcal{R}_p}\sum_{c\in\mathcal{C}_{rp}} i_{rpct} \leqslant \bar{I}_p, \quad \forall p\in\mathcal{P}, t\in\mathcal{T} \tag{13}$$

$$l_{vt} \leqslant \overline{Q}_v, \quad \forall v\in\mathcal{V}, t\in\mathcal{T} \tag{14}$$

$$s_{ri} \in \{0,1\}, \quad \forall r\in\mathcal{R}, i\in\mathcal{I}_r \tag{15}$$

$$x_{v((r,i,t),(q,j,w))} \in \{0,1\}, \quad \forall v\in\mathcal{V}, ((r,i,t),(q,j,w))\in\mathcal{A}_v \tag{16}$$

$$q_{vrpct} \geqslant 0, \quad \forall v\in\mathcal{V}, r\in\mathcal{R}_v, p\in\mathcal{P}_r, c\in\mathcal{C}_{rp}, t\in\mathcal{T} \tag{17}$$

$$l_{vt} \geqslant 0, \quad \forall v\in\mathcal{V}, t\in\mathcal{T} \tag{18}$$

$$i_{rpct}, i^+_{rpct}, i^-_{rpct} \geqslant 0, \quad \forall r\in\mathcal{R}, p\in\mathcal{P}_r, c\in\mathcal{C}_{rp}, t\in\mathcal{T} \tag{19}$$

The objective function (1) minimises the total cost consisting of the costs of initial ballast sailings, the costs associated with performing voyages and the ballast sailings to successive voyages, costs of assigning voyages to spot ships and costs of assigning spot shipments. The last penalty term is included to avoid excess inventory and stock-out during the planning horizon. Constraints (2) ensure that a ship leaves its origin to go to another node, i.e. to serve another voyage or end its route by going to the artificial destination node, d_v. Constraints (3) force the ship to end its journey at the artificial destination node. Constraints (4) are the flow conservation constraints ensuring that the same ship arrives and leaves a particular node. Constraints (5) ensure that all voyages are performed, either by a ship in the fleet or by a spot ship. Constraints (6) and (7) define feasible loading and discharging quantities at each port in the network. A ship v can load or discharge cargoes at any port of a trade route r in a particular time period, if and only if it serves a voyage on that trade route scheduled during this time period. Thus we need to link the arrival of a ship at the first port of a trade route, denoted by time t', to the start time for loading or discharging, denoted by t, at each successive port in the same trade route. A particular cargo c to be served in a voyage is always associated with a pair of ports, an origin port p^O_c and a destination port p^D_c. Constraints (7) force the amount of cargo c loaded at its origin port p^O_c by a particular ship at a time t to be equal to the amount of cargo c discharged at its destination port p^D_c at time t', where t' and t are related by the sailing time of the ship between the two ports.

Constraints (8)–(10) represent the inventory balance constraints for the individual cargoes at each port. Constraints (8) are the initial conditions for the inventory level for each cargo in each port and trade route. Constraints (9) and (10) derive the inventory level on subsequent periods based on the production/consumption level and the loading/discharging quantities, respectively, in the immediately preceding periods. In a trade route, a particular loading port for some cargo may also be a discharge port for some other cargo. So, a particular port belonging to a given trade route may act as both loading and discharge port for different cargoes.

We do not explicitly calculate the shipments and timings related to spot assignments. Further, it might not always be feasible to fulfil all the transportation demands. In reality it is not very rare to use spot services of other shipping companies to transport a small load of cargo between a pair of ports along a route. We are implicitly modelling this by adding the variable i^+_{rpct} and deducting a variable i^-_{rpct} to the actual inventory variable i_{rpct} in the constraints. i^+_{rpct} represents the surplus production inventory meant to be served by spot shipping and i^-_{rpct} represents the demand shortfall at a discharge port. In the optimal solution of the mathematical model, maximum of one of these turns out to be greater than zero for a particular cargo and time period. Here we penalize these variables with high costs in the objective function (1) to minimize the requirements of spot shipping to serve the cargo.

We assume that a ship completes all the cargo transportation meant for a trade route during a voyage and finishes the voyage empty. Initial shipload is given by initial load on-board a ship, as shown by constraints (11). Constraints (12) calculate the total load onboard each ship in each time period. Constraints (13) ensure that the cargoes stored at a port are within the inventory capacity limits in each time period. These constraints consider the fact that a port can be part of several trade routes. Constraints (14) make sure that the total load onboard a ship at any time period should not exceed the maximum available capacity of the ship. Finally, constraints (15)–(19) enforce the binary and non-negativity conditions on the respective decision variables.

3. Example for illustration

To illustrate the FDIMP and the model described in Section 2, a simple example is presented. The example, as presented in Fig. 3, consists of two routes, r and q and two ships, v_1 and v_2.

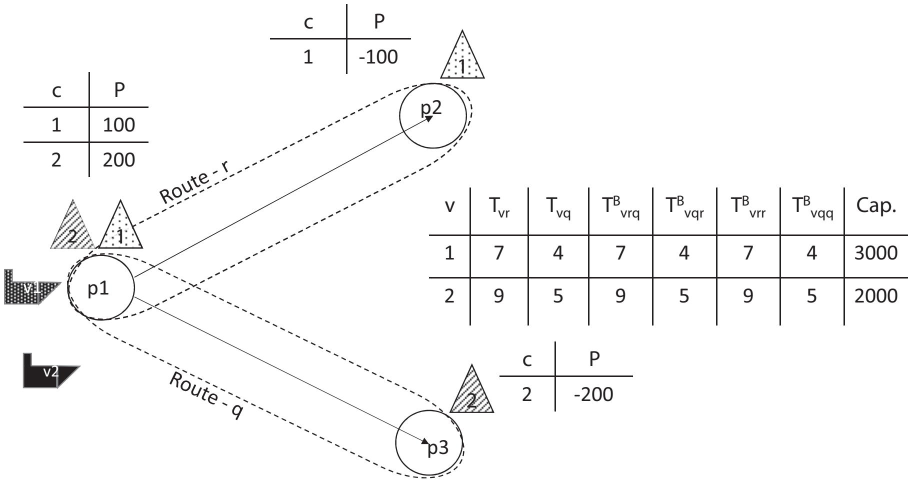

Fig. 3. Test problem for illustration.

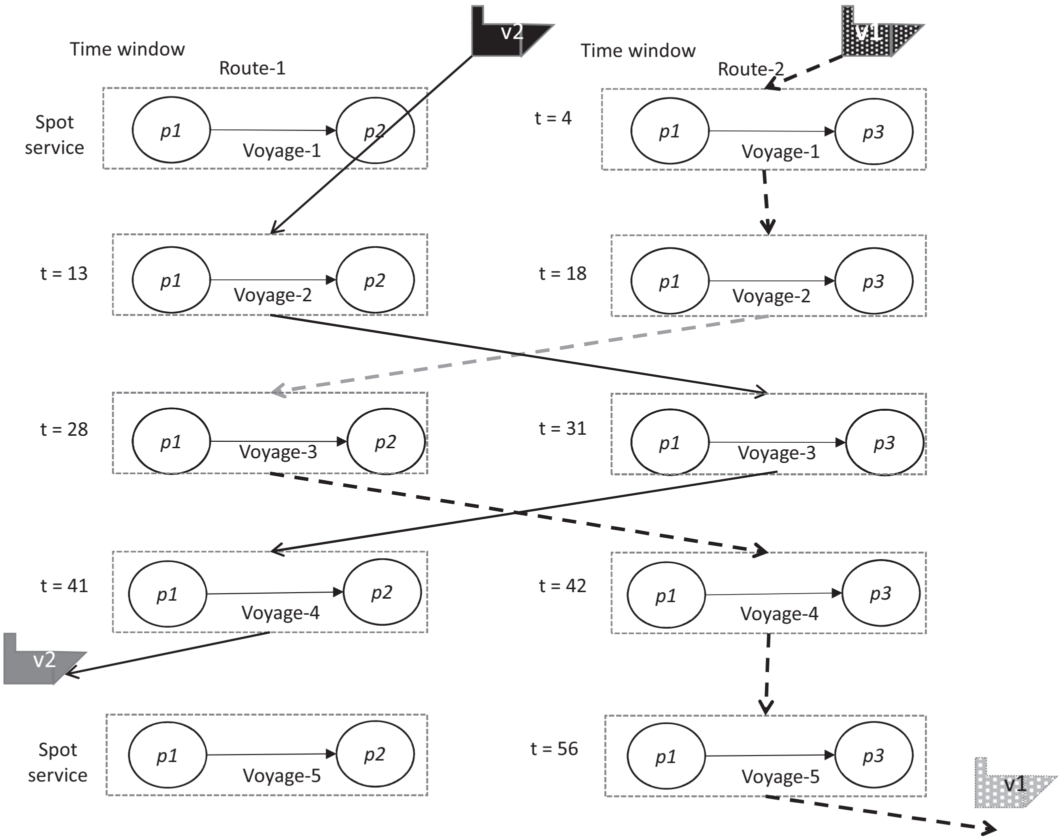

Fig. 4. Optimal fleet deployment planning for test problem.

Table 1
Quantities loaded/discharged during voyages.

Ship	Time	Route	Port	Cargo	q_{vrpct}	Ship	Time	Route	Port	Cargo	q_{vrpct}
1	4	2	1	2	800	2	13	1	1	1	1300
	8	2	3	2	−800		22	1	2	1	−1300
	18	2	1	2	2800		31	2	1	2	2000
	22	2	3	2	−2800		36	2	3	2	−2000
	28	1	1	1	1500		41	1	1	1	1100
	35	1	2	1	−1500		50	1	2	1	−1100
	42	2	1	2	2800						
	46	2	3	2	−2800						
	56	2	1	2	700						
	60	2	3	2	−700						

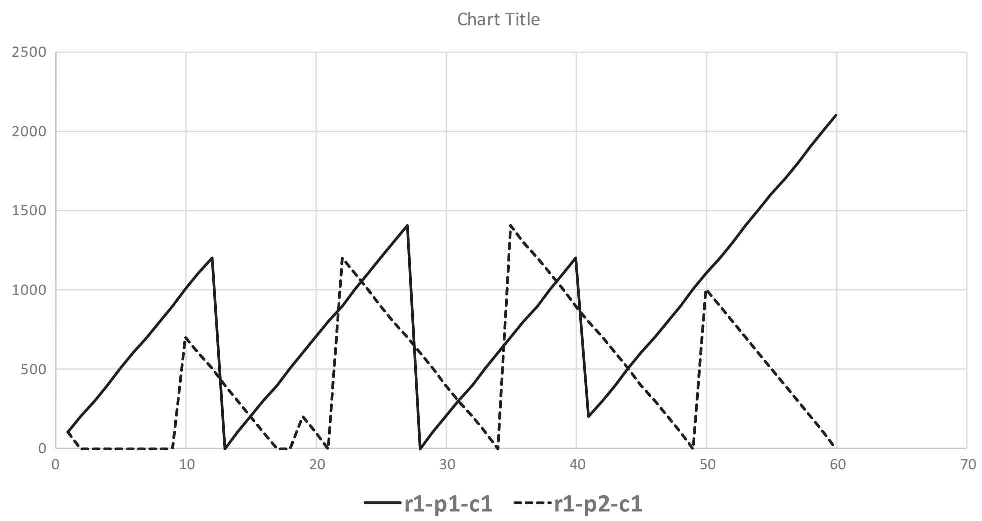

Fig. 5. Inventory levels of cargo c_1 at the loading and discharge ports on trade route r during the planning horizon.

Route r consists of two ports, p_1 and p_2, where p_1 is the loading port and p_2 the discharge port. There is only one cargo associated with these two ports, represented as c_1. Per day production and consumption of cargo c_1 at ports p_1 and p_2, respectively, is 100 units. Similarly, cargo c_2 is handled on trade route q, with loading port as p_1 and discharge port as p_3. The production and consumption of cargo c_2 at ports p_1 and p_3, respectively, is 200 units per day. Ships v_1 and v_2 have maximum carrying capacities of 3000 units and 2000 units, respectively. It takes seven days for ship v_1 to complete a voyage on trade route r and four days to complete a voyage on trade route q. The ballast sailing time between the two routes and corresponding times for ship v_2 are given in tabular form in Fig. 3. Ship v_1 is initially situated at port p_1 and ship v_2 is near to port p_1 by a days travel duration. The maximum storage capacities for the three ports p_1, p_2 and p_3 are 5000, 3000 and 3000, units respectively. The initial inventory of each cargo at the loading ports is 0 units and at the discharge ports is 200 units at the beginning of the planning horizon. A planning horizon of 60 days is considered for this example. A voyage is scheduled on each route every 15th day starting from the first day of the planning horizon. A time window of ±4 days is considered for each voyage.

Fig. 4 gives the optimal solution to the fleet deployment in terms of voyages served by each ship and start times of each voyage.

The extension of the fleet deployment problem considered in this paper calculates the quantities to be loaded or discharged at each port during the voyages in order to ensure that the inventory levels are within the storage limits at the various ports. The quantities loaded and discharged by each ship along the trade routes are given in Table 1. Fig. 5 presents the variation in inventory levels of cargo c_1 at the loading port p_1 and discharge port p_2 across the timeline. The flat parts in the inventory level curve for port p_2 represent cargo shipments fulfilled by spot.

4. A rolling horizon heuristic

The FDIMP is too large and complex to be solved in reasonable time by a MIP based commercial solver. In the literature, rolling horizon heuristics (RHHs) have been proposed as a suitable solution technique for complex, multi-period MIP models. Applications of RHH can be found in Stauffer and Liebling (1997) for a rolling-mill and in Mercé and Fontan (2003) for capacitated lot sizing application. There are also some successful implementations of RHHs in the maritime routing literature. Sherali et al. (1999) discuss two rolling horizon algorithms for an oil tanker routing and scheduling problem. There, good quality solutions for large intractable problem instances could be achieved. Rakke et al. (2011) report good quality solutions in reasonable solution time from the implementation of RHHs to a liquefied natural gas inventory routing problem. Furthermore, Andersson et al. (2015) present an RHH as a good solution approach to a fleet deployment problem in ro–ro shipping.

The RHH is an iterative, MIP based heuristic, and it uses a branch-and-bound technique to solve shorter sub-horizons of the main problem at a time, while moving ahead in the planning horizon in incremental steps. In the next sub-section, we describe the implementation of this heuristic to FDIMP.

The RHH is an iterative heuristic where the entire planning horizon or period (TP) is divided into three sections at each particular iteration, k: The beginning section, denoted by TP_k^B, the central section, denoted by TP_k^C, and the forecasting section, denoted by TP_k^F. The overall model is similar to the original MIP formulation for the FDIMP, although the model is modified according to some rules for each section to make it easier to solve. The central section TP_k^C is the main planning section and has the same model structure as in the original formulation described in Section 2. Let us denote the length of this section, in periods, by T^C. In the beginning section TP_k^B, the planning is considered partly frozen with solutions obtained from the previous iteration, i.e. a subset of the decision variables associated with this period is fixed to their values obtained in the last iterations. In the last (forecasting) section TP_k^F, the model is relaxed as per a simplification strategy. After the modifications are incorporated for each section, as described above, the model is solved as a MIP for the three sections. In the next iteration $k+1$, TP_k^C is moved ahead by T^C periods or the length of the forecasting period, whichever is shorter. The iterations are continued until we are able to freeze the values of all variables for the entire planning horizon. The whole procedure is illustrated in Fig. 6.

In the FDIMP, the ship routing variables $x_{v((r,i,t),(q,j,w))}$ are the main binary decision variables in the model. Binary variables related to voyages served by spot ships are dependent on the ship routing variables and were not explicitly modified. As our freezing strategy in the beginning section TP_k^B, we freeze the values of these binary variables. Similarly, these variables are relaxed to continuous variables in the forecasting section TP_k^F. Furthermore, as in Andersson et al. (2015), we have chosen 30 days as the length of the central section, while the forecasting section consists of the remaining periods until the end of the planning horizon. The beginning section consists of all periods until the central section.

The pseudo code for the heuristic is presented as Algorithm 1.

Algorithm 1. Rolling horizon heuristic algorithm

procedure ALGORITHM – RHH
  $k \leftarrow 1$
  $t_1 \leftarrow 1$
  $t_2 \leftarrow T^C$
  $TP_k^B \leftarrow \emptyset$
  $TP_k^C \leftarrow [t_1, t_2]$
  $TP_k^F \leftarrow [t_2, |\mathcal{T}|]$
  while $t_2 \leqslant |\mathcal{T}|$ **do**
    if $k > 1$ **then**
      for $w \in TP_k^B$ **do**
        Freeze the values of $x_{v((r,i,t),(q,j,w))}$ variables to the values obtained in the last solution
      end for
    end if
    for $w \in TP_k^C$ **do**
      Consider the $x_{v((r,i,t),(q,j,w))}$ variables as binary
    end for
    for $w \in TP_k^F$ **do**
      Relax all binary variables as continuous variables
    end for
    Solve the FDIMP model with the above modifications
    $k \leftarrow k+1$
    $t_1 \leftarrow t_1 + T^C$
    $t_2 \leftarrow t_2 + T^C$
    $TP_k^B \leftarrow [1, t_1]$
    $TP_k^C \leftarrow [t_1, t_2]$
    $TP_k^F \leftarrow [t_2, |\mathcal{T}|]$
  end while
end procedure

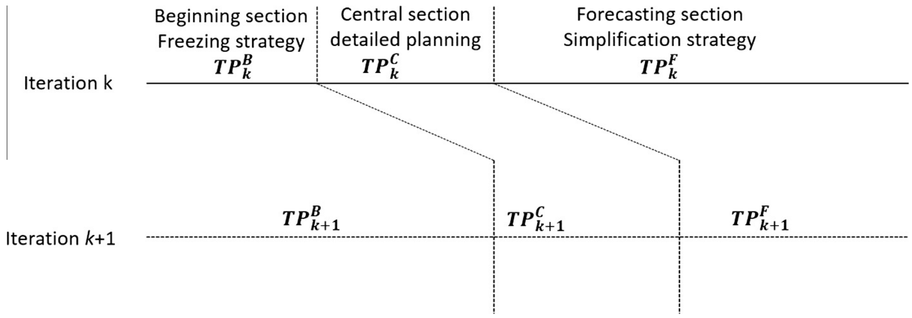

Fig. 6. Overview of the RHH iterations with moving sub-horizons.

5. Computational study

The mathematical model presented in Section 2.2 and the RHH solution technique described in Section 4 have been implemented in IBM CPLEX 12.6.2 (academic version) with Python 2.7.10 programming language. All computational tests are performed using a DELL Precision T5610 with Intel Xeon CPU E5-2620 v2 @ 2.10 GHz 6 cores CPUs and 32.0 GB RAM.

5.1. Test instances

Six test instances with 3/1, 5/2, 10/3, and 24/5 ships/trade routes, respectively, have been generated and used in the computational study. These test instances are reduced versions of a real sized problem faced by a ro–ro shipping company, which operates more than 50 ships and serves nine trade routes. This means that the information on routes and ports with respective sea distances and corresponding sailing times and costs are derived from real data. Other data like ship capacities, number of voyages in each trade route during the planning horizon, time windows for starting the voyages, cargoes traded within a trade route and daily demand/consumption data of respective cargoes at each port are estimated or calculated by the authors. Ship capacities are estimated as a random number varying between 5000 and 7500 units of a standard size vehicle. The number of cargoes in a trade route is estimated as the number of origin–destination pairs, and, for all these cargoes, inventory management is considered at both the origin and the destination ports. The daily production or consumption units of a cargo at the respective ports are estimated as a random number between 80 and 200 units of cargo. Any mismatch between fleet capacity and excess transportation requirement is taken care of by expensive spot shipments, incorporated as slack capacity in the mathematical model. The cost associated with assigning a whole voyage to a spot ship is roughly estimated to be almost double the regular cost of serving the voyage with a ship from the companys fleet. Planning horizons of 4 and 6 months are tested for computational performance. Table 2 summarizes the test instances developed for the computational study. The instances are named according to the number of ships (v), trade routes (r), and length of the planning horizon (t). For each test instance, the number of ships, trade routes, voyages, ports, cargoes, and length of planning horizon (in months) are given.

5.2. Computational results

The computational results for solving the MIP model are presented in Table 3. The size of the model for each of the instances is presented in terms of number of constraints, binary variables and non-zero coefficients. Furthermore, Table 3 gives details related to the best MIP solution obtained, the best lower bound, the integer gap (in %) and computational time (in seconds). The reported computational times include the time to read the data, load the optimization model and the running time to find the best reported solution. Each instance was run for a maximum of 24 h solution time. The run timings

Table 2
Test instances used in the computational study.

Test instance	# ships	# trade routes	# voyages	# ports	# cargoes	Planning horizon (months)
3v1r4t	3	1	16	11	49	4
3v1r6t	3	1	24	11	49	6
5v2r4t	5	2	32	18	112	4
5v2r6t	5	2	48	18	112	6
10v3r4t	10	3	48	23	128	4
24v5r4t	24	5	80	32	165	4

Table 3
Computational results from the MIP model for the test instances.

Test instance	Problem size (MIP)			Best MIP solution	Best LB	Integer Gap (%)	Time (sec)
	# Constr.	# Binary var.	# N.Z. coeff.				
3v1r4m	57,615	9302	64,067	56.54	56.54	0.00	136
3v1r6m	478,014	22,692	214,718	79.40	66.42	19.60	87,196
5v2r4m	194,981	30,151	145,403	125.90	125.90	0.00	1679
5v2r6m	284,032	45,513	396,868	140.70	127.91	10.00	91,712
10v3r4m	477,627	386,265	26,678,768	182.76	125.36	31.40	89,800
24v5r4m	757,441	464,923	34,859,804	216.33	188.31	14.90	142,707

Table 4
RHH solution results.

Instance	Best solution	Gap from best lower bound (%)	Time (sec)
3v1r4m	56.54	0.00	143
3v1r6m	79.40	19.60	55,432
5v2r4m	125.90	0.00	1,764
5v2r6m	141.04	10.26	49,664
10v3r4m	146.65	17.00	77,078
24v5r4m	216.40	14.90	81,803

shown in Table 3 include model building time in CPLEX, so are in some cases more than a day. The MIP model could be solved to optimality for the two smallest instances, 3v1r4t and 5v2r4t, within reasonable solution times. For the other four instances, we found feasible integer solutions and reported the lower and upper bounds as well as the integer gaps. The computational results show that the run time increases dramatically with increase in number of binary variables and non-zero coefficients in the model. Moreover, the size of the model as well as the computational times increase with an increased length of the planning horizon. For test instances involving 10 or more ships and a planning horizon of 6 months, the commercial solver could not even build the complete MIP model within 24 h. So, these instances are not presented in Table 3.

Table 4 presents the results of the rolling horizon heuristic algorithm on the six problem instances. The integer gap here is calculated based on the lower bound achieved when solving the MIP model. When comparing the RHH results in Table 4 with the MIP results in Table 3, several inferences can be drawn. For small test instances with 3 and 5 ships and 4 months planning horizon, the RHH solution times are comparable to the MIP solution times. For these instances RHH could also provide optimal solution values like the MIP solver. For larger test instances with 10 and 25 ships and 4 months planning horizon and for those instances involving a 6 months planning horizon, the RHH gives either comparable or better solutions than the MIP solver in lesser run time.

6. Conclusions and future work

With the emergence of ro–ro shipping companies offering integrated maritime logistics services to clients, it becomes pertinent to develop integrated models for logistics planning. In this regard, we propose a mathematical model for addressing the integrated planning of inventory, cargo shipments and ship routing on various trade routes served by a ro–ro shipping company. This modelling approach combines inventory management at the ports of vendor managed cargo served by the ro–ro shipping company with optimal fleet deployment of available ships to the given voyages on various trade routes served by the company. The planning problem is called a fleet deployment and inventory management problem (FDIMP). We have presented a small example that illustrates the various elements of the problem and the underlying model.

Test instances are created from real planning problems of a ro–ro shipping company. Out of the six test instances, only two instances could be solved to optimality. The computational results showed that the RHH obtained good solutions within shorter run times and performed better than solving the problem by a commercial MIP solver for all instances of realistic size.

The FDIMP is a complex problem, so there are several interesting directions for future research. In order to find optimal (or near optimal) solution, the focus should be on exact techniques for solving the planning problem. The FDIMP consists of a fleet deployment problem and a multi-commodity inventory management problem, and it would be interesting to study different decomposition approaches. Furthermore, the possibility of tightening the formulation and introducing suitable cuts could also be explored for the problem. In order to solve large instances of the problem and get good solutions, advanced heuristics should be developed.

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