Journal of Optimization in Industrial Engineering Vol.12, Issue 1, Winter and Spring 2019, 151- 165
DOI: 10.22094/JOIE.2018.544109.1517

An Integrated Approach for Facility Location and Supply Vessel Planning with Time Windows

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Received 23 September 2017; Revised 24 December 2017; Accepted 08 February 2018

Abstract

This paper presents a new model of two-echelon periodic supply vessel planning problem with time windows mix of facility location (PSVPTWMFL-2E) in an offshore oil and gas industry. The new mixed-integer nonlinear programming (MINLP) model consists of a fleet composition problem and a location-routing problem (LRP). The aim of the model is to determine the size and type of large vessels in the first echelon and supply vessels in the second echelon. Additionally, the location of warehouse(s),optimal voyages and related schedules in both echelons are purposed. The total cost should be kept at a minimum and the need of operation regions and offshore installations should be fulfilled. A two-stage exact solution method, which is common for maritime transportation problems, is presented for small and medium-sized problems. In the first stage, all voyages are generated and in the second stage, optimal fleet composition, voyages and schedules are determined. Furthermore, optimal onshore base(s) to install central warehouse(s)and optimal operation region(s) to send offshore installation's needs are decided in the second stage.

***Keywords*:** Supply vessel planning; Offshore Oil and gas industry; Fleet composition; Location- routing problem.

1. Introduction

In this paper, a two-echelon periodic supply vessel planning problem with time windows (PSVPTWMFL-2E) is presented. The new model is an extension of the basic supply vessel planning (SVP) model. The location and routing decisions which are related to strategic and operational decisions, have critical rolesin a company's success(Jelodari and Setak, 2015).Since companies try to decrease transportation costs by using rational ways and effective tools, capacitated vehicle routing problem(CVRP) has been receiving much attention by researchersfor decades (Yousefi khoshbakht et al., 2015). On the other hand, the studies show that the location and routing decisions cannot be considered seprately.If they are considered independent it will cause suboptimal planning results (Kocu et al., 2016).

Location-routing problem(LRP) includes some facilities with the opening cost and a set of customeres with known demands. The aim of the basic LRP is to minimize the total cost of optimal location(s) of facilities, optimal number of vehicles and relates routes while the needs of customers are satisfied (Drexl and Schneider, 2015). LRP is an NP-hard combinatorial optimization problem.Then, different heuristic (meta-heuristic) algorithms have been introduced to solve and reduce the solution time of LRP; for instance, greedy randomized adaptive searsh procedure (GRASP)by Prins et al.(2006), genetic algorithm (GA) by Derbel et al.(2012), simulated annealing (SA) by Yu et al.(2010), adaptive large neighborhood searh (ANLS) by Hemmelmayr et al.(2012) and variable neighborhood search (VNS) by Jarboui et al.(2013). Also, there are a few exact methods to solve this kind of problems.The most important methods are a lower bound algorithm for the capacitated and uncapaciated LRP by Albareda-Sambola et al.(2005) and a branch-and-cut (B&C) algorithm by Belenguer et al.(2011).

A two-echelon LRP (LRP-2E) is known as one of the most difficult problems in LRPs.As it is shown in Fig 1, routes are designed to send requirements to the depots which should be located. The first echelon is made by these routes and the second echelon is made by the new routes from the selected depots to final customers (Prodhon and Prins,2014). The LRP-2E was studied for the first time by Jacobsen and Madsen (1980) in a newspaper distribution.

Optimal fleet composition mixed by designing voyages and schedules was presented by Fager holt and Lindstad (2000) as the SVP problem. The basic SVP model consisted of one onshore base to berth supply vessels and some offshore installations in order to produce oil and gas continuously in upstream. Upstream is one of the major parts of offshore oil and gas supply chain. Helicopters and supply vessels are the only ways to transport people and send requirements to offshore installations. Using helicopters to send requirements is very expensive, so supply vessels are supposed to carry materials, equipment

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and other consumables of installations and return their backloads to the onshore base. The purpose of the basic SVP model is to decide the number of supply vessels, related voyages and schedules to send needed requirements to offshore installations, while routing and fleet composition costs should be minimized. Fig 2 shows the basic SVP model.

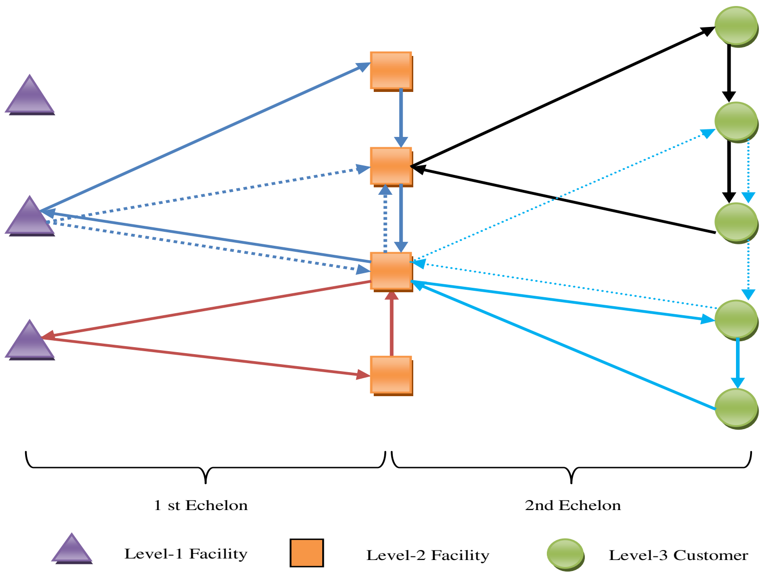

Fig. 1. Two-echelon location-routing problem

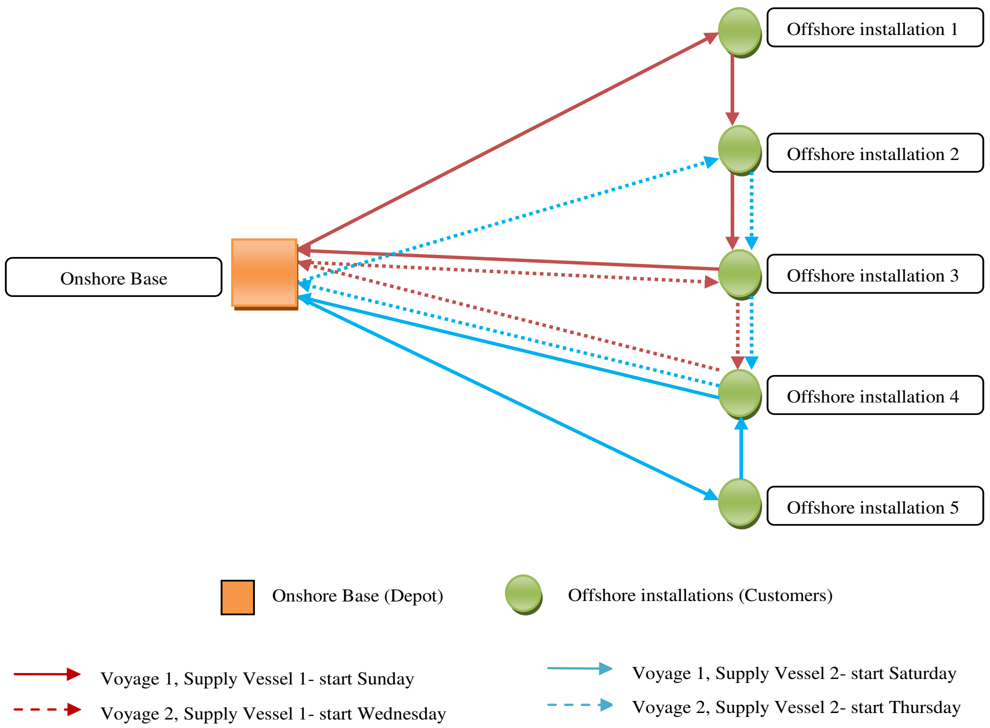

Fig. 2. Basic SVP model

Fagerholt and Lindstad (2000) presented the basic SVP model in a real project, which was requested by the Statoil Company that is the leading operator on the Norwegian continental shelf. In the model one onshore base and some offshore installations were considered. The main goal of the project was to analyze the effect of having some installations open during night. The results showed that by using the suitable scenario, the company can save about seven million dollars during a year. A as et al. (2007) studied the installation's capacity effect on the optimal routes. They presented a new mixed-integer linear not able to solve large instances.

programming (MILP)model for real-life cases, which was Gribkovskaia et al. (2007) considered pickup, delivery and backload in the basic SVP model. In the new model, supply vessels must start and finish their voyages at the same onshore base. The aim of the model was to keep the chartering and sailing costs at a minimum. Some heuristic algorithms and a tabu search (TS) algorithm were presented for large cases. Iachan (2009) presented a fleet composition and routing model for a special kind of supply vessels. The model was implemented in Petrobras (the biggest Brazilian oil company), which operates in exploration, production, refining, marketing and transportation oil and oil byproducts. A GA was used to solve the model. A as et al. (2009) studied loading and unloading capabilities and also capacity of supply vessels to reduce the total cost. These features in upstream logistics have a key role to decide on fleet composition. Shyshou et al. (2010) studied a simulation method to decide the optimal number of fleets for anchor handling operations in offshore mobile installations.

Halvorsen-Weare and Fagerholt (2011) presented a robust SVP model by considering several approaches. A simulation method was used to decide the optimal fleets. The result of computational study showed an improvement potential if some consideration was noticed. Halvorsen-Weare et al. (2012) presented a two-stage voyage-based approach to determine the optimal number and type of supply vessels, related voyages and schedules in the Statoil Company. The model consisted of different service time for installations during night. A what-if analysis in order to find the possibility of using one less supply vessel was conducted. Shyshou et al. (2012) presented an ALNS that its performance was as well as exact methods for small instances. Norlund et al.(2015) studied the speed of supply vessels as an important parameter.The results showed that considering robustness and reducing cost and emissions can not happen at the same time. A simulation-optimization method was used in this study.In another study by Christiansen et al. (2016), a real-life case of fuel supply vessels was pressented.In this model an arc-flow and a path-flow model were formulated. The results showed that the path-flow model had the better performance than the arc-flow model. Fuel supply vessels are supposed to feed large ships which are anchored in a port. Cuesta et al. (2017) introduced a new vehicle routing problem(VRP) with selective pickups and deliveries (VRPSPD) and a multi VRP with pickups and deliveries (MVRPPD) model. VRPSPD model needed less changes in the current planning and the computational study showed that it could be solved in a ratioanl time.

In thePSVPTWMFL-2Emodelwhich will be defined in the next section, some heterogeneous marine-vehicles with different speed, capacity and chartering cost are supposed. Also, some potential onshore bases in both echelons to locate onshore-base(s), with different capacity and opening costs are considered. The purpose of the model is to decide the optimal number and type of large and supply vessels, related voyages and schedules. Furthermore, locating the optimal onshore base(s) to install the central warehouse(s) in the first echelon and locating optimal operation region(s) to fulfilled final customer's needs are aimed.

The contributions of this paper are as follows. The PSVPTWMFL-2Eas an extension of the SVP problem is presented for the first time. In this model, some potential depots that should be located as the optimal onshore-base(s) in both echelons with different features (e.g., capacity) are considered. An optimal number and type of large vessels in upstream oil and gas supply chain are mentioned for the first time. Considering the model as a periodic problem in both echelons is another contribution of this paper. The other contributions of this paper are some novel real-life aspects (e.g., installing central warehouse(s) in optimal onshore base(s)).The methodology introduced by Halvorsen-Weare et al. (2012)was used in both echelons with some changes. Capacity limitation of large and supply vessels and the reliable length of voyages are considered in the mathematical model.

The rest of this paper is organized as follows. Section 2defines the problem. Section 3introduces the solution methodology. In Section 4, the computational results are shown. Finally, Section 5 provides the conclusions.

2. Problem Definition

In this section, the new model of two-echelon periodic supply vessel planning problem with time windows mix of facility location (PSVPTWMFL-2E) is presented. On shore bases, operation regions and offshore installations make three dependent levels in the new model (Fig 3).

In the first level (i.e., potential onshore bases), large vessels are supposed to carry customer's requirements. In order to load and unload large vessels, some onshore base(s) are needed. In the second level (i.e., operation regions), the produced oil and gas by offshore installations are refined. In order to refine oil and gas continually in this level, their requirements must be sent regularly. In the third level, offshore installations are supposed to produce oil and gas from the sea reservoirs.

As shown in Fig.4, the only way in order to send requirements of offshore installations and onshore bases is using marine vehicles. By considering the volume of needed cargoes in operation regions, which is much more than the requirements of offshore installations, large vessels are selected to carry them. Large vessels are allowed to sail more than once during time horizon. For example, in Fig. 3, large vessel 1 is planned to sail on Wednesdays and Fridays. Since there is no enough space on offshore installations, the requirements sent to operation region's warehouses contain offshore installation requirements too. Also, supply vessels, which are smaller and their rating costs are less, are selected to carry offshore installation requirements. Supply vessels (e.g., large vessels) are allowed to sail more than one voyage during time horizon (i.e., supply vessels 1 and 2 in Fig. 3). In addition, all marine vehicles in a certain voyage must be visited more than one operation region or offshore installation.

In the following, the assumptions and objective of the model are discussed in Section 2.1 and 2.2, respectively.

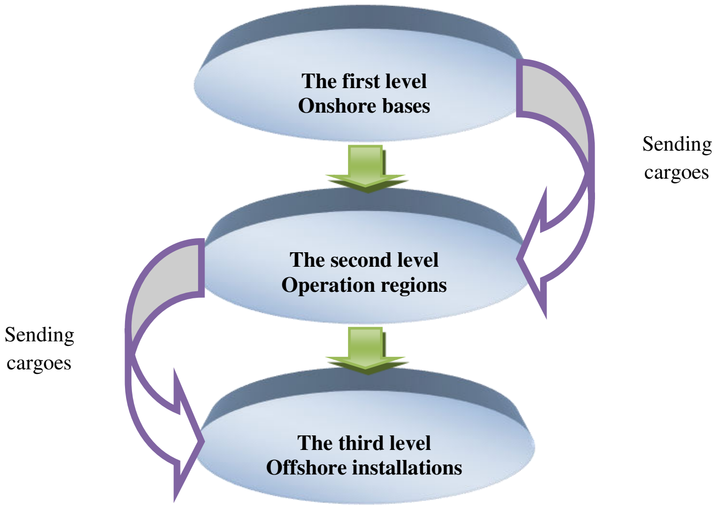

Fig. 3. Levels in the PSVPTWMFL-2E model

In the first level (i.e., potential onshore bases), large vessels are supposed to carry customer's requirements. In order to load and unload large vessels, some onshore base(s) are needed. In the second level (i.e., operation regions), the produced oil and gas by offshore installations are refined. In order to refine oil and gas continually in this level, their requirements must be sent regularly. In the third level, offshore installations are supposed to produce oil and gas from the sea reservoirs.

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In the following, the assumptions and objective of the model are discussed in Section 2.1 and 2.2, respectively.

2.1. Assumptions

Following are some special assumptions of this model in the first and second echelons.

2.1.1. The first echelon

1. Each voyage starts from a potential onshore base and serves one or more operation regions in the second level and returns to the same onshore base.
2. The needs of operation regions are single-commodity. Also the needs are certain at the start of the time horizon.
3. Potential onshore bases are capacitated and have different capacities and opening costs.
4. There is no limitation for using different onshore bases and large vessels.
5. Different kinds of large vessels with different capacity and chartering costs are considered.
6. A time horizon by considering seven days is supposed to send cargoes from the first level to the second level.
7. The potential onshore bases are open between 08:00 and 16:00 for loading cargoes by large vessels.
8. Operation regions are open between 07:00 and 19:00 for unloading needs, which are sent from onshore base(s).
9. The loading time for large vessels in onshore bases is considered eight hours. It is supposed that large vessels are ready before 08:00 in potential onshore bases and they will start their voyages at 16:00.
10. The unloading time for large vessels in operation regions, is considered between two and six hours.
11. Different potential onshore bases have different opening costs and capacities to install central warehouse(s).
12. The demands of operation regions are considered in cubic meters.
13. The volume of backloads of operation regions is considered less than their demands.
14. Because of non-optimal usage of large vessel's capacity and uncertainty, the duration of a voyage is limited between two and four days. Also the number of visits is considered between two and five visits for each voyage.
15. The duration of a voyage is a function of the distances, speed of large vessels, service time and waiting time until opening hours for all operation regions, which should be visited on a voyage.
16. The maximum number of visiting an operation region in a certain day by large vessels is one.

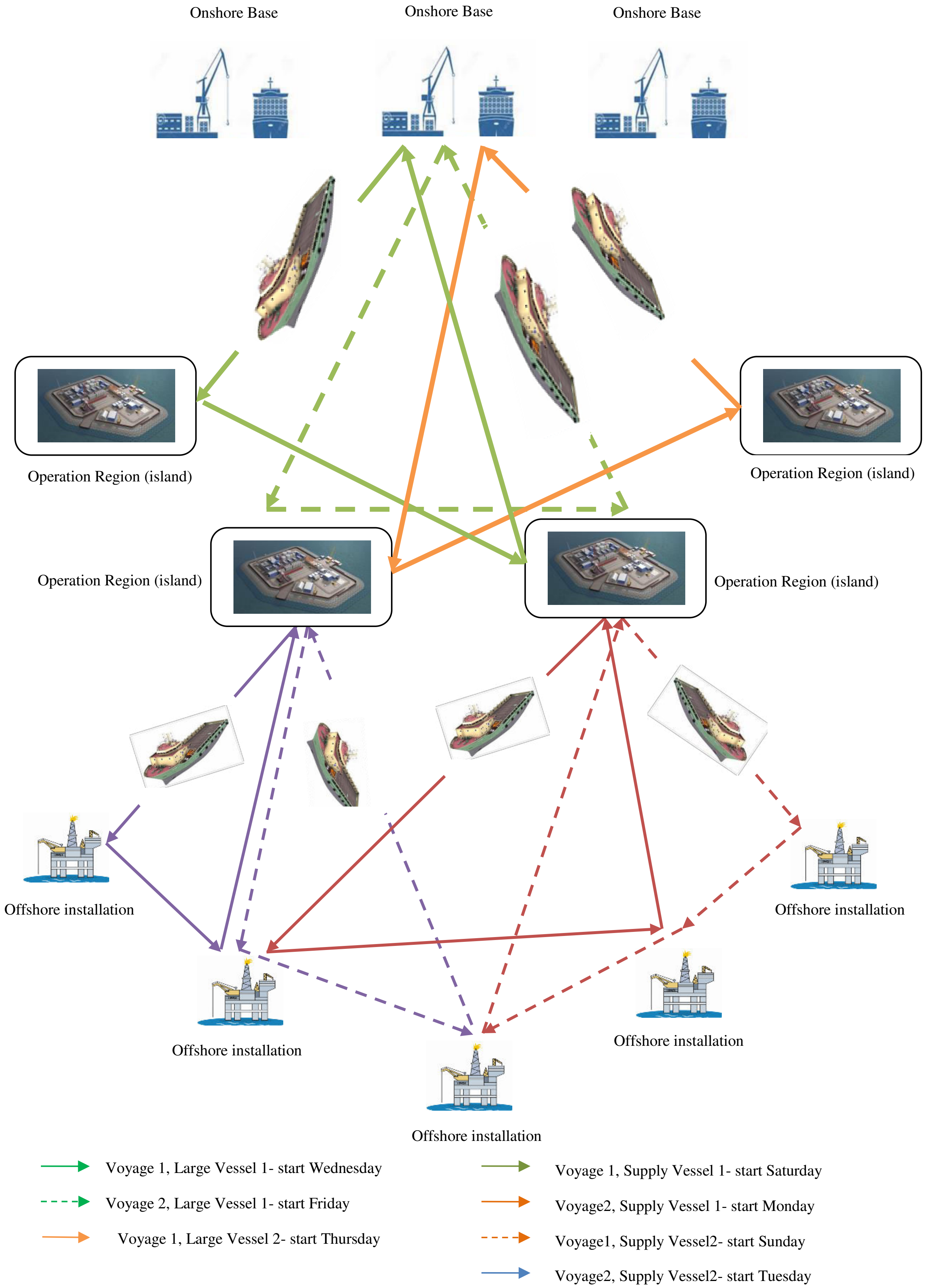

Fig. 4. PSVPTWMFL-2E model (i.e., three onshore bases, four operation regions and five offshore installations)

2.1.2.The second echelon

1. Each voyage starts from an operation region and serves one or more offshore installations in the third level and returns to the same operation region.
2. The offshore installations requirements are single commodity. The requirements are certain at the start of the time horizon.
3. There is no limitation for using different operation regions and supply vessels.
4. Different kinds of supply vessels with different capacity and chartering costs are considered.
5. A time horizon by considering seven days is supposed to send cargoes from the second level to the third level.
6. The operation regions are open between 08:00 and 16:00 for sending cargoes to offshore installations.
7. Offshore installations are open between 07:00 and 19:00 for unloading requirements, which have been sent form operation regions.
8. The loading time for supply vessels in operation regions is considered eight hours. It is supposed that supply vessels are ready before 08:00 in operation regions and they will start their voyages at 16:00.
9. The unloading time for supply vessels in offshore installations is considered between two and six hours.
10. Some offshore installations need to be visited a number of certain times during a week by supply vessels.
11. Operation regions have special warehouses by different features to store offshore installation's requirements.
12. The demands of offshore installations are considered in cubic meters.
13. The volume of backloads of offshore installations is considered less than their demands.
14. Because of non-optimal usage of supply vessel's capacity and uncertainty, the duration of a voyage is limited between two and four days. Also the number of visits is considered between two and five visits.
15. The duration of a voyage is a function of the distances, speed of supply vessels, service time and waiting time until opening hours for all offshore installations which should be visited on a voyage.
16. The maximum number of visiting an offshore installation in a certain day by supply vessels is one.

2.2. Objectives

This system is purposed to decide the optimal number and type of large vessels, related voyages and their schedules in the first echelon. Also selecting potential onshore base(s) to install central warehouse(s) and berth the large vessels is aimed in the first echelon. In the second echelon, the optimal number and type of supply vessels, related weekly voyages and their schedules are aimed. Also deciding the optimal operation region(s) to send offshore installation's needs is purposed in this echelon.

Facility location problems and fleet composition mix of routing problems are NP-hard alone and the combination of them isvery difficult optimization problems. In the following section, an exact two-stage solution approach will be presented.

3. Methodology

The solution approach presented by Halvorsen-Weare et al (2012) for marine transportation problems was used to solvethePSVPTWMFL-2E model as depicted in Fig. 5. This approach contains two main stages.

In the first stage all voyages in both echelons are generated (i.e., Stages 1.1 and 1.2). The voyage generation process is a common method to solve maritime transportation problems and a path flow approach is used instead of an arc flow approach. This kind of formulation can be helpful in order to decrease the solution time and to solve small and medium-sized problems in a reasonable time. By applying this method, one variable is defined per voyage rather than per edge or leg. This structure is easier to solve than applying direct formulation. A voyage generation can often easily include practical restrictions.

As it is shown in Fig 5, the distance matrix between onshore bases, operation regions and offshore installations, and also the opening hours of operation regions and offshore installations, the maximum and minimum number of visits on each voyage and the speed of large vessels and supply vessels are given as inputs for stage 1.1 and stage 1.2. The output of this stage is all candidate voyages for large vessels and supply vessels in both echelons.

In the second stage(Mathematical Model), the optimization model for a two-echelon periodic supply vessel planning problem with time windows mix of facility location (PSVPTWMFL-2E) in an offshore oil and gas industry is presented. The parameters from stage 1 are used in the mathematical model. The problem is to determine optimal fleet composition, optimal voyages and schedules in both echelons. Also, optimal onshore base(s) to install central warehouses in the first echelon and optimal operation region(s) to send offshore installations requirements in the second echelon are determined.

The capacity of large and supply vessels, demand of operation regions and offshore installations, require number of visits for offshore installations, time horizon in both echelons, the capacity of potential onshore bases and operation regions, spread of departure and the related costs are given as inputs for the second stage.

3.1. Voyage generation process

In order to solve real-sized instances in an acceptable time, a voyage generation process is used. The distances between potential onshore bases, operation regions and offshore installations are supposed in this process. All possible voyages in the first and second echelons are generated by considering some limitations. Each voyage must start and finish at the same place. The number of operation regions in the first echelon and offshore installations in the second echelon to visit in a certain voyage is limited between two and five. Each onshore base or operation region is not allowed to visit more than once on a voyage. There are two pools of marine vehicles. The first one contains large vessels by different capacities, speed and chartering costs in the first echelon. The second one contains supply vessels by different capacities, speed and chartering costs in the second echelon. In the first echelon, for each large vessel and each potential onshore base a traveling salesman problem (TSP) should be solved and in the second echelon, a TSP should be solved for each supply vessel and each operation region. Time windows for operation regions and offshore installations in order to load and unload cargoes are given. The voyage's duration is calculated based on the service time and the distances between potential onshore-base(s), operation regions and offshore installations. If marine vehicles reach to the operation regions or offshore installations during closing hours, they have to wait until opening hours. Also if the unloading is not finished during opening hours, 12 hours must be added to the total time. This trend continues while the marine vehicles come back to the place where they started their voyages. It is supposed that the time of loading backloads are considered in the service time. Ideal weather conditions are supposed and uncontrollable events have not been considered. The duration of each voyage is fixed, and varies for each supply vessel or large vessel. Unlike the previous studies, the capacity of supply vessels and voyage's time are not examined in stage 1 and are considered in the mathematical model. The cost of voyages is calculated by considering the amount of fuel utilized during the voyages multiplied by the cost of fuel (the rate of fuel consumption is different for sailing and loading/unloading in operation regions).If the shortest distance is not equal to the shortest time, the shortest distance is acceptable because of using less fuel. A pseudo code for the voyage generation process is given in Fig 6.

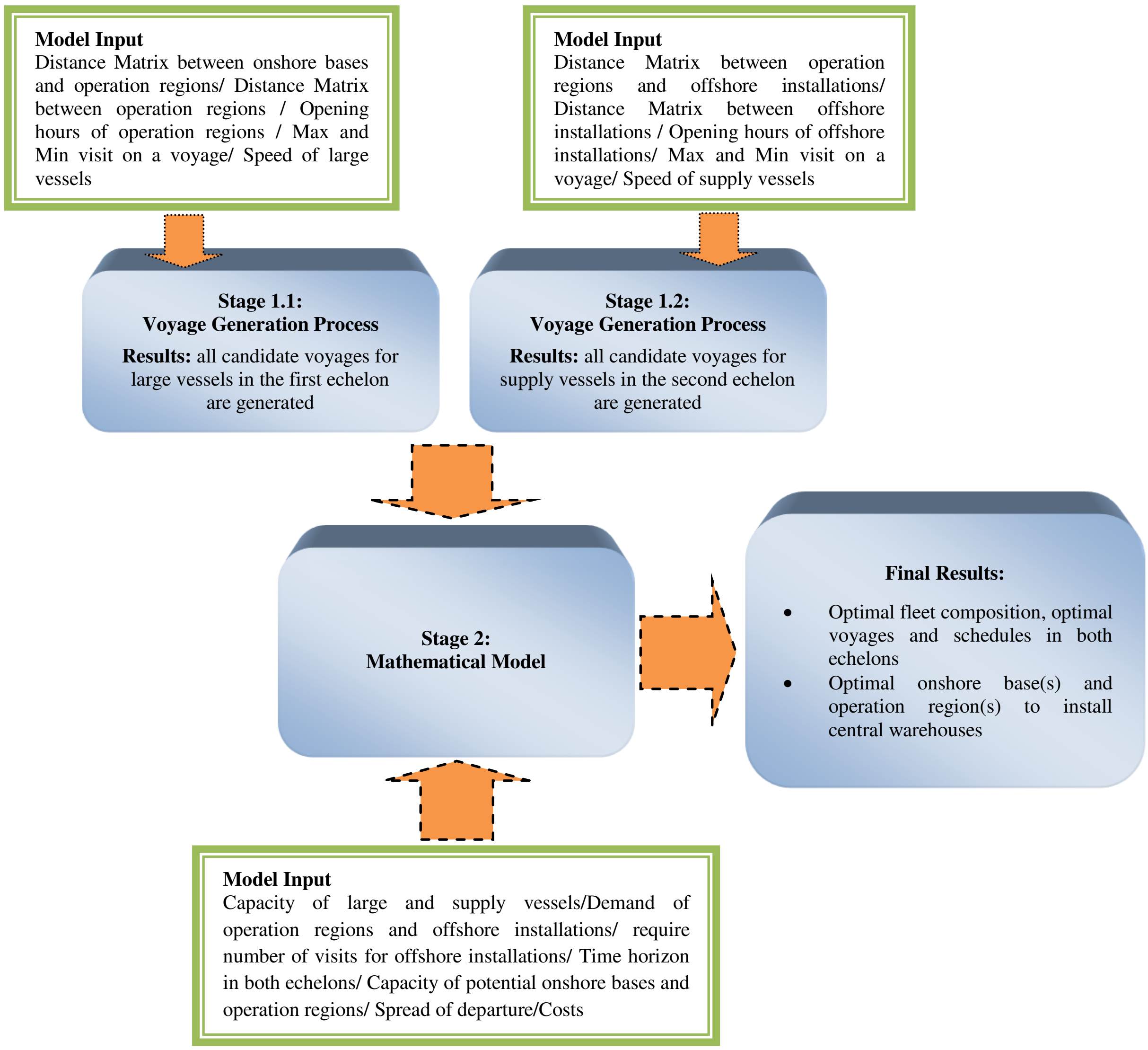

Fig. 5. Schematic overview of the methodology

Voyage generation process
Create sets of large vessels (LV Set in stage1.1)/sets of supply vessels (SV Set in stage1.2) with different sailing speed
Enumerateall sets of operation regions (OR Set in stage1.1)/offshore installations(OF Set in stage1.2) that satisfy the number of visited operation regions (stage1.1)/offshore installations(stage1.2) limitations in a voyage
For all Potential onshore bases Set (stage1.1)/ Operation regions Set (stage1.2)
Forall OR Set (stage1.1)/OF Set (stage1.2)
For all LV Set in stage1.1/ SV Set in stage1.2
Find a voyage by solving a TSP with time windows which starts and ends at the same onshore base (stage1.1)/operation region (stage1.2) where all operation regions (stage1.1) in OR Set/ all offshore installations (stage1.2) in OF Set are visited exactly once.
End Forall LV Set/SV Set
End Forall OR Set/ OF Set
End For all Potential onshore bases Set/ Operation regions Set
Return all Voyages Set

Fig. 6. Voyage generation process

3.2. Mathematical model

This section presents the mathematical model for the PSVPTWMFL-2Eproblem. The objective function that is shown by Z is to choose the most cost-effective large vessels and supply vessels, optimal onshore base(s), optimal operation region(s) to send requirements to offshore installations and pick the best generated voyages in both echelons, which fulfill the constraints.

Let B be the set of alternative onshore bases, U be the set of all operation regions and O be the set of offshore installations. Then, define V_1 and V_2 as the sets of large vessels and supply vessels respectively, which can be chartered. Sets of R_1 and R_2 contain all generated voyages in Stage 1. Furthermore, let T_1 and T_2 be the sets of days in the planning horizon (seven days in the first echelon and seven days in the second echelon) respectively. Also, let L be the set of allowable durations of using marine vehicles.

The cost per unit chartered and used vessels per period represents by $c_{k_1}^{ch_1}$ for large vessels and $c_{k_2}^{ch_2}$ for supply vessels. All sailing costs of large vessel k_1 from onshore base I on voyage r_1 shows by $c_{ik_1r_1}^{sc_1}$ and also all sailing costs of supply vessel k_2 from operation region j on voyage r_2 shows by $c_{jk_2r_2}^{sc_2}$. The duration of voyage r_1 sails by large vessel k_1 from onshore base i, and the duration of voyage r_2 sails by supply vessel k_2 from operation region j, are shown by $ti^1{}_{ik_1r_1}$ and $ti^2{}_{jk_2r_2}$, respectively. The allowable days of sailing large vessel k_1 shows by $f_{k_1}^1$ and the allowable days of sailing supply vessel k_2 shows by $f_{k_2}^2$. The allowable duration of voyages is set between l_r and h_r. The capacity limitation of large vessel k_1 and supply vessel k_2 are presented by $cap_{k_1}^{v_1}$ and $cap_{k_2}^{v_2}$,respectively.

Furthermore, $c_i^{fc_1}$ and $c_j^{fc_2}$ shows the cost of installing the central warehouse in onshore base i and operation region j , respectively. The variable cost per unit of cargo in onshore base i and operation region j are shown by c_i^b and c_j^u, respectively.

m_j^1 and m_s^2 show the demand of operation region j and offshore installation s, respectively. The number of needed visits for offshore installation s is shown by sn_s .Further $a_{jr_1}^1$ and $a_{sr_2}^2$ arethe results of Stage 1 and represents weather operation region j on voyage r_1 and offshore installation S on voyage r_2 are visited or not. The capacity limitation of onshore base I and operation region j are presented by cap_i^b and cap_j^u, respectively.Finally, in order to conduct sensitive analysis, parameter p^1 and p^2 is considered as a number of needed warehouses in both echelons.

The binary variable $Z_{ik_1}^1$ is one if large vessel k_1 is assigned to onshore base i, and also the binary variable $Z_{jk_2}^2$ is one if supply vessel k_2 is assigned to operation region j; otherwise, they are zero. The binary variable Y_i^1 is one if onshore base j is selected to berth the large vessel k_1, and zero otherwise. The binary variable Y_j^2 is one if operation region j is selected to berth the supply vessel k_2, and zero otherwise. The binary variable $X_{ik_1r_1t_1}^1$ is one if large vessel k_1, on voyage r_1, from onshore base I and in day t_1 sails, and zero otherwise. The binary variable $X_{jk_2r_2t_2}^2$ is one if supply vessel k_2, on voyage r_2, from operation region j and in day t_2 sails and zero otherwise.Two positive variables for the quantity of sending cargoes from onshore bases to operation regions, and operation regions to offshore installations are shown by $Q_{ijk_1r_1t_1}^b$ and $Q_{jsk_2r_2t_2}^u$,respectively. The mathematical model is presented below.

$$\begin{aligned}\text{Min } Z = & \sum_{i\in B}\sum_{k_1\in V_1} c_{k_1}^{ch_1} Z_{ik_1}^1 + \sum_{j\in U}\sum_{k_2\in V_2} c_{k_2}^{ch_2} Z_{jk_2}^2 + \sum_{i\in B} c_i^{fc_1} Y_i^1 + \sum_{j\in U} c_j^{fc_2} Y_j^2 + \sum_{i\in B}\sum_{k_1\in V_1}\sum_{r_1\in R_1}\sum_{t_1\in T_1} c_{ik_1r_1}^{sc_1} X_{ik}^1 \\ & + \sum_{j\in U}\sum_{k_2\in V_2}\sum_{r_2\in R_2}\sum_{t_2\in T_2} c_{jk_2r_2}^{sc_2} X_{jk_2r_2t_2}^2 + \sum_{i\in B}\sum_{j\in U}\sum_{k_1\in V_1}\sum_{r_1\in R_1}\sum_{t_1\in T_1} c_i^b Q_{ijk_1r_1t_1}^b \\ & + \sum_{j\in U}\sum_{s\in O}\sum_{k_2\in V_2}\sum_{r_2\in R_2}\sum_{t_2\in T_2} c_j^u Q_{jsk_2r_2t_2}^u\end{aligned} \quad (1)$$

s.t.

$$\sum_{i\in B}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} a^1_{jr_1}X^1_{ik_1r_1t_1}Q^b_{ijk_1r_1t_1}Z^1_{ik_1} - m^1_j \geq 0 \quad ,j\epsilon U \tag{2}$$

$$\sum_{j\in U}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} a^2_{sr_2}X^2_{jk_2r_2t_2}Q^u_{jsk_2r_2t_2} - m^2_s = 0 \quad ,s\epsilon O \tag{3}$$

$$\sum_{j\in U}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} a^2_{sr_2}X^2_{jk_2r_2t_2}Z^2_{jk_2} - sn_S \geq 0 \quad ,s\epsilon O \tag{4}$$

$$\sum_{j\in U}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} Q^b_{ijk_1r_1t_1} - cap^b_i \leq 0 \quad ,i\epsilon B \tag{5}$$

$$\sum_{s\in O}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} Q^u_{jsk_2r_2t_2} - cap^u_j \leq 0 \quad ,j\epsilon U \tag{6}$$

$$\sum_{i\in B}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} Q^b_{ijk_1r_1t_1} - m^1_j - \sum_{s\in O}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} Q^u_{jsk_2r_2t_2} = 0 \quad ,j\epsilon U \tag{7}$$

$$\sum_{i\in B} Y^1_i - p^1 \leq 0 \tag{8}$$

$$\sum_{j\in U} Y^2_j - p^2 \leq 0 \tag{9}$$

$$\sum_{i\in B} Z^1_{ik_1}Y^1_i - 1 \leq 0 \quad ,k_1\epsilon V_1 \tag{10}$$

$$\sum_{j\in U} Z^2_{jk_2}Y^2_j - 1 \leq 0 \quad ,k_2\epsilon V_2 \tag{11}$$

$$\sum_{i\in B}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} ti^1{}_{ik_1r_1}X^1_{ik_1r_1t_1} - f^1_{k_1} \leq 0 \quad ,k_1\epsilon V_1 \tag{12}$$

$$\sum_{j\in U}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} ti^2{}_{jk_2r_2}X^2_{jk_2r_2t_2} - f^2_{k_2} \leq 0 \quad ,k_2\epsilon V_2 \tag{13}$$

$$ti^1{}_{ik_1r_1}X^1_{ik_1r_1t_1} - l_r \geq 0 \quad ,i\epsilon B\ ,k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{14}$$

$$ti^1{}_{ik_1r_1}X^1_{ik_1r_1t_1} - h_r \leq 0 \quad ,i\epsilon B\ ,k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{15}$$

$$ti^2{}_{jk_2r_2}X^2_{jk_2r_2t_2} - l_r \geq 0 \quad ,j\epsilon U\ ,k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{16}$$

$$ti^2{}_{jk_2r_2}X^2_{jk_2r_2t_2} - h_r \leq 0 \quad ,j\epsilon U\ ,k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{17}$$

$$\sum_{r_1\epsilon R_1} X^1_{ik_1r_1t_1} + \sum_{r_1\epsilon R_1}\sum_{g=0}^{l-1} gX^1_{ik_1r_1((t_1+g)mod|T_1|)} - 1 \leq 0\ ,i\epsilon B\ ,k_1\epsilon V_1, t_1\epsilon T_1, l\epsilon L \tag{18}$$

$$\sum_{r_2\epsilon R_2} X^2_{jk_2r_2t_2} + \sum_{r_2\epsilon R_2}\sum_{g=1}^{l-1} X^2_{jk_2r_2((t_2+g)mod|T_2|)} - 1 \leq 0\ ,j\epsilon U\ ,k_2\epsilon V_2, t_2\epsilon T_2, l\epsilon L \tag{19}$$

$$\sum_{i\in B}\sum_{j\epsilon U} Q^b_{ijk_1r_1t_1} - cap^{v_1}_{k_1} \leq 0 \quad ,k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{20}$$

$$\sum_{j\epsilon U}\sum_{s\epsilon S} Q^u_{jsk_2r_2t_2} - cap^{v_2}_{k_2} \leq 0 \quad ,k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{21}$$

$$\sum_{i\epsilon B}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1} a^1_{jr_1}X^1_{ik_1r_1t_1} - 1 \leq 0 \quad ,j\epsilon U, t_1\epsilon T_1 \tag{22}$$

$$\sum_{j\epsilon U}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2} a^2_{sr_2}X^2_{jk_2r_2t_2}-1\le 0 \quad ,s\epsilon O, t_2\epsilon T_2 \tag{23}$$

$$X^1_{ik_1r_1t_1}\ \epsilon\ [0,1] \quad ,i\epsilon B\ ,k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{24}$$

$$X^2_{jk_2r_2t_2}\ \epsilon\ [0,1] \quad ,j\epsilon U\ ,k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{25}$$

$$Y^1_i\ \ \epsilon\ [0,1] \quad ,i\epsilon B \tag{26}$$

$$Y^2_j\ \ \epsilon\ [0,1] \quad ,j\epsilon U \tag{27}$$

$$Z^1_{ik_1}\epsilon\ [0,1] \quad ,i\epsilon B, k_1\epsilon V_1 \tag{28}$$

$$Z^2_{jk_2}\epsilon\ [0,1] \quad ,j\epsilon U, k_2\epsilon V_2 \tag{29}$$

$$Q^b_{ijk_1r_1t_1}\ge 0 \quad ,i\epsilon B, j\epsilon U, k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{30}$$

$$Q^u_{jsk_2r_2t_2}\ge 0 \quad ,j\epsilon U, s\epsilon O, k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{31}$$

The objective function (1) minimizes the total costs of chartering large vessels and supply vessels and sailing costs in echelons plus locating onshore base(s) to install the central warehouse(s) and selecting operation region(s) to send requirements of offshore installations by considering inventory variable costs. Constraints (2) and (3) assure that each operation region and each offshore installation is served the needed demand, respectively. Since supply vessels are the only way to send cargoes to offshore installations, each offshore installation needs a number of certain visits during the time horizon, so the number of needed weekly visits of each offshore installation is checked by Constraints (4). The limitations of onshore base's capacity and operation region's capacity to send cargoes are indicated by Constraints (5) and (6). Constraints (7) show that all cargoes that enter to an operation region from different onshore bases minus operation region's demand must be equal to all cargoes which are sent to different offshore installations in the time horizon. P^1 onshore base(s) and P^2 operation region(s) are ensured by Constraints (8) and (9), respectively. Constraints (10) and (11) state vessels cannot be assigned to more than one onshore base or one operation region.

Marine vehicles in order to be kept in a good condition should not be used whole the time horizon, so Constraints (12) and (13) check the number of days, in which each large vessel and supply vessel can be used during a week, respectively. Constraints (14)-(17) show that the duration time of each voyage should be between l_r and h_r in both echelons. Constraints (18) and (19) mean that a large vessel or supply vessel does not start a new voyage before it returns to the same onshore base or operation region. Constraints (20) show that for each voyage in a certain day, the volume of cargoes sent by a large vessel cannot be exceeded of its capacity, and Constraints (21) show that for each voyage in a certain day, the volume of cargoes sent by a supply vessel cannot be exceeded of its capacity. Constraints (22) and (23) mean that each operation region or offshore installation must not be visited more than once in a day, respectively. The reason is, if there is a requirement in an offshore installation during the week and the weekly visits of that offshore installation already have been done, there would be no supply vessels to fulfill the requirement. Constraints (24) to (31) define the domains of variables.

In order to define the problem as a linear programming (LP), Constraints (2), (3), (4), (10) and (11) must be changed to Constraints(32), (33), (34), (35)and (36) and also Constraints (37)-(42)must be added to the previous ones.

$$\sum_{i\epsilon B}\sum_{k_1\epsilon V_1}\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} Q^b_{ijk_1r_1t_1}-m^1_j\ge 0 \quad ,j\epsilon U \tag{32}$$

$$\sum_{j\epsilon U}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} Q^u_{jsk_2r_2t_2}-m^2_s=0 \quad ,s\epsilon O \tag{33}$$

$$\sum_{j\epsilon U}\sum_{k_2\epsilon V_2}\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} a^2_{sr_2}X^2_{jk_2r_2t_2} - sn_S \geq 0 \quad ,s\epsilon O \tag{34}$$

$$\sum_{i\epsilon B} Z^1_{ik_1} - 1 \leq 0 \quad ,k_1\epsilon V_1 \tag{35}$$

$$\sum_{j\epsilon U} Z^2_{jk_2} - 1 \leq 0 \quad ,k_2\epsilon V_2 \tag{36}$$

$$\sum_{r_1\epsilon R_1}\sum_{t_1\epsilon T_1} X^1_{ik_1r_1t_1} - MZ^1_{ik_1} \leq 0 \quad ,i\epsilon B, k_1\epsilon V_1 \tag{37}$$

$$\sum_{r_2\epsilon R_2}\sum_{t_2\epsilon T_2} X^2_{jk_2r_2t_2} - MZ^2_{jk_2} \leq 0 \quad ,j\epsilon U, k_2\epsilon V_2 \tag{38}$$

$$Q^b_{ijk_1r_1t_1} - M\left(a^1_{jr_1}X^1_{ik_1r_1t_1}\right) \leq 0 \quad ,i\epsilon B, j\epsilon U, k_1\epsilon V_1, r_1\epsilon R_1, t_1\epsilon T_1 \tag{39}$$

$$Q^u_{jsk_2r_2t_2} - M\left(a^2_{sr_2}X^2_{jk_2r_2t_2}\right) \leq 0 \quad ,j\epsilon U, s\epsilon O, k_2\epsilon V_2, r_2\epsilon R_2, t_2\epsilon T_2 \tag{40}$$

$$\sum_{k_1\epsilon V_1} Z^1_{ik_1} - MY^1_i \leq 0 \quad ,i\epsilon B \tag{41}$$

$$\sum_{k_2\epsilon V_2} Z^2_{jk_2} - MY^2_j \leq 0 \quad ,j\epsilon U \tag{42}$$

Since each large vessel can be assigned only to one onshore base, we should be sure about assigning it to that onshore base before sending to operation regions. Thus, Constraints (37) state that a large vessel could be sailed form an onshore base, if it has been assigned to this onshore base previously. Constraints (38) state that a supply vessel could be sailed form an operation region, if it has been assigned to this operation region previously. Since the needed cargoes can be sent to onshore bases or offshore installations by the certain voyages, certain marine vehicles and certain days, Constraints (39) and (40) have been defined to impose that if a voyage from an onshore base or operation region by a vessel and in a certain day does not exist, no cargo must be sent on this voyage. Finally, Constraints (41) and (42) assure that if onshore base$j$or operation region j has not selected in an optimal solution, no vessel can be assigned to this onshore base or operation region, respectively.

4. Computational Results

The solution approach presented in Section 3 is tested on a real-life case carried out by the Iranian National Oil Company (NIOC). In Section 4.1, the case study and related results are described. A real-life problem instances and numerical results for small and medium instances are discussed in Sections4.2 and 4.3, respectively.

4.1. Case description

The Iranian Offshore Oil Company (IOOC) is a subsidiary of the NIOC and is one of the world's largest offshore oil producing companies in the Iranian side of the Persian Gulf and the sea of Oman. This company has main six offshore installations, four main offshore operation regions and three active offices along the Persian Gulf and the sea of Oman coastline. Each operation region has a separate set of supply vessels and each onshore-base office has a separated set of large vessels. Supply vessels and large vessels are scheduled by manual planning methods for years. On the other hand, the data of warehouse inventories in operation regions and onshore bases are not joined to each other and installing central warehouse(s) in order to solve this problem while the total costs of installing warehouse(s), chartering fleets, sailing costs are kept minimum aimed by the IOOC.

4.1.1. Case study results

After conducting the PSVPTWMFL-2E model for the IOOC case, the advantages of this model compared with the current situation are appeared. The results indicate that the PSVPTWMFL-2E model by using the voyage-based solution method gives an optimal solution in a reasonable time. The total cost of the model is \$1,807,063that consists of \$1,650,000 fixed cost to install the central warehouses and \$157,063 for sailing costs. The number of supply vessels can be reduced from four (i.e., current situation) to two and the number of large vessels can be reduced from two to one (i.e., current situation). By using an optimal number of marine vehicles, the IOOC can save \$128,438 in a week and \$6,678,776 in a year, which is four times more than the cost of installing central warehouses. By using the PSVPTWMFL-2E model in the real SVP problem for the IOOC, the acceptable results are obtained showing that the model is suitable for this kind of problems.

4.2. Problem instances

The performance of the solution approach is studied by using 24real-lifeproblem instances. These instances arenumbered by the number of potential onshore bases, the number of operation regions and the number of offshore installations. For example, problem instance 2-3-4 has two potential onshore bases, three operation regions and four offshore installations.

The number of potential onshore bases, operation regions and offshore installations in the problem instances varies from two to three, three to four, three to ten, respectively. Opening hours between 07:00 and 19:00 are considered for all operation regions and offshore installations. Also the number of weekly visits of each offshore installation varies from two to four and the total number of visits for each problem instance varies from 6 to 24.The weekly demands for each operation region and each offshore installation varies from 1000 to 1500 m^3 and 100 to 150 m^3, respectively. The service time in both echelons is considered between two and six hours.

For all problem instances, five large vessels and five supply vessels are available that can be chartered. The time charter rates are considered above USD 61,500 for all large vessels and above $31,500 for all supply vessels per week, depending on the speed and capacity of vessels. The sailing cost and waiting cost for all vessels varies from $100 to $200 and from $38 to$50 for each hour, respectively. The capacity of large vessels and supply vessels for loading varies from 5000 m^3 to 7000 m^3 and 1000 m^3 to 1400 m^3, respectively. The speed of large vessels is 10 knots and the speed of supply vessels is 12 knots. The large and supply vessels are available for six days during a week.

In each echelon, the time horizon is considered seven days. The duration of voyages should be between two and four days and the number of operation region's visits and offshore installation's visits should be between two and five, because of uncertainty. The capacity at the potential onshore bases varies from 5000 m^3 to 7000 m^3. Also the capacity at the operation regions varies from 1000 m^3 to 2500 m^3. The fix and variable cost at potential onshore bases varies from $750,000 to $850,000 and from $1.375 to $1.25 per one cubic meter, respectively. Also, the fix and variable cost at operation regions varies from $900,000 to $970,000 and from $1.45 to$1.575per one cubic meter, respectively.

Matlab and GAMS (22.1) software are used to generate voyages and solve the mathematical model, respectively. All results are obtained on a 2.8 GHz, Intel(R)Core(TM)i7(4CPUs) computer with 8GB of memory using all available cores.

4.3. Numerical results

Table 1 shows the results of solving the problem instances by using the two-stage's solution approach. # variables and # weekly visits refer to the number of variables and the number of needed weekly visits for each problem instance, respectively. The CPU time for generating voyages in both echelons and the CPU time for Stage 2 are presented in the next columns. Opt. gap refers to the optimal gap reported form GAMS (22.1) software (gap between the objective value and the best lower bound). # Large vessels/# Supply vessels refers to the number of large vessels and supply vessels in the solution. # Optimal OB/OR refers to the optimal number of selected onshore bases and operation regions to install warehouses. # Voy. selected refers to the number of voyages in the solution.

Table 1
Results of the two stage's solution approach

Problem Instance i-j-s	# Variables	# Weekly visits	CPU voy.gen. First echelon (seconds)	CPU voy.gen. second echelon (seconds)	CPU time Stage 2 (seconds)	Opt.gap	# Large vessels/ # Supply vessels	# Optimal OB/OR	# Voy.selected 1st echelon/ 2nd echelon
2-3-3	**2,833**	6	0.179	0.192	2.346	0.00	1/1	1/1	1/2
2-3-4	**6,926**	8	0.179	1.357	16.909	0.00	1/2	1/1	1/3
2-3-5	**17,531**	10	0.179	9.620	36.409	0.00	1/2	1/1	1/4
2-3-6	**42,311**	12	0.179	35.986	94.024	0.00	1/2	1/1	1/4
2-3-7	**95,230**	14	0.179	143.186	236.841	0.00	1/2	1/1	1/4
2-3-8	**199,600**	16	0.179	413.650	1815.571	0.00	1/3	1/1	1/4
2-3-9	**391,750**	18	0.179	1132.465	4888.541	0.00	1/3	1/1	1/5
2-3-10	**725,335**	20	0.179	1908.523	4107.397	0.00	1/3	1/1	1/6
3-3-3	**3,397**	6	1.098	0.192	2.561	0.00	1/1	1/1	1/2
3-3-4	**7,492**	8	1.098	1.345	39.841	0.00	1/2	1/1	1/3
3-3-5	**18,097**	10	1.098	9.620	104.550	0.00	1/2	1/1	1/4
3-3-6	**42,877**	12	1.098	35.986	215.391	0.00	1/2	1/1	1/4
3-3-7	**95,796**	14	1.098	143.186	744.234	0.00	1/2	1/1	1/4
3-3-8	**200,166**	16	1.098	413.650	3454.596	0.00	1/3	1/1	1/4
3-3-9	**392,316**	18	1.098	1132.465	6003.122	0.00	1/3	1/1	1/5
3-3-10	**725,901**	20	1.098	1908.523	>10000	0.01	-	-	-
3-4-3	**8,058**	6	1.326	0.260	18.563	0.00	1/1	1/1	2/2
3-4-4	**13,518**	8	1.326	1.357	159.877	0.00	1/2	1/1	2/3
3-4-5	**27,658**	10	1.326	13.496	409.102	0.00	1/2	1/1	2/4
3-4-6	**60,698**	12	1.326	66.292	2153.385	0.00	1/2	1/1	2/4
3-4-7	**131,258**	17	1.326	181.273	3292.027	0.00	1/2	1/1	2/4
3-4-8	**270,417**	20	1.326	748.327	7583.861	0.01	1/3	1/1	2/4
3-4-9	**526,617**	22	1.326	1323.157	>10000	0.02	-	-	-
3-4-10	**971,397**	24	1.326	2435.421	>10000	0.02	-	-	-

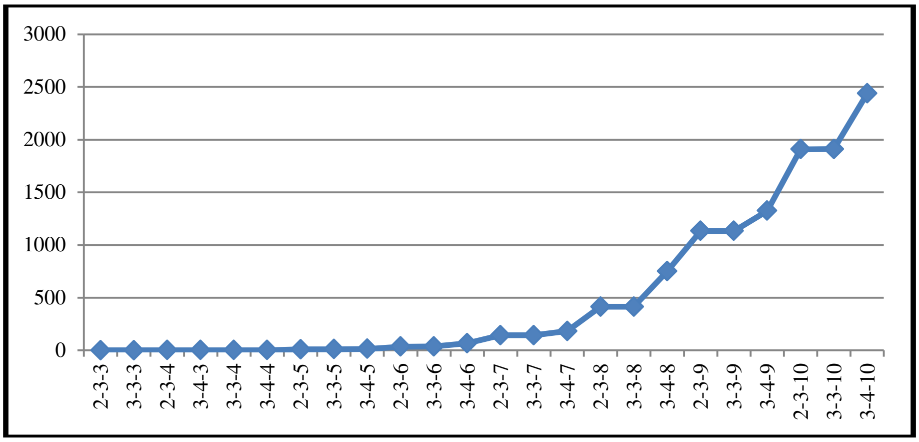

Fig. 7. Changes of the generation time of the total voyage
X axis shows the name of instance and *Y* axis show the generation time of the total voyage

As shown in Fig 7, the time of voyage generation process is influenced by the number of potential onshore bases and the number of operation regions. When the total number of onshore bases and offshore installations is less than 11, the total voyage generation process time is less than 150 seconds. Also when the total number of onshore bases and offshore installations is more than 11, the total voyage generation process time will increase exponentially.

On the other hand, the time of solving the mathematical model will get more by adding more potential onshore base(s) or operation regions or offshore installations. When the total number of all onshore bases, operation regions and offshore installations is less than 13, the total mathematical model time is less than 750 seconds and when the total number of all onshore bases, operation regions and offshore installations is equal or more than 13, the total time will increase exponentially too(Fig 8).

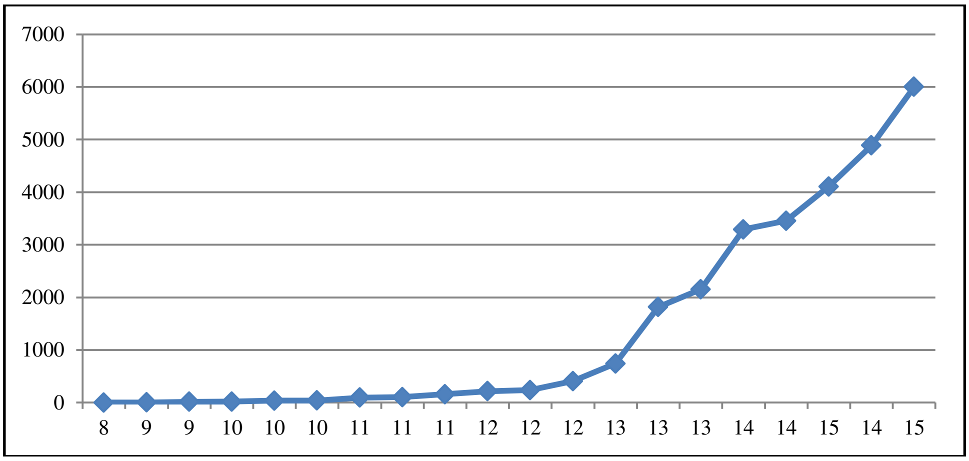

Fig. 8. Changes of the solution time for solving the mathematical model
X axis shows the total number of all onshore bases, operation regions and offshore installations for each instance and *Y* axis show the solution time of the mathematical model

The changes of the total solution time are the same as the changes of the solution time solving the mathematical model. If the summation of potential onshore-base, operation regions and offshore installations is less than 13, the changes of the total solution time will be linear and reasonable. If the summation of potential onshore-base, operation regions and offshore installations is equal or more than 13, the changes of the total solution time will increase exponentially. However, the optimality gap reported form GAMS software is around 2%, the solution approach is not capable to solve large-sized instances (e.g., more than 15 potential onshore-base, operation regions and offshore installations) during time limitation (i.e., 10,000 seconds).So It is concluded that this solution approach is suitable for small and medium real life cases faced by the NIOC and the optimal fleet composition, the optimal warehouse location and the optimal voyages in both echelons are obtained in a reasonable time while the total cost is kept at minimum.

5. Conclusions

A two-echelon periodic supply vessel planning problem with time windows for the facility location (PSVPTWMFL-2E) in an offshore oil and gas industry was studied in this paper. It was an extension of the SVP problem. In this model, some potential depots that should be located as the optimal onshore-base(s) in both echelons with different features were considered. These depots were supposed to send customer's requirements. An optimal number and type of large vessels in an upstream oil and gas supply chain was mentioned for the first time. Considering the model as a periodic problem in both echelons was another contribution of this paper. Additionally, some novel real-life aspects (e.g., installing central warehouse(s) in optimal onshore base(s) to reduce total cost)were considered as new contributions of this paper. In order to solve the model, a two-stage solution approach was presented for small and medium cases. In the first stage, all possibilities of voyages (in both echelons) were generated. In the second stage, the optimal onshore base(s) to install central warehouse, optimal operation region(s) to store requirements of offshore installations, optimal fleet composition and sizing, and optimal voyages (in both echelons) were determined. The computational study, which was carried out on as a real-life case in IOOC, showed that all small and medium real-life instances could be solved by this approach using GAMS software (CPLEX solver) in a reasonable time. The following research directions can be studied in the future:

1- Using an exact method to solve large-sized instances.
2- Considering environmental aspects for vessels and their voyages in both echelons.
3- Using an arc flow approach for the PSVPTWMFL-2Emodel.
4- Proposing a robustness approach to reduce the risk of uncontrollable events.

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This article can be cited: Amiri M., Sadjadi S. J., Tavakkoli-Moghaddam R. & Jabbarzadeh A. (2019). An Integrated Approach for Facility Location and Supply Vessel Planning with Time Windows. *Journal of Optimization in Industrial Engineering*. 12 (1), 151- 165

http://www.qjie.ir/article_538388.html
DOI: 10.22094/joie.2018.544109.1517