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Minimization of emissions in periodic supply vessel planning through speed optimization

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Abstract

One of the most costly resources used in upstream logistics are platform supply vessels. The main function for such type of vessels is transportation of goods and personnel to and from offshore oil platforms. We present here a large neighbourhood search heuristic with speed optimization for a real-world periodic supply vessel planning problem faced by Statoil. Formerly, that problem was grounded on fixed speed and given fuel consumption rate for each vessel. However, in order to integrate the economic benefits with environmental aspects we implement speed optimization algorithm with variable vessel speed and evaluate fuel consumption by cubic function of speed. A computation study shows that the solution solves problem of realistic size and that variable speed allows archiving object of minimization fuel emissions and cutting down expenses.

Keywords: maritime transportation; periodic routing; fleet sizing; multiple vehicle use; supply operations, fuel consumption; speed optimization; emissions

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Contents

1. Introduction

Oil and gas production and exploration processes are the key activities on the Norwegian Continental Shelf. Logistics of these processes is divided into downstream and upstream logistics. The purpose of the first one involves the manufacturing and marketing of oil and gas products and delivering them to customers. While upstream logistics includes supplying the offshore installations with all necessary goods. The task considered in this thesis is related to upstream logistics of the Statoil, one of the largest Norwegian offshore oil and gas operators. The Company uses extensively supply vessels to transport load to and from offshore installations to secure permanent work on them. Providing the offshore installations with supplies is one the most complicated tasks, because to achieve a reliable and cost-effective supply service accurate planning is required. The complexity of planning platform supply vessels routes and schedules made this subject interesting for the thesis work.

But at the same time nowadays emissions from commercial shipping are the point of intense research in the world shipping community. But the influence of ecological factors in the practice of logistics activities is insufficiently studied. This thesis is considered from the point of view of an effective mechanism of the environmentally-oriented logistics in order to integrate the economic benefits with environmental aspects.

According to the Kyoto Protocol, Norway is obligated not to increase emissions of climate gases for the first commitment period in 2008 to 2010 by more than one per cent to compare with the level of 1990 year. In spite of the fact that shipping was not included in the list of Kyoto global emissions reduction target for contaminants, the preparations for decreasing vessels fuel consumption should be undertaken at present. Due to the fact that the process of implementing measures is quite complicated and long, Statoil starts thinking about taking appropriate steps by this time.

The emission control measures are divided into technological and operational. The first type of measures includes usage of more efficient than current engines or ship hulls, development and utilization of alternative fuels (bio-fuels), obligatory cold ironing in ports or scrubbing technology. The second one involves speed reduction, routes optimization and other approaches based on logistics. In our thesis the operational emission control measure as speed reduction is considered.

The problem of solving the periodic routes and schedules of vessels from single onshore base to offshore installations with minimal ecological destructive impact on the environment is urgent, but not adequately explored in our time. Our aim is to analyze present-day real-world vessel planning problem on the ground of Statoil Company and develop supply solution taking into consideration minimization of emissions. The periodic weekly vessel routes and schedules based on the optimal speed of each ship for every sailing leg are worked out in the thesis. We refer to the problem as the periodic supply vessel planning problem with speed optimization (PSVPPSO).

The objective of the work described in this thesis is to design and develop heuristic algorithm for offshore supply operations performed by supply vessels. The remaining part of the thesis is structured as follows. Section 2 describes the literature on the topic relevant to this thesis. In Section 3 the detailed problem description is given. Section 4 describes the mathematical model with relevant definitions. In Section 5 all stages and description of large neighbourhood search heuristic with constant and variable speed are presented. Section 6 describes the test instances and represents computational evaluation of the large neighbourhood search heuristic Conclusions are given in Section 7.

2. Literature review

The problem considered in the thesis can be classified as a periodic vessel routing and fleet sizing problem with time window, multiple usages of vessels, speed optimization. A number of problem aspects stand out from the classification, namely periodic routing, fleet sizing and mix, and multiple uses of vehicles during the multi-period planning horizon.

Many authors have been worked on periodic vehicle routing problem and there is a wide variety of literature on this topic. At the same time most of the research focused on narrow aspects of that problem. Cordeau et al. (2004), Delgado et al. (2005), Polacek et al. (2007), Alegre et al. (2007) and Hemmelmayr et al. (2009) involve routing and scheduling decisions, but duration of vessel voyage is not limited like in our case. Gribkovskaya et al. (2007) studied routing side of periodic vessel supply planning problem, while Fagerholt and Lindstad (2000) focused on scheduling and vessel assignment. As far as exact methods for the PSVPP are concerned, Halvorsen-Weare et al. (2009) have proposed several of them. The first uses an arc flow model, the second is based on the preliminary generation of all cheapest feasible voyages.

Fagerholt and Lindstad (2000) address the problem of finding an efficient fleet composition and schedule for delivering supplies from a single onshore depot to multiple offshore installations in the North Sea. The fleet size and mix routing problem was studied by Golden et al. (1984). The objective was to determine optimal fleet size and mix by minimizing a total cost function which includes fixed cost and variable cost components.

Taillard et al. (1996) studied the VRP with multiple usages of vehicles. The problem of assigning each vehicle to one or more routes over a planning period of fixed duration. Brandao and Mercer (1997) presented a tabu search algorithm for the multi-trip vehicle routing problem. The method was developed to tackle real distribution problems, taking into account most of the constraints that appear in practice. And in 1998 they compared a simplified version of this tabu search

algorithm (only multiple trips and maximum driving time per day are considered) with the heuristic presented by Taillard et al., mentioned above.

Some authors tried to combine ship routing and scheduling with speed determination. Benford (1981) propose to select the mix of available ships and sea speeds that can perform the required service at maximum profitability to the owner. Brown et al (1987) and Bausch et al. (1998) brought in the variable value for speed for each sailing leg, but they had fixed schedule for each vessel. Papadakis and Perakis (1989), Fagerholt (2001) studied very similar problem with variable speed but with no time-windows at all in first case, and soft ones in the second. The main disadvantage of the last approach is size limits. There is no possibility to generate optimal solutions to large unconstrained problems.

There are, however, a number of papers that consider the economic impact of speed reduction especially for container vessels. Andersson (2008) considered the case of a container line where the speed for each ship reduced from 26 knots to 23 knots and one more ship was added to maintain the same throughput. Corbett et al. (2009) in the paper the effectiveness and costs of speed reductions on emissions from international shipping evaluates whether vessel speed reduction can be a potentially cost-effective CO_2 mitigation option for ships calling on US ports. Cerup-Simonsen (2008) developed a simplified cost model to demonstrate how an existing ship could reduce its fuel consumption by a speed reduction in low and high markets to maximize profits. Ronen (2010) studies the effect of oil price on the trade-off between sailing speed and increasing the fleet size. The cost model was constructed to analyse the trade-off between speed reduction and adding vessels to a container line route, and devise a simple procedure to identify the sailing speed and number of vessels that minimize the annual operating cost of the route.

Psaraftis et al (2009c) in their paper focus on operational measures that have a direct link to logistical operations, and investigate related tradeoffs. Measures such as reduction of speed, change of number of ships in the fleet, and possibly others, will generally entail changes in overall emissions.

Traditionally, models for ship routing and scheduling problems are based on fixed speed and a given fuel consumption rate for each ship. Fagerholt et al. (2010), in their work under the name reducing fuel emissions by optimizing speed on shipping routes present a multi-start local search heuristic to solve the problem of determination the optimal speed for each sailing leg of a given ship route.

Similar problems like the PSVPP but relaxed constraints have been studied by Fagerholt (1999), Fagerholt and Lindstad (2000) and Gribkovskaia et al. (2008). The role of supply vessels in offshore logistics is described by Aas et al. (2009).

3. Problem description

The problem, described in this thesis, is the case of Statoil. Therefore in this section we will give a short description of Statoil upstream logistics. The objective of this thesis is develop approach that during the main goal of vessel charter costs and fuel consumption costs minimization determines the best speed in order to curb the growth of greenhouse gases worldwide.

Our problem illustrated in Figure 1 includes offshore installations that are supplied from single onshore base.
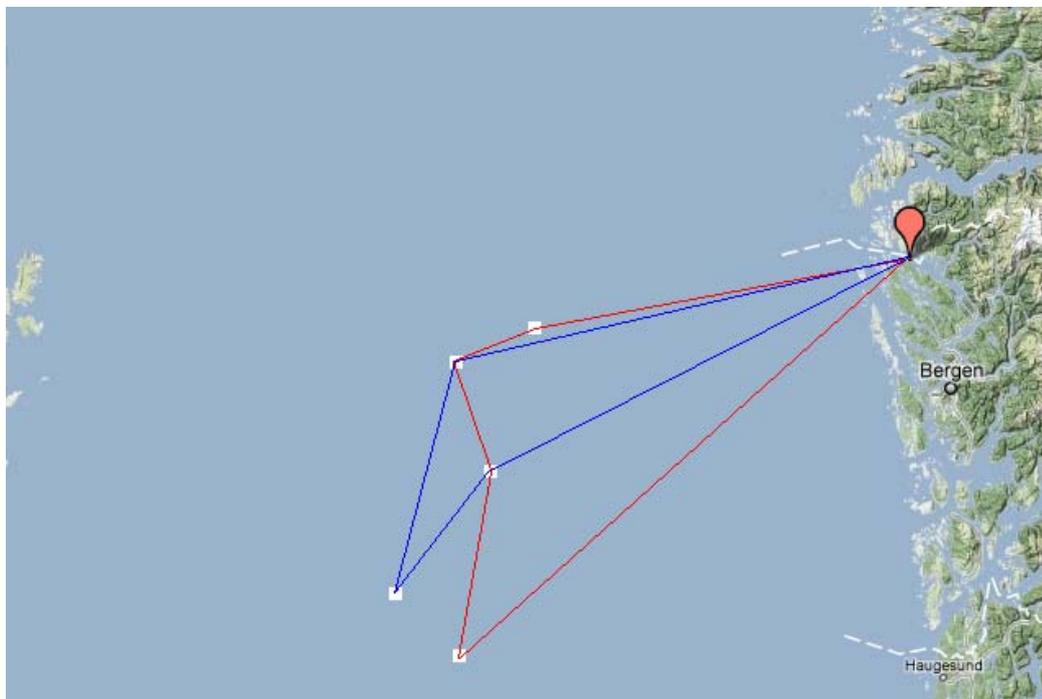

Figure 1. Periodic supply vessel planning problem with 5 installations.

Red ball represents Mongstad onshore base, while white squares are the real offshore installations. Blue and red lines are hypothetical voyages.

The following practical constraints must be taken into account in our problem:

1) Voyage duration limits.

2) The limits of installation visits per voyage.

3) Vessel deck capacity.

4) Weekly demand of each installation.

5) The visit requirement for each installation during the week.

6) The capacity and schedule of onshore base.

Restriction on the voyage duration is due to factors that too short voyages are not desirable, too long voyages cause to much uncertainty. Hence, the minimum duration of two days and maximum of three days are introduced. Moreover, each vessel could service only limited number of installations, there is a minimum and maximum number of visits per voyage.

Every installation has its own schedule of working hours. Some are opened round the clock and can be supplied at any time, while others are closed from 19:00 till 7:00. In addition, all vessels should start all voyages from onshore base at 16:00. It is also assumed that vessels return to the depot not late than 8 hours before departure time, if next voyage starts on the same day. Concerning day-offs, the onshore base is closed on Sundays.

Weekly vessel schedule is decided depending on planned demands of the installations. All of them have to be visited certain number of times during the week. It is also essential that the installation visits are fairly evenly spread throughout the week. Additionally, the total demand of all installations in each vessel voyage may not exceed the vessel deck capacity.
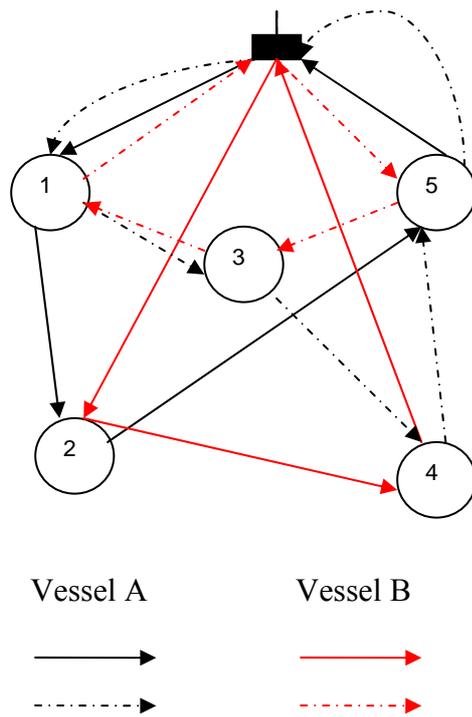
Figure 2: Example with five installations, two vessels and four voyages.

The simple solution example is shown on the figure two. It represents sample with two supply vessels that have to visit five installations. Some of them need to be visited two times a week when others require more often supply. Two platform supply vessels fulfill all required demand from installation. To carry out all orders each of them sails two voyages. This figure does not show all complicating aspects of the supply vessel planning problem.

Traditionally in that type of problems every ship has a fixed service speed established before schedule planning. In our case the speed between two installations can vary according to our choice. Every vessel has its minimum and maximum border and can differ in that limits. It also means that time and costs for that voyage also vary depending on the appointed speed.

The fuel consumption is strongly dependent on speed. We know the fuel consumption costs per ton and amount of tons of fuel all vessel used each hour during voyages sailing with fixed speed of 12 knots per hour. Therefore we could calculate total fuel consumption costs and then improve results of both aims: the total expenses and environmental benefits from speed reduction.

The rate of fuel consumption of a vessel (1) is approximately proportional to the cube of the vessel's speed Alderton et al. (2005):

$$\frac{Consumption_{new}}{Consumption_{fixed}} = \left(\frac{Speed_{new}}{Speed_{fixed}} \right)^3 \tag{1}$$

The main peculiarity of our approach that made our contribution to solving periodic supply vessel planning problem with variable speed tangible is the way of calculation total fuel consumption costs (2). Shyshou (2010) implemented large neighbourhood heuristics with fixed speed. In his work when the speed is fixed, fuel consumption is proportional to distance sailed, hence the total fuel consumption costs equals sailing cost and depend only on distance sailed. In our turn we use variable speed that influences the reduction of total costs and leads to the lower average speed for the fleet and hence lower fuel consumption.

$$TotalFuelConsumptionCosts = \frac{FCC}{V_{fixed}} \sum_{i \in V} \sum_{j \in L_i} d_{ij} V_{ij\,new}^2 \tag{2}$$

Sets:

V – a set of all voyages

L_i – a set of all sailing legs of voyage $i \in V$

Parameters:

FCC - fuel consumption on fixed speed 12 knots (ton/hour)

V_{fixed} - preliminary fixed vessel speed, equals 12 (knots/hour)

Variables:

$V_{ij\,new}$ - new speed for voyage $j \in L_i$ between two installations installations of voyage $i \in V$

d_{ij} - voyage distance of sailing leg $j \in L_i$ between two installations of voyage $i \in V$

Statoil spends sufficient part of all expenses to hire supply vessels from the shipping companies. There are basically two types of hire contracts: long-term and short-term. It is obvious that short-term vessels are much more expensive and are usually hired when there is a shortage of long-term ones. A natural question is how to service all installations with available long-term supply vessels with minimum expenses and fuel emissions.

Different authors have previously studied ship routing and scheduling problems with variable speed. Fagerholt et al. (2010) presents several algorithms to solve speed optimization problem for a fixed ship route. However this problem is different from our one for the reason that they count the minimum cost speed for a given route with a given starting time and ending time. In out case we have no fixed ending point for each voyage except time restriction that all vessels should start all voyages from onshore base at 16:00. Consequently, we could not use directly these algorithms without modification. We study and analyzed existent methods and develop a new combined approach for solving periodic supply vessel planning problem with variable speed.

4. Mathematical Model

The supply vessel planning problem can be formulated mathematically as an arc flow model and has been already studied by Halvorsen-Weare at al.(2009).

Formulation:

$$\min \sum_{j \in V} c_j Y_j + \sum_{j \in V} \sum_{k \in R_j} \sum_{t \in T} c_{jk} X_{jkt} \tag{3}$$

subject to

$$\sum_{j \in V} \sum_{k \in R_j} \sum_{t \in T} a_{ijk} X_{jkt} \geq s_i, \quad \forall i \in N \tag{4}$$

$$\sum_{k \in R_j} \sum_{t \in T} d_{jk} X_{jkt} - f_j Y_j \leq 0, \quad \forall j \in V \tag{5}$$

$$\sum_{j \in V} \sum_{k \in R_j} X_{jkt} \leq b_t, \quad \forall t \in T \tag{6}$$

$$\sum_{k \in R_{jl}} X_{jkt} + \sum_{k \in R_j} \sum_{q=1}^{l-1} X_{jk,(t+q)\bmod|T|} \leq Y_j, \quad \forall j \in V, \forall t \in T, l \in L \tag{7}$$

$$\underline{p_r} \leq \sum_{j \in V} \sum_{k \in R_j} \sum_{h=0}^{h_r} a_{ijk} X_{jk,(t+h)\bmod|T|} \leq \overline{p_r}, i \in N_r, t \in T, r \in F \tag{8}$$

$$Y_j = 0,1 \quad j \in V \tag{9}$$

$$X_{jkt} = 0,1 \quad j \in V, \tag{10}$$

Notation:

Sets:

V – a set of available supply vessels

N – a set containing all offshore installations

R_j – a set of preliminary generated cheapest feasible voyages vessel $j \in V$ may sail

T – a circularly ordered set representing the days of the planning horizon

F - a set of all possible visit frequency values

N_r - a subset of the installations requiring r visits per week $r \in F$

L - a set of all possible voyage durations measured in days

R_{jl} - a set of preliminary generated cheapest feasible voyages for vessel $j \in V$ with a duration of l days $l \in L$

Parameters:

c_j - the weekly charter cost for using vessel $j \in V$

c_{jk} - the sailing and service cost associated with vessel $j \in V$ sailing voyage $k \in R_j$

s_i - the required number of visits per week for installation $i \in N$

a_{ijk} - binary constants equal to 1 if and only if vessel j visits installation i on voyage k. $i \in N$, $j \in V$, $k \in R_j$

d_{jk} - represents the duration (in days) of voyage k sailed by vessel j (rounded up to the nearest integer) $j \in V$, $k \in R_j$

f_j - the number of days vessel j is available for during the planning horizon $j \in V$

b_t - the upper bound on the number of vessels leaving the onshore base on day $t \in T$

r - visit frequency, $r \in F$

h_r - the length of an auxiliary sub-horizon for the installations, $r \in F$

$\underline{p_r}$ - the lower bound on the number of visits during the sub-horizon h_r

$\overline{p_r}$ - the upper bound on the number of visits during the sub-horizon h_r

Variables:

X_{jkt} equals 1 if vessel j starts voyage k on day t, $j \in V$, $k \in R_j$, $t \in T$, otherwise equals 0.

Y_j equals 1 if vessel j is used $j \in V$, otherwise equals 0.

The objective function (3) expresses the minimization of the sum of vessel charter costs and of voyage sailing and service costs. Constraints (4) guarantee that each installation will be visited a given number of time during the week. Constraints (5) define the duration of all voyages done by a vessel may not exceed the total available number of days of this vessel. Constraints (6) are depot capacity constraints: the total number of vessels departing from onshore base to installations on a given day could not exceed depot's capacity. Further, Constraints (7) ensure that no vessels are starting on a new voyage before returning to the base from the previous voyage, for example if vessel starts l-day duration voyage on day t then it is not allowed to assign it to other voyages within period $[t+1, t+l-1]$. Constraints (8) ensure the uniformity of departures to the installations, depending on their visit frequency. Constraints (9), (10) set the binary requirements for variables X_{jkt}, Y_j respectively.

The modulus function (mod) is used in constraints (7) and (8) as this is a periodic routing problem, where the schedule repeats itself every $/T/$ day.

5. Large neighbourhood search heuristics for PSVPPSO

In this section we present a large neighbourhood search heuristic for the PSVPP with speed optimization. That type of algorithm with permanent speed was first described in Ph.D. thesis by Alexander Shyshou (2010), where one of the papers was dedicated to the large neighbourhood search heuristic for a periodic supply vessel planning problem arising in offshore oil and gas operations. The main difference and the point that makes this thesis valuable is the introduction of variable speed parameter. The description, the flow charts of large neighbourhood search heuristics for PSVPP and speed optimization algorithm, generation of initial solution and simple improvement procedures are provided in this part of the thesis.

5.1 Large neighbourhood search heuristic

The main idea of algorithm is to find a solution that consists of a set of voyages for particular number of available vessels. The starting point to build that solution is the construction of feasible initial solution.

5.1.1 Initial constructive heuristic

A flowchart for constructing an initial feasible solution is depicted in Figure 1. Every step of that procedure has to meet the requirements of constrained problem, e.g. the number of vessel departures on a given day is limited by onshore base capacity.
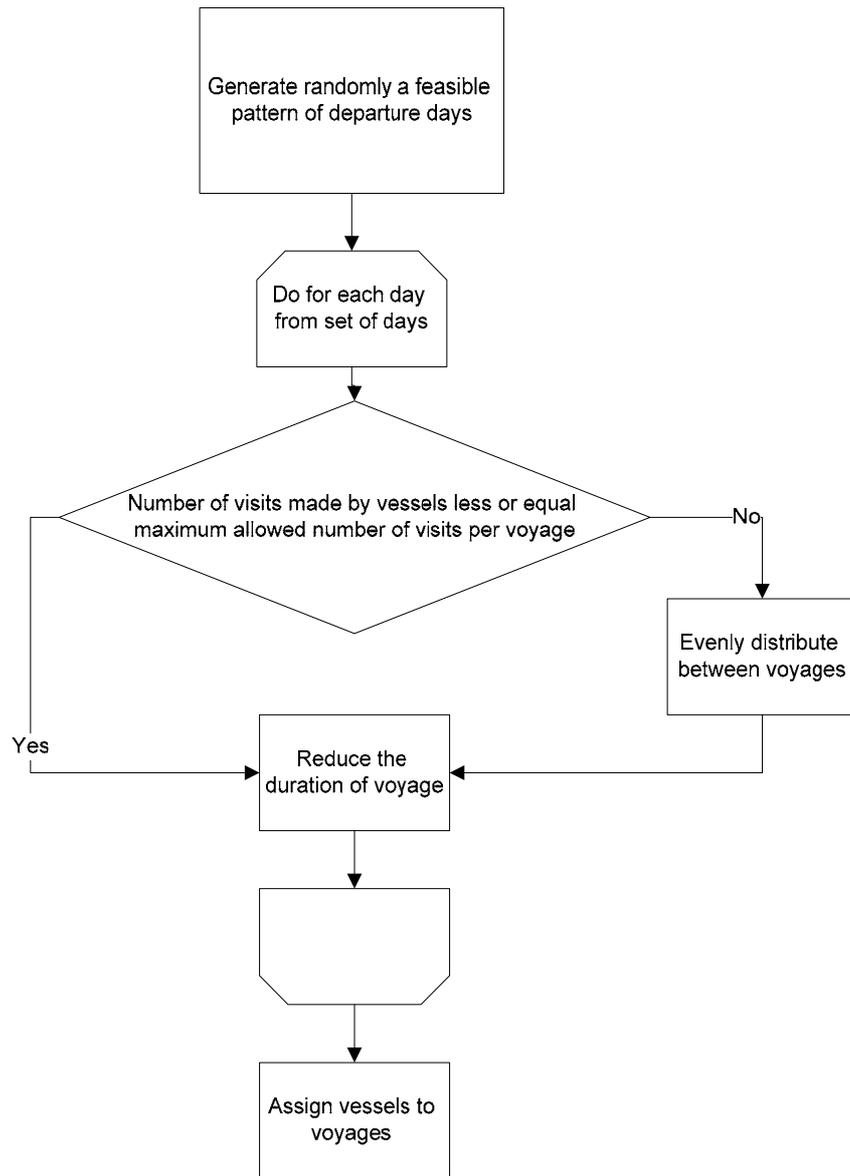
Flow-chart 1. Initial constructive heuristic

To reduce the duration of each voyage an intra-voyage optimization is used. At the last step the smallest available vessels with sufficient capacity are assigned firstly. If there is no way to assign vessels to all voyages, the entire procedure should be repeated until any feasible solution will be found.

5.1.2 Improvement stage

The improvement procedure consists of several methods:

-        intro-voyage optimization,
-        reducing the number of voyages,
-        reassigning vessels to voyages,
-        relocation visits to other voyages.

The main idea of intro-voyage optimization routine is to reduce the duration of a voyage by removing one visit at a time, then finding the first possible position to insert that visit which reduces the voyage duration. That type of strategy calls first-accept strategy. We repeat this operation is until no more improvement could be done.

We may to reduce number of voyages by looking for time slot. If it is possible to find these time slots new planning for vessels can be applied and schedule becomes more compact. Obviously it helps to reduce number of vessels used in our solution and as a result to cut down the expenses for using extra ships. To reduce number of voyages in our schedule we do next operation for each voyage: remove one visit at a time and try to insert it into another voyage. If we can do this operation for all visits of chosen voyage without solution feasibility violation we accept the changes.

To reduce the fleet size and the average capacity of the fleet without increasing its size we apply the reassigning vessels to voyages procedure. There are two main steps to archive this purpose:

- Change if possible the vessel fulfilled the voyage to a smaller vessel or to another used vessel.
- Accept the changes in case if all voyages performed by the vessel can be reassigned.

To relocate visits to other voyages the routine demonstrated on flow-chart 2 should be fulfilled.

```
                    ┌─────────────────────┐
                    │   For each voyage    │
                    └─────────────────────┘
                              │
                              ▼
                    ┌─────────────────────┐
                    │  Do for each visit of│
                    │   current voyage     │
                    └─────────────────────┘
                              │
                              ▼
                    ┌─────────────────────┐
                    │  Evaluate al feasible│
                    │ relocations of visit to other│
                    │      voyages         │
                    └─────────────────────┘
                              │
                              ▼
                    ╱─────────────────────╲
                   ╱  If current relocation ╲
                  ╱  brings the largest      ╲
                  ╲  improvement in the objective╱
                   ╲─────────────────────╱
         Yes                              No
          │                               │
          ▼                               │
   ┌──────────────┐                       │
   │ Remember relocation│                 │
   │   as the best one  │                 │
   └──────────────┘                       │
          │                               │
          ▼                               ▼
       ┌─────────────────────┐
       └─────────────────────┘
                  │
                  ▼
       ┌─────────────────────┐
       └─────────────────────┘
                  │
                  ▼
       ┌─────────────────────┐
       │  Implement the best  │
       │     relocation       │
       └─────────────────────┘
```
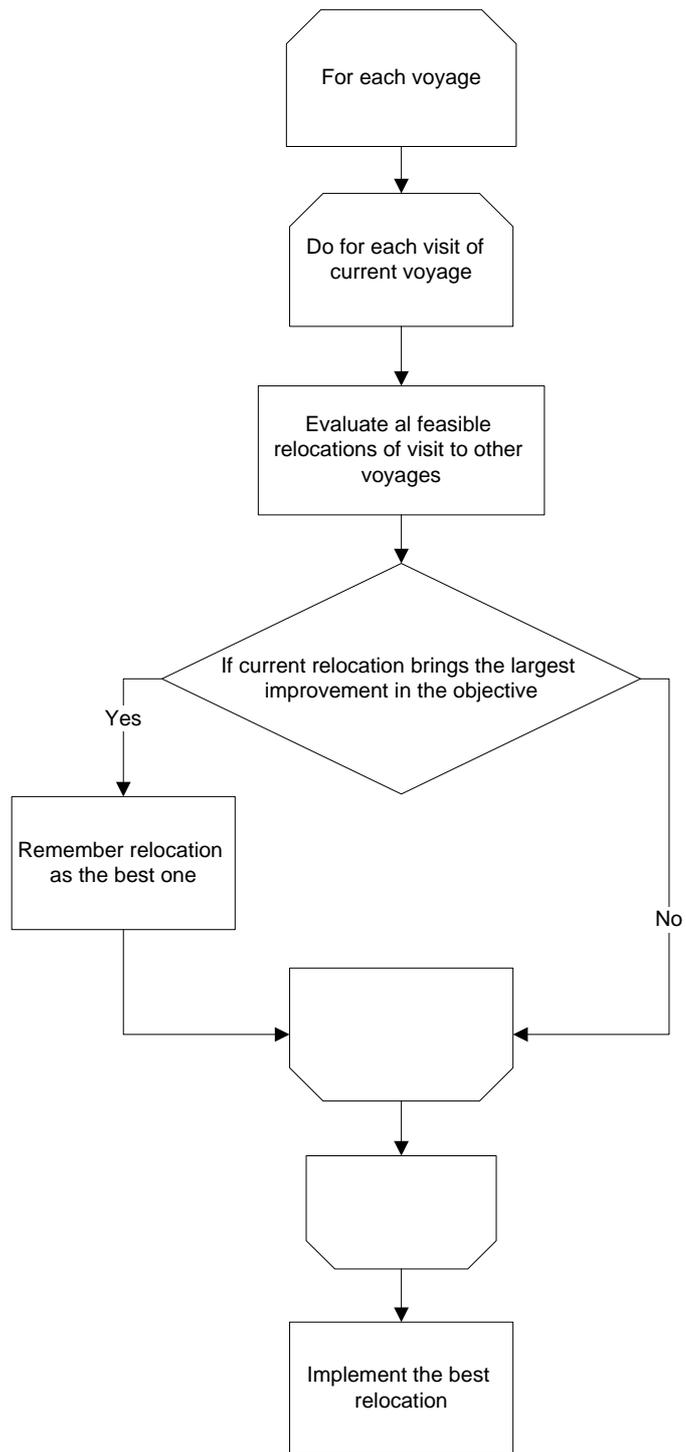
Flow-chart 2. Relocation visits to other voyages

The relocation is considered as feasible if next conditions hold:

- It does not exceed vessel capacity of the destination voyage, i.e. the voyage to which the visit is relocated.

- The uniformity of departures to the installations.

- The voyages durations after the relocation satisfy their lower and upper limits.

5.1.3 LNS algorithm with constant speed

This type of algorithm was first proposed by Shaw (1998) and developed by Shyhou (2010). At each iteration, we define the set of all feasible solutions that can be reached from initial by voyage modification (Shyshou et al., 2010b). We determine the set of voyages for PSVPP, choose a particular vessel from the list of the ones available and fix it to one of the voyages.

The heuristics consists of removal, reinsertion and improvement stages. The detailed description for large neighbourhood search heuristics is shown on the flow-chart 2.

The main difference from our algorithm is the lack of variable speed usage. Shyshou et al. (2010) apply speed as a constant parameter equals 12 knots for every ship. It implies that sailing time and fuel consumption costs between two installations depend on beforehand fixed distance, hence they are constant. Further, we describe our algorithm with variable speed parameter, where sailing time and fuel consumption costs between two installations are also variables determined by chosen speed.

```
                    ┌─────────────┐
                    │ Start for every │
                    │   restart    │
                    └──────┬──────┘
                           │
                    ╱──────────────╲
                   │    Initial     │
                   │    feasible    │
                   │    solution    │
                    ╲──────────────╱
                           │
                    ┌─────────────┐
                    │ Do removal stage │
                    │  for n iterations │
                    └──────┬──────┘
                           │
┌──────────────┐      ╱──────────────╲
│ Empty voyage │◄─Yes─│ if we removed some voyages at one of │
│ creation stage│     │   the previous iterations    │
└──────┬───────┘      ╲──────────────╱
       │                     │ No
       │              ┌─────────────┐
       └─────────────►│ Visit reinsertion │      ┌──────────────────────┐
                      │    stage     │      │ An LNS iteration starts with a │
                      └──────┬──────┘      │ random removal of several │
                             │             │ visits from a number of │
                      ╱──────────────╲     │ voyages and putting them in │
                     │ If bank of not inserted visits empty and found │ a bank of not inserted visits │
                     │        solution is feasible        │
                      ╲──────────────╱
                             │
          ┌─────────────┐  ╱──────────╲   ┌─────────────┐
          │   Local     │─►│ Found solution │─Yes─►│ Update new │
          │ improvement │  │   is better   │      │  solution  │
          │   stage     │   ╲──────────╱       └─────────────┘
          └─────────────┘        │ No
                          ╱──────────────╲
                         │ S= sum of all voyages │
                         │      duration      │
                         │ F =min number of days │
                         │ one of the used vessels is │
                         │      available      │
                         │ M= total number of │
                         │    vessels used    │
                          ╲──────────────╱
                                 │
                            ╱────────╲
                           │  S/F<M   │──Yes──┐
                            ╲────────╱        ▼
                                 │ No    ┌─────────────┐
                                 │       │ Fleet-size  │
                                 │       │ reduction stage │
                                 ▼       └──────┬──────┘
                            ┌─────────┐         │
                            │   End   │◄────────┘
                            └─────────┘
```

Flow-chart 3. Large neighborhood heuristics algorithm

5.2 Speed optimization algorithm

The main idea of including speed optimization algorithm for a given route that represents a sequence of offshore installations with strict visit requirements is to determine the speed for each leg with the ultimate goal of minimizing fuel consumption. That formulation of the problem is based on the Fagerholt et al (2010).

Before adjusting LNS heuristic with constant speed, we have done preliminary work to establish the way to identify appropriate speed to reduce fuel emissions. There were several ways to reduce emissions in our routine:

1) set reduced constant speed (less than 12 knots);

2) reduce speed after building all voyages and assigning vessels to them by LNS;

3) modify LNS heuristics by implementing speed optimization algorithm at the improving schedule stage.

In our work we follow the third way. Our purpose is to keep the speed of all vessels at a level of minimum fuel consumption taking into consideration that the main function of vessels scheduling is to visit and supply with minimum costs all installations.

We will implement a recursive smoothing algorithm (RSA) for solving the periodic supply vessel planning problem with variable speed. The main idea of RSA is that the minimum cost speed for a given route will be the same for all sailing legs and determined as fraction of total sailing distance and subtraction of starting and ending time. We try to hold the speed is low as possible and without sudden leap on all legs of the voyage. The speed reduction allows us to introduce innovative method of calculation fuel consumption costs.

In this paper the load of the ships is not taken into consideration when the algorithm is used. We consider the same as Norstad at al.(2010) do that all vessels have the same fuel consumption function for all sailing legs.

The detailed description for recursive smoothing algorithm is shown on the flow-chart 4.
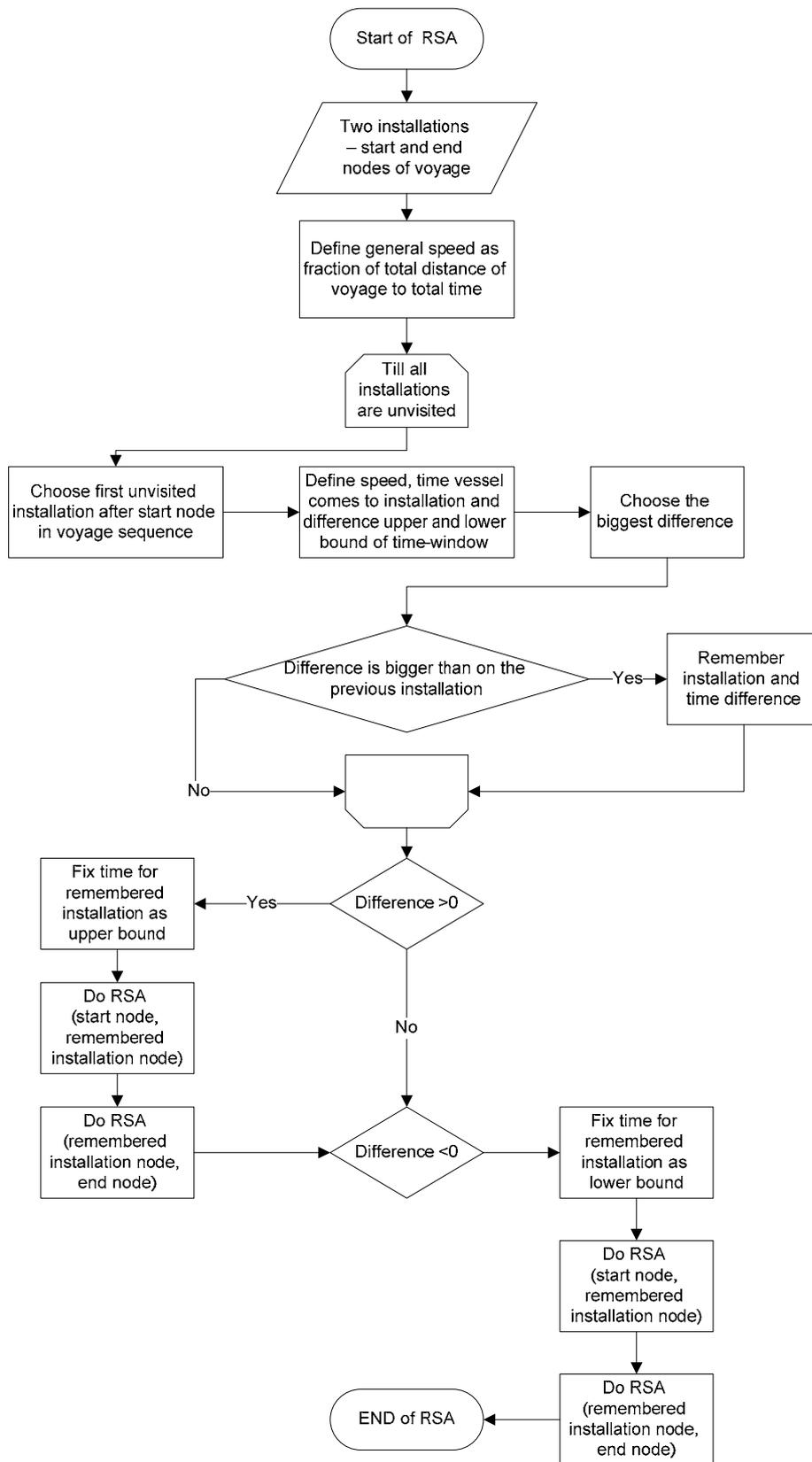
Flow-chart 4. A recursive smoothing algorithm.

5.3 Large neighbourhood search heuristic with speed optimization

The description of the large neighbourhood search heuristic (LNS) for the periodic supply vessel planning problem with speed optimization is described in that section of the thesis.

The brief outline of our algorithm includes the same several steps that large neighbourhood search heuristic with constant speed: removal, reinsertion and improvement steps. As it was described earlier we implement speed as a variable parameter, hence this novelty entails determining sailing time and fuel consumption costs between two installations also as variable values.

For p restarts we randomly generate initial feasible solution with the initial constructive heuristic and then for n-iterations do all the following steps shown on flow charts 5, 6 and 7.
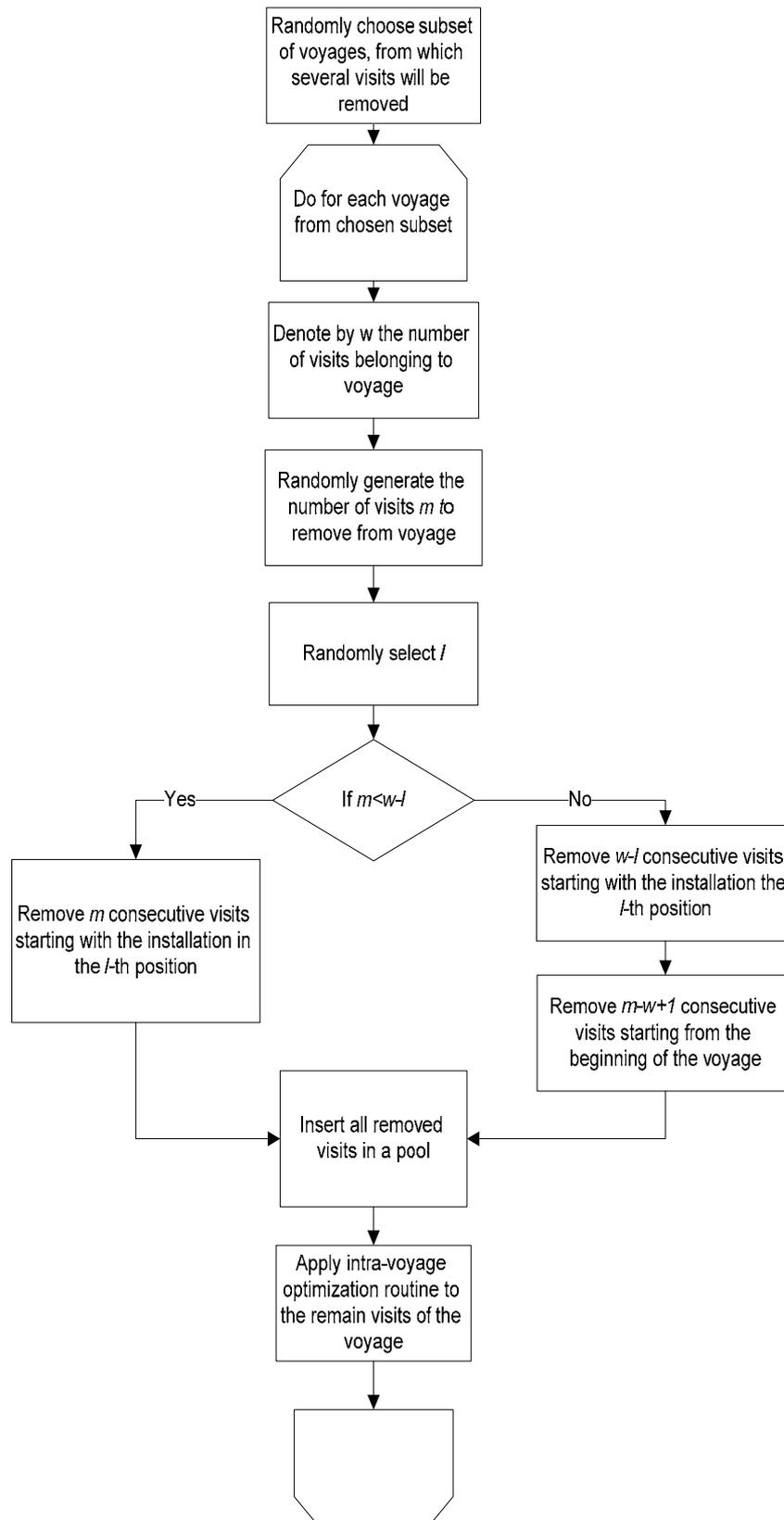
Flow-chart 5. The removal step.

This first stage includes next steps:

- choose random number of voyages,
- remove some installation from them,
- put these installations in a bank of not inserted visits,
- apply the intra-voyage optimization to the remaining visits.

If we remove some voyages when trying to reduce the number of vessels used at the previous iteration, we try to find a time slot where a new voyage could be created. The slot must meet the requirement such as:

- the vessel should be free during that time,
- the voyage should be not less than minimum duration limit,
- the same requirements for previous voyage performed by vessel.

In case if we find time slot for possible future insertion we create empty voyage and proceed to reinsertion stage.

On second stage we have to insert installation to voyages while it is possible to do or until the bank of not inserted visits has any installation inside. We try to find feasible insertion, again apply the intra-voyage optimization procedure and identify the best possible variant. The method to identify feasible reinsertions is shown on flow chart 6. Particularly that stage was chosen to implement the recursive smoothing algorithms to identify the best speed to archive to goals: cut costs and decrease fuel consumption, hence decrease fuel emissions. The initial variant of recursive smoothing algorithms requires given starting and ending time of the voyage. We know that start time for each voyage, but we do not know when exactly every voyage ends. Therefore, we modify the initial variant and apply in simultaneously with intro-voyage optimization algorithm.
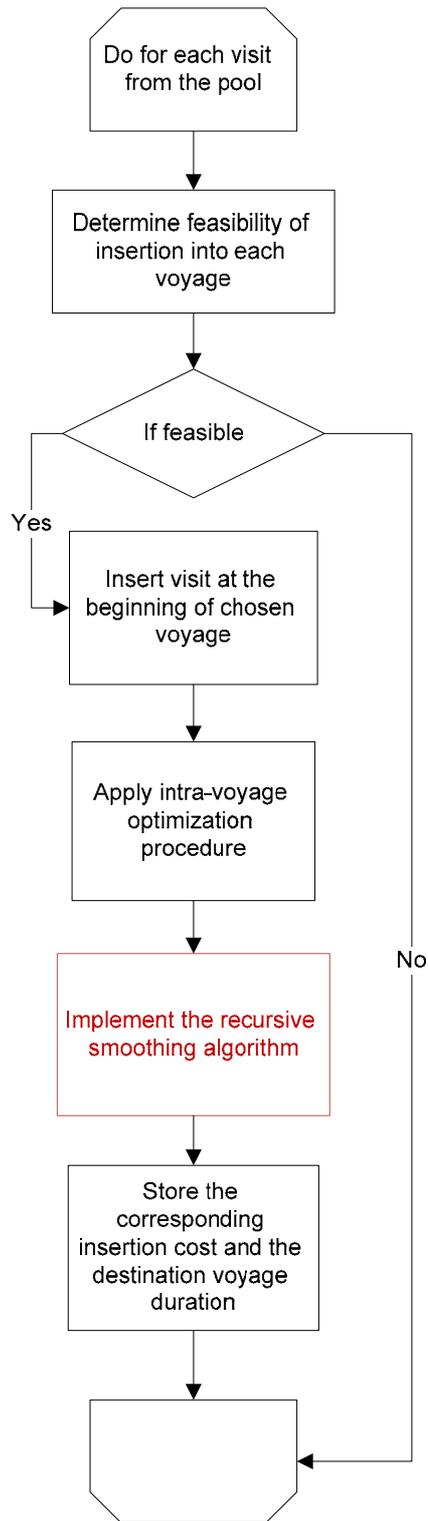
Flow-chart 6. The search of insert positions.

After determining feasible reinsertion positions, we identify the best one:

1.   For visits in the pool with only one feasible insertion voyage:

Choose the visit yielding the smallest values of the lexicographic ordering:

- o duration increase in days of the destination voyages,
- o objective function increase,
- o fuel emissions increase.

2.   For visits in the pool with several feasible insertion positions:

Choose the visit with the smallest duration increase in days of the destination voyages and the largest regret value ordered lexicographically.

1. Insert chosen visit at the beginning of the voyage.
2. Apply intra-voyage optimization procedure.
3. Implement recursive smoothing algorithm.

We implement intra-voyage optimization procedure and recursive smoothing algorithms cooperatively. First we try to reduce the duration of a voyage by mixing the positions in the voyage implementing removing-reinserting steps till we could find any improvements. And then for each voyage we count the best speed with RSA routine to utilize as less fuel as possible and as a result exploit less fuel consumption.

If there are no more visits in the pool after procedure of determining feasible positions, we can proceed with the improving routines in the following order shown in the flow-chart 7.
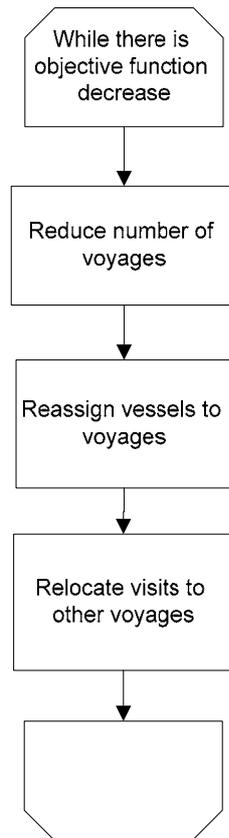
Flow-chart 7. The improvement procedures order.

Taking into account that Statoil does not own supply vessels the final step of heuristic is sufficiently important. As it was described earlier there are basically two types of hire contracts: long-term and short-term. Short rates are noticeable much higher than the long-term ones. Our purpose consists in avoiding situations where spot vessels should be hired because of a shortage of vessels on long-term contracts. In that case we check if the sum of all voyage durations divided by time period (in our case, one week) equals or bigger than the total number of vessel used in the sailing plan, we apply the sequence showed on flow chart 8 to reduce the number of vessels used.
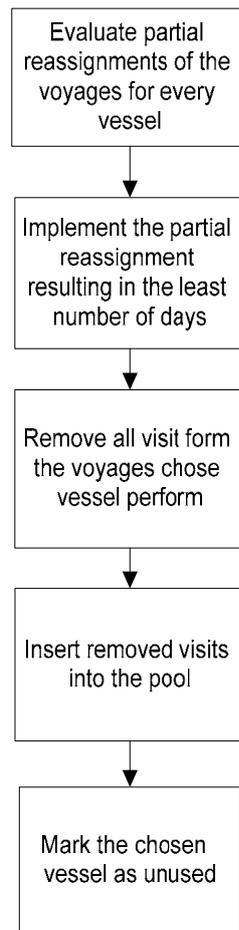
Flow-chart 8. The number of vessel reduction procedure.

Our algorithm always returns a feasible solution on account of the initial solution is also feasible.

1. Computational experiments

In this section we first describe the test instances. We then proceed to the computational evaluation of the large neighbourhood search heuristic. Clearly, the difficulty of the PSVPP is mostly related to the problem size, namely to the number of installation visits.

The Large neighbourhood search heuristic with speed optimization was coded in C++ and implemented in Microsoft Visual C++ 2005. All computational tests were run on a personal computer with a 2.70 GHz Intel Pentium Dual-Core processor and 2 GB of RAM under Windows 7. We have been concerned with running times of our approach.

6.1. Test instances description

The actual data provided by Statoil form the basis for instances for evaluation our solution. Halvorsen-Weare et al. (2009) and Shyshou et al. (2010) have evaluated their solution methods on the same set of instances. These instances differ in size of installation number: the smallest include three installations and the largest - fourteen. The name of an instance includes four numbers:

- the number of installations;
- the number of available vessels;
- the total number of installation visits;
- the number of installations closed between 19:00 and 7:00.

Regarding each vessel we keep informed about next operational characteristics:

- capacity (ton);
- fixed vessel costs (NOK);
- fuel consumption costs (NOK/ton)
- fuel consumption on base (ton/hour);
- fuel consumption on installation (ton/hour);
- fuel consumption on fixed speed 12 knots (ton/hour);

We select a set of possible operating speeds for each vessel. It is assumed that the vessel maintains exactly chosen speed from formed set on its way between two installations.

6.2. Assessment of the large neighbourhood search heuristic

In this section we present the computational results for our LNS heuristic with speed optimization.

In the LNS heuristic there are several beforehand user-defined parameters such as:

1) the number of restarts,

2) the number of LNS iterations at each restart,

3) the number of voyages from which several visits are removed.

In order to determine trade-off between solution quality and computation time we separate all data into:

o   smaller instances (tree to eight installations),

o   medium instances (nine and ten installations),

o   larger instances (eleven to fourteen installations).

After some preliminary estimation the number of restarts and the number of iterations for each restart were distributed according to instance size as it is shown in Table 1:

Instance	(restarts, iterations)
3-5-0	(10,10)
4-5-0	(10,10)
5-5-0	(10,10)
6-5-0	(10,10)
7-5-0	(10,10)
8-5-0	(10,10)
9-5-0	(10,75)
10-5-0	(10,75)
11-5-0	(10,200)
12-5-0	(10,200)
13-5-0	(10,200)
14-5-0	(10,200)

Table 1. The user-defined parameters in the LNS heuristic.

Using constant speed often led to a solution where the vessels are unevenly utilized. This is as we mentioned earlier because the speed is constant and fuel consumption depends on distance that vessel sail. In this situation the task in the context of minimization fuel emissions would be tied to total travel distance. In our case variable vessel speed was applied during the process of constructing schedules,

voyages and assigning vessels to these voyages. It gives us more flexibility during the process of constructing the solution.

Computational results for basic instances are reported in Table 2.

Instance	Voyages	Number of Vessels	Average Speed	Percent of Costs Improvement
3-5-16-0	6	2	11,72	2,4017
4-5-21-0	6	3	11,6	3,288
5-5-23-0	6	3	10,93	3,88
6-5-25-0	6	3	11,4	3,411
7-5-30-0	6	3	11,28	3,127
8-5-36-0	6	4	11,26	3,1
9-5-42-0	6	4	11,22	2,79
10-5-43-0	7	4	11,34	2,3369
11-5-47-0	8	4	11,63	1,4466
12-5-51-0	8	5	11,8	1,4007
13-5-55-0	9	5	11,826	1,08786
14-5-59-0	9	5	11,859	1,000333

Table 2. Computational results for basic instances.

Computational results for basic instances with time windows are reported in Table 3.

Instance	Voyages	Number of Vessels	Average Speed	Percent of Costs Improvement
5-5-23-1	6	3	10,43	3,18
6-5-25-2	6	3	10,79	3,03
7-5-30-3	6	3	10,67	2,795
8-5-36-2	6	4	10,76	2,99821
9-5-42-2	6	4	10,72	2,953
10-5-43-3	7	4	10,96	2,24
11-5-47-3	8	4	11,03	1,497
12-5-51-3	8	5	11,49	1,181
13-5-55-3	9	5	11,526	0,9056
14-5-59-3	9	5	11,609	0,7455

Table 3. Computational results for basic instances with TW.

During the minimization costs process we determined the better variable speed in order to limit the growth of greenhouse gases worldwide. The results in average speed on basic instances with and without time windows differ from each other :
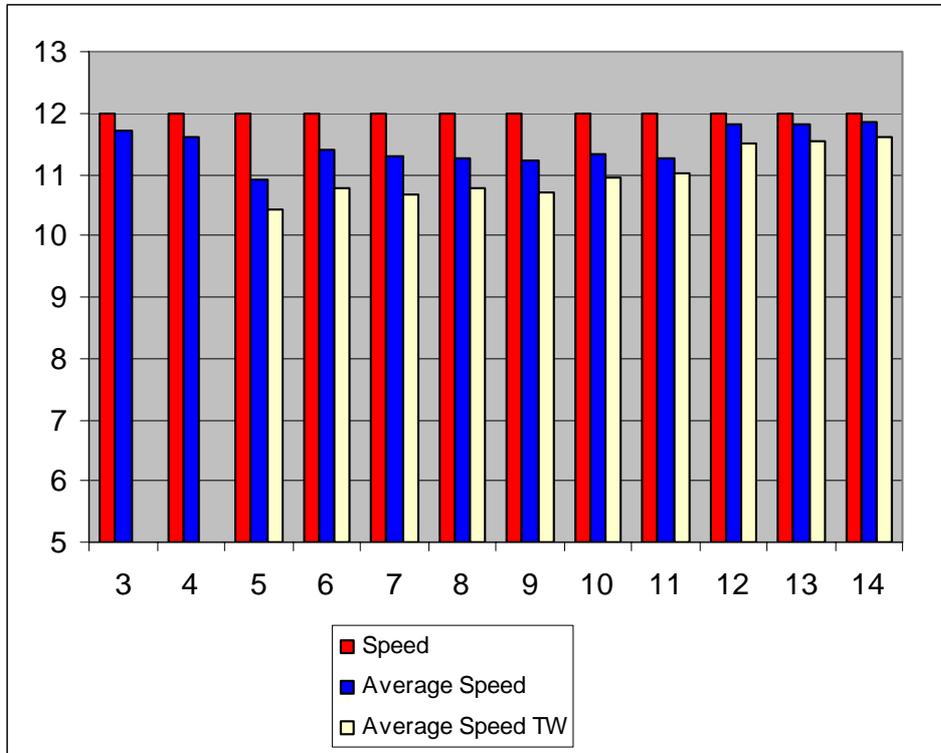

Figure 3. Speed comparison

As total fuel consumption costs depends on quadratic function of speed (2), while reducing average speed on voyages we cut total fuel consumption costs. And simultaneously we reduce total percent of fuel emission made by vessels.

There is also interdependence between average speed and cost improvement. We consider the designed fixed speed of all our vessels as 12 knots, while variable speed could vary from 10 to 14 knots. But as the figure 3 indicates the average speed on all sets of instances without time windows is between 11 to 12 knots, while speed on sets of instances with time windows is less.

There is no way to compare results and computation time of our heuristic with optimal algorithm solution. In practice no comparative data are available for larger instances because it is not possible to solve this problem with exact methods. The results of total costs including fuel consumption costs are presented on Figure 4.
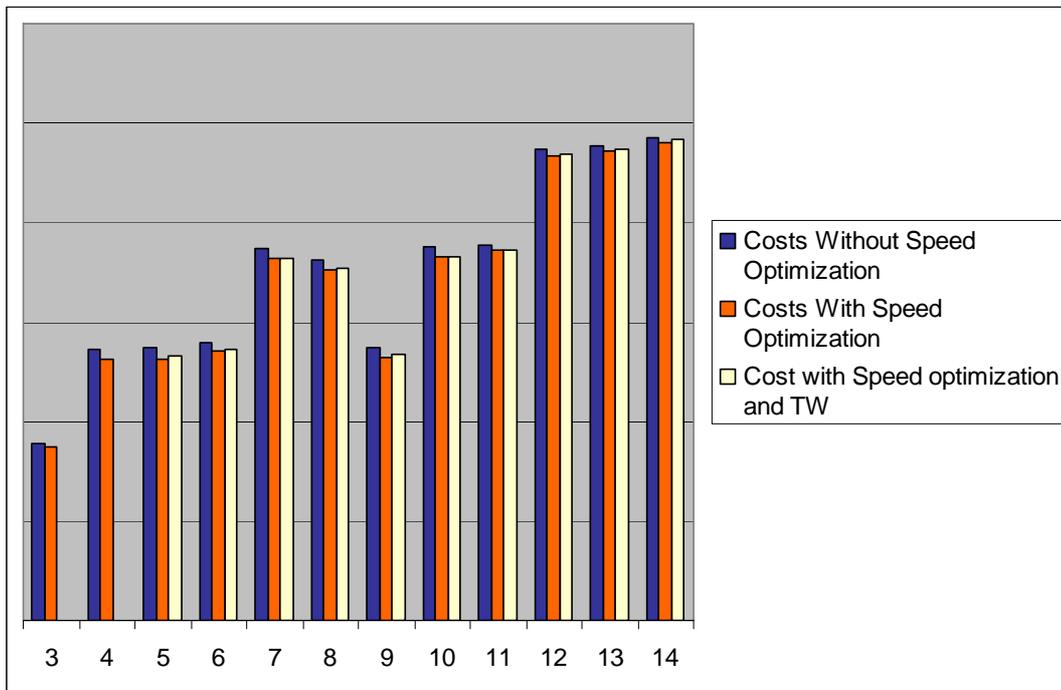

Figure 4. The costs comparison

The search for opportunities to cut costs while maintaining the necessary level of service is pretty hard but accomplishable task. The speed introduction as a variable parameter in LNS heuristics allows us to gain till almost 4% savings in costs. We assume that saving costs are the difference in total costs calculated by large neighbourhood heuristics with constant speed and by one with variable speed. But it is evident from the figure 4 that with the increasing number of installations and constant number of available supply vessels percent of cost savings is decreasing. Even though it would seem that with increasing number of installations and visits during the week, we obtain more flexibility at improvement stage of LNS routine, the increase of delivery frequency shortens the opportunity to vary in speed size.
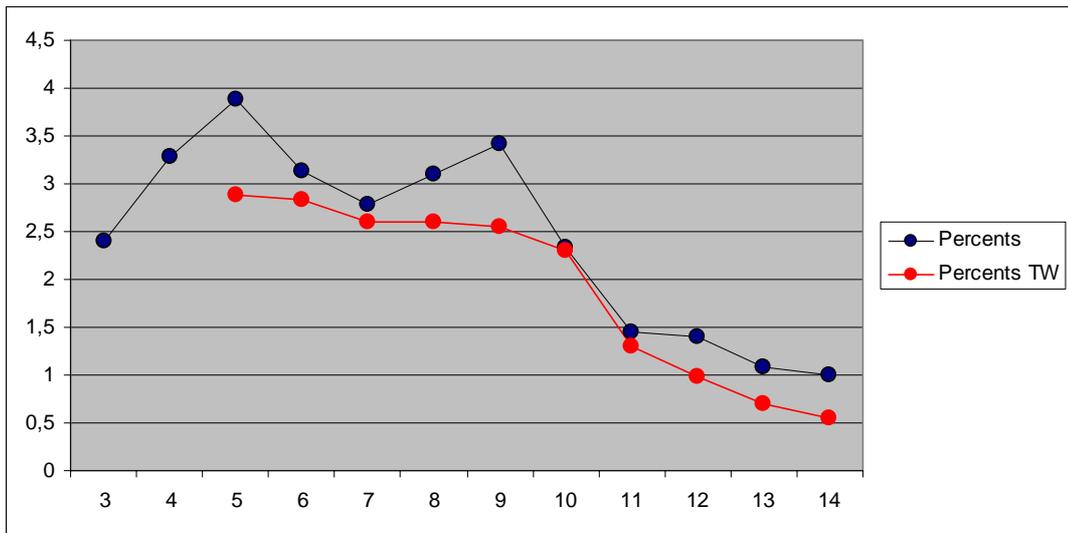
Figure 5. Percents of total costs reduction

The results of fuel consumption costs reduction are influenced by our preliminary decision of the number of restarts and the number of LNS iterations at each restart in LNS heuristic. The average percent of larger group of instances without time windows (11-14 installations) noticeably differ from smaller and medium groups, e.g. average 3,2% and 2,7% correspondingly compared to 1,2%.

As it was mentioned earlier speed reduction is more sizeable on instances with time windows than without that type of restrictions. It means that we achieve better results in minimization fuel emissions. However, the total costs do not show the same tendency. Speed optimization on instances with time windows shows better improvement due to the reason of waiting time spaces appearance. In this case we definitely prefer to sail with smaller speed than wait on the installation. This approach would have worked for total fuel consumption costs, if it depended only on chosen reduced speed. But the formula (2) that was given in third section of the master thesis demonstrates the total fuel consumption costs dependency on both speed and distance. And the voyages distances increase due to the fact of adding extra constraint of installation working hour limits.

7.   Conclusions

The supply vessels are one of the most costly resources in upstream logistics of oil and gas production. Therefore the problem consisting of finding scheduled voyages and the mix of vessels to perform these voyages requires thorough planning. Moreover, nowadays emissions from platform supply vessels are at the centre of attention of the world shipping community. Consequently, we consider our work from the point of view of an effective mechanism of the environmentally-oriented logistics.

We have studied and analyzed existent methods and develop a new combined approach. We have presented a large neighbourhood search heuristic with speed optimization for the periodic supply vessel planning problem in order to minimize fuel emissions. We adjust recursive smoothing algorithm and implement it simultaneously with into-voyage optimization routine in our heuristic to determine vessel speed for each leg along the voyage for every vessel.

Speed reduction will always result in a lower fuel consumption expenses and lower fuel emissions. However, due to vessel charter costs and other ship costs, total costs may decrease or may not decrease with speed reduction, depending on the algorithms and initial data. Taking speed as a decision variable allows us to improve costs due to decreasing the total fuel consumption costs.

Computational experiments, based on real data from Statoil, demonstrate that the heuristic is quite efficient for the instances considered and can be used to solve larger instances of the problem.

Statoil holds the opinion of improving their route planning, which is necessary in order to make their transport as energy efficient as possible. This thesis could help to achieve this goal in practice.

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