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LOG950 Logistics

Heuristic for Robust Periodic Supply Vessel Planning

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Abstract

In the upstream offshore petroleum logistics, supply vessels play crucial role as the largest contributor to the costs. Therefore, for this industry detailed supply vessel planning is significantly important. In the literature, this type of problem is called Periodic Supply Vessel Planning Problem (PSVPP). The problem is directed to the construction of the weekly delivery schedule that meet all requirements under cost minimization. Weather conditions may highly affect the performance of the schedule, leading to frequent delays that consequently result to high penalties. With the aim to include stochasticity of the weather to consideration, we develop robust assumptions. These assumptions are further incorporated to the existing heuristics approach for schedule construction. Experiments verify that developed heuristic algorithm significantly increases schedule stability.

KEYWORDS: offshore logistics, routing, scheduling, weather uncertainty, large neighborhood heuristics, robustness.

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1.0 Introduction

Petroleum industry is an important area in energy supply and economic sector of many different countries. The economy of Norway depends on the oil-extracting sector, which contributes to about one-third part of general state revenues. Norway is the largest producer of oil and gas in the Northern Europe.

The problem described in this thesis is a real-world problem faced by Norwegian oil and gas company Statoil ASA. Oil production in Norway is carried out offshore, offshore installations require regular service with on time deliveries in order to provide efficient production. In our case, the onshore supply base is located in Mongstad and the installations are located in the North Sea. For delivery of commodities to installations special supply vessels are used on regular basis. Deliveries to offshore installations are provided according to repetitive weekly schedule. Weekly schedule represents a set of vessels, each having a collection of voyages assign to specific departure time. The set of installations visited by a particular vessel on a particular departure day in a certain sequence is called a voyage. Supply of offshore installations is associated with high costs such as vessel charter costs and fuel costs. In addition, in case of schedule disrupt, there are downtime costs and the costs of hiring extra vessel or helicopter. Therefore, an efficient planning of deliveries to supply installations represents an important task.

Weather conditions on the Norwegian continental shelf, especially in wither are quite harsh and uncertain, with high waves and strong winds. Uncertain weather conditions influence vessel sailing and service times at installations. According to guidelines for safe offshore operations, it is not allowed for supply vessels to perform service at installations when wave height exceed certain values. This in turn may cause disruption of the schedule due to voyage duration increase and as follows later arrival to start a next voyage according to the schedule. As result, companies sustains loses in the form of downtime costs and spot vessel cost. For these reasons, schedule should be constructed so that it is robust against uncertain weather conditions.

In this thesis, we consider robust Periodic Supply Vessel Planning Problem (PSVPP). Existing literature related to robust PSVPP is quite scarce. Robustness is implemented in a simple way, just by adding a slack at the end of a voyage. Furthermore, problems related to robust supply vessel planning, considered so far are of small or medium sizes. We develop new approaches of robustness incorporation into delivery schedule and use Large Neighborhood Search (LNS) heuristic that provides possibility to deal with problems of large size.

The remaining part of the thesis is organized as following: chapter 2 describes the details of the problem structure. In chapter 3, is provide relevant to the studied topic literature and comparison to the studied problem. In chapter 4, we present solution methods, which may be able to help in finding of the solution approach for examined problem. In chapter 5, we set the objective of this master thesis. In chapter 6 is shown the solution approaches with detailed explanations of the logic. Chapter 7 present the experiments with their analysis. In chapter 8, we summarize accomplished work and suggest some directions for the futures research. Finally, is presented the list of references and tables with experiments.

2.0 Problem description

The problem that is considered in the thesis is formulated as a variant of the periodic supply vessel-planning problem (PSVPP). In this chapter, we specify the problem with all inherent to it characteristic, describe the aspects that are needed to be taken into account for problem definition.

2.1 *Periodic Supply Vessel Planning*

Periodic Supply Vessel Planning Problem (PSVPP) deals with finding the cheapest schedule for a given planning horizon for a fleet of supply vessel that serves a set of offshore installations taking into account all required constraints. The PVSPP involves simultaneous decisions on identifying the optimal vessel fleet composition needed to perform service from onshore supply base to offshore installations, sequence of installation to visit on each voyage and assignment of voyages to vessels and to departure times. From the point of combinatorial complexity, it involves three NP-hard problems such as scheduling, packing and routing problems (Lenstra and Kan 1981). PSVPP may be considered on three levels – operation planning, tactical planning and strategic planning. Operational planning involves to everyday planning. It deals with operations on the specific voyage, such as selection of vessel speed, vessels loading and unloading operations at the supply base or at the offshore installations and routing decisions in relation to weather conditions. Tactical planning deals with construction of a weekly schedule. It involves decisions on the fleet size, vessel routing and scheduling, and inventory management. Strategic planning is used to maximize the service quality with resource restrictions or to minimize total expenses under service restrictions. The planning horizon for strategic planning is longer than one year. It deals with market and trade selection decisions, fleet size decisions, transportation system and network design. Vessel weekly schedule is used repeatedly until there are no reasons to make changes. There are examples of possible causes, where service companies may need revisions in the current planning: new installations need to be serviced, changes in the working hours, major changes at the demand or in the required number of visits for some installations. Problem dimensions depend on number of supply bases, offshore installations and supply vessels. For the definition of the problem and its restrictions, we need to look closer to its structure.

2.1.1 Supply base

The onshore supply base provide loading/unloading cargo operations for installations as the starting point. A cargo is to be delivered either to or from the platforms. Supply base serves certain set of installations and it has a limited number of supply vessels.

Several restrictions follow from supply base characteristics. Supply base can provide loading and unloading services within its opening hours. In Norway, working hours are usually specified from 8:00 to 16:00. Service time for vessel on the base is approximately 8 hours. Departure time for vessels is assumed to be flexible throughout the day. Under flexible, is understood that departures from the supply base may take place at specific points in time which are optional. In addition, there is limited storage capacity at the base and limited number of berths that restricts the number of vessels serves simultaneously.

2.1.2 Offshore installations

The offshore installations execute main operations for production of oil and gas. Each offshore installation has its requirement for the minimum number of visits per week and weekly demand measured as a volume of cargo needed to be delivered. Demand per visit is calculated as weekly demand divided by number of visits per week. Departure to installations should be evenly spread during the week, depending on the visit frequency. Furthermore, installations may be closed during the night. Opening hours are different depending on the type of an installation. Drilling installations are open permanently, while production platforms are opened from 7:00 till 19:00. Time for the execution of service is called service time. During schedule construction, planners should take into account that arrival time to a night-closed installation should be such that the service could be performed before closing time in the same day. Visual example of installations location is presented at the Figure 1.

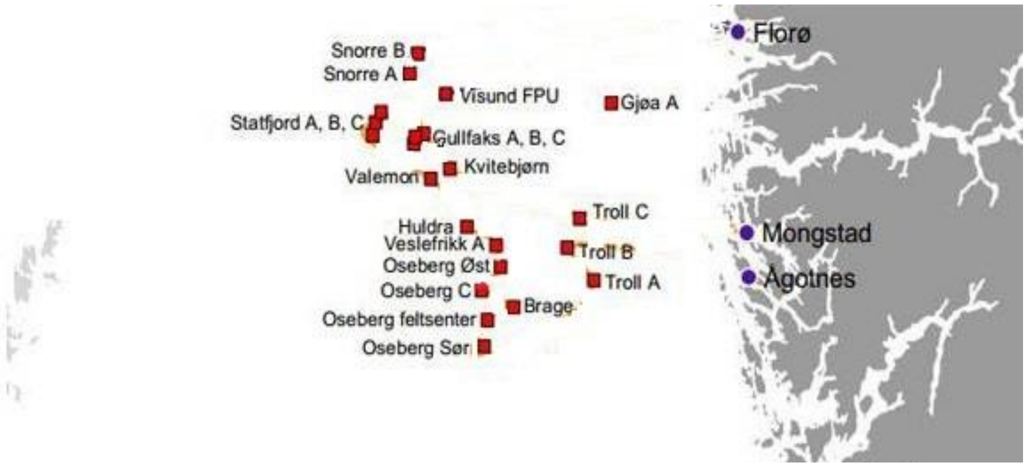

Figure 1 - Visual example of 22 installations

2.1.3 **Supply vessels**

The platform supply vessels (PSV) are used to deliver cargo to and from offshore installations. Vessel fleet is heterogeneous because vessels have different capacities and sailing speed. That means that some PSVs are unable to sail voyages that can be sailed by other PSVs because the total demand exceeds vessels capacity. Costs of using a supply vessels are subdivided into fixed vessel charter costs and variable fuel cost that depends on fuel consumptions rate and vessel speed. Fuel consumption differs depending on the type of operation performed by a vessel, such as: loading/unloading at the supply base, sailing, loading/unloading at an installation and waiting at an installation for servicing.

2.1.4 **Routes and voyages**

By the route, we understand set of voyages assigned to a particular PSV during the week. The voyage is defined as a sequence of installations to visit by a PSV starting and ending at the supply base.

There are also some requirements to voyages and routes. Voyage has a maximum duration in days that is explained by maximum lead-time delivery requirements. As well, there is a limit on the maximum number of installations per voyage. In addition, it should be guaranteed that there is no overlap between voyages assigned to the same vessel. Since, each installation must receive the required number of visits during the week; the number of routes in the schedule, containing certain installations should be equal to visit frequency.

2.1.5 **Objective**

Based on the above described characteristics and requirements inherent to the problem, we may formulate objective of the PSVPP: construct a weekly sailing plan such that the total vessels charter cost and fuel cost, and the costs of sailing, servicing and waiting are minimized. In order to reach this objective, we need to define the number of used PSVs and their type, voyages for each vessel and their departure times and sequence of installations for each voyage such that the total costs are minimized, provided that all constraints are respected.

2.1.6 **Weekly schedule**

As it was mentioned above, supply vessels schedule is represented by a set supply vessels, collection of voyages assigned to the departure time. Each voyage is represented by a set of installations in a certain sequence with start and end at the offshore base.
The Figure 2 below shows an example of a weekly schedule. In this example, there are three vessels: Star, Simphony, and Foresight. A time units in this schedule in 8 hours. Each vessel has two voyages during a week. For example, vessel Star has two voyages, departing from supply base at 16.00 on Monday and at 16.00 on Thursday (in absolute time at 88 hour). Time units marked by a cross correspond to the time spent for loading/unloading operations at the base. For each voyage, specified installations to be visited in their visiting sequence (for example, set of installations for voyage two of vessel Star in their visiting sequence is:

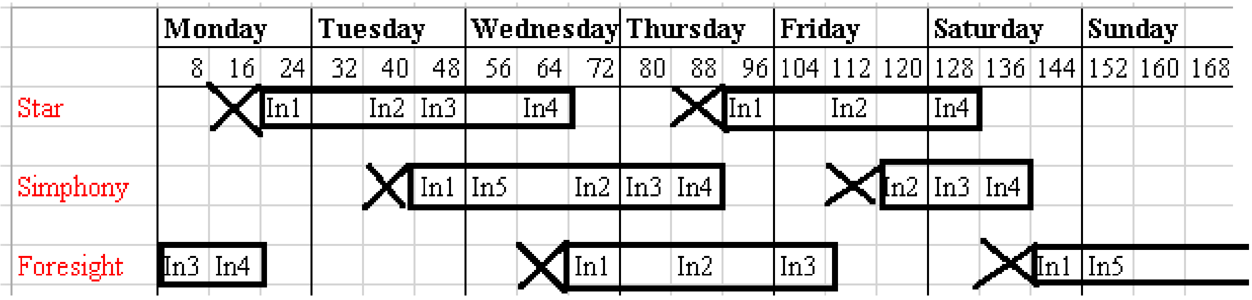

Figure 2 - Example of weekly sailing plan

In1, In2, In4).

2.2 ***Problems in current planning***

The major weakness in the current planning is that it does not account for weather conditions. For example, according to the schedule, a vessel finishes service at an installation right before its closing time or if it arrives to supply base right before start of loading/unloading for the next voyage. Then, in case of bad weather, the schedule became infeasible. It turns out that feasibility of the schedule depends on two factors: weather conditions and natural slacks between arrival to the base and departure on the next voyage, and slacks between end of service at an installation and night-closing time. Under natural slack, it is understood the time remaining after the end of a service at an installation to the latest time of ending the service. As well, there may be natural slack between the arrival time of a vessel to the base and the time of loading to the next voyage. Of course, if natural slacks in a schedule are large enough to absorb worsening weather conditions, then schedule feasibility will not be disrupted. The example of large natural slack at the supply base is shown at Figure 3 the below.

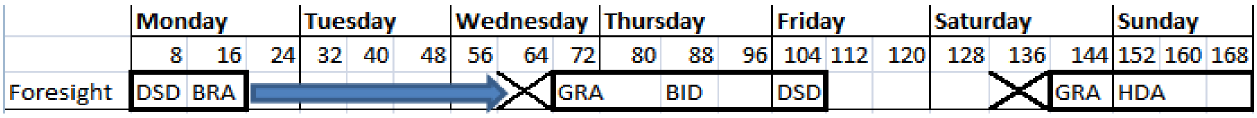

Figure 3 - Large natural slack example at the supply base

As we may see from the picture, vessel Foresight returns to the base after first voyage on Monday evening, then it has large natural slack (blue arrow), that is more than one day, before servicing. However, if natural slacks are too small than even minor changes in a weather will result in schedule disruption, the examples of small natural slacks at the base is presented at the Figure 4.

As we can see at the Figure 4, there is no idle day for the vessel between voyages, as it was at Figure 3. At the Figure 5 and Figure 6 are shown examples without natural slack

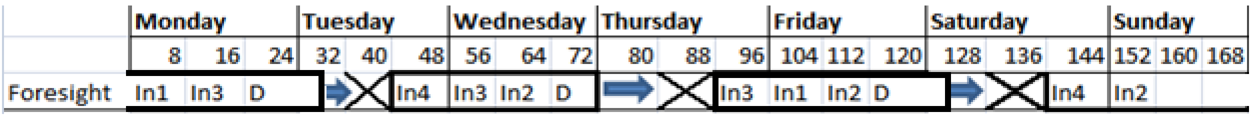

Figure 4 – Small natural slack example at the supply base

and with large natural slack at the installation with TW respectively. Opening hours and closing hours for the TW are shown as red stick. As we may see, an installation has two visits in two different voyages. At the first voyage vessel arrives at the same installation on

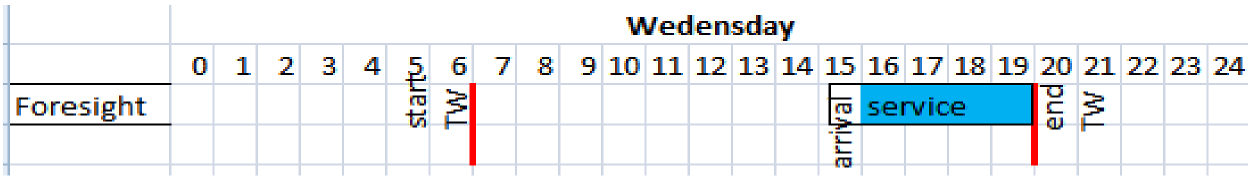

Figure 5 -Example of absence natural slack at the night closed installation

Wednesday 15.00 and starts to perform the service at 16 p.m. and ends it right before closing

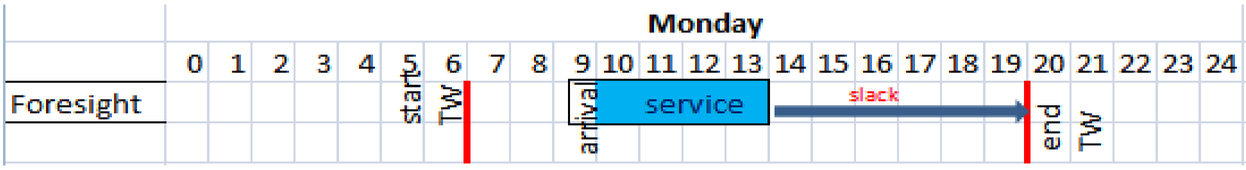

Figure 6 – Example of large natural slack at the night closed installation

hours, so there are no slack at all. At the second voyage, vessel arrives at the installation at 9 a.m. on Monday, starts the service at 10 a.m. and perform it till 13 p.m. further we have 6 hours natural slacks (blue arrow) before closing.

Therefore, weather conditions may highly affect the schedule with those small natural slacks. Consequently, additional expenses are incurred due to setting up of a new voyage (out of plan), downtime or hiring a spot vessel. Therefore, it would be reasonable to foresee "artificial" slacks at installations with time windows and at the supply base, sufficient to provide robustness of the schedule against certain level of weather conditions. The presents of such slacks should be controlled during schedule construction.

3.0 Literature review

In this section, we examine dedicated to PSVPP and robust VRP papers. First four articles are related to PSVPP.

Halvorsen-Weare et al. (2012) present an exact approach represented as a two-phase model that deals with different complicated aspects of PSVPP such as service capacity at the supply base, minimum and maximum route duration requirement, visit frequency and spread for the departures of vessels. At the first phase, all feasible cheapest voyages are generated. At the second phase, voyages with corresponding costs are used as input to a voyage-based set covering model with numerous side constraints. This approach can find optimal solution for the cases where are considered less than 12 instances than the problem size became larger, problems are unsolvable for this method. In order to manage uncertainty in planning they add slacks to each voyage duration.

Shyshou et al. (2012) proposes to use a Large Neighborhood Search (LNS) heuristic for PSVPP with possibility to have nearly optimal solution on large size instances. It finds optimal or near-optimal solutions by repeatedly trying to improve the current solution by exploring neighborhoods of the current solution.

Approaches considered above provide sailing plan for real problems in reasonable time, but without consideration of stochastic factors. Remaining part of the literature review is direct to incorporation robustness for the planning in PSVPP and different variants of VPR.

Halvorsen-Weare and Fagerholt (2011) use simulation-optimization approach for the construction of robust vessel schedule to the PSVPP taking into consideration weather conditions. In the first phase, all cheapest feasible voyages are generated with a fixed spread and use a simulation procedure to create robustness measure for voyages that cannot be completed within their duration. The voyage robustness measure and penalty for not delivered cargo are used as input for objective function for set-covering model at the second phase. The weather is described by a discrete number of weather states and modeled as Markov chain. To simulate voyages they use estimations of weather impact on vessels speed and service duration. The weaknesses of that approach are that it is based on penalty cost, which is quite difficult to estimate, and that voyage robustness is measured by amount of not-delivered cargo within the pre-defined voyage duration, found deterministically with the least time objective and fixed speed.

Another approach for dealing with weather uncertainty is presented in (Norlund, Gribkovskaia, and Laporte 2015) as combined usage of optimization and simulation. Solution methodology consists of three parts. At the first phase the shortest duration voyages, which are speed-optimized for reduction of fuel consumption are generated. At the second phase, voyages were simulated with respect to weather conditions. To incorporate robustness in weekly schedule, it was introduced a robustness parameter that represents a lower bound of probability that each voyage is feasible within its assigned duration. Value of robustness parameter is associated with a certain variety of weather conditions a schedule should maintain in considering planning period. The third phase was about solving of set-covering model for minimization of costs. This approach has two weaknesses. First, it cannot be used on large size problems. The second problem is that on the paper are generated robustness voyages that cannot guarantee robustness of the whole schedule.

Two following papers are not applicable to the PSVPP but they represent approaches to achieve robustness in different variants of VRP.

Sörensen and Sevaux (2009) developed approaches for finding robust and flexible for the capacitated vehicle routing problem. For this purpose, they combined a sampling based approach to estimate the robustness or flexibility of a solution with metaheuristic optimization technique. Their approach is based on the assumption that the decisions maker's risk preferences should be taken to account when choosing a robust or flexible solution. Under robust solution in this approach, we understand the solution that has high quality without readjustment to the stochastic parameters. Flexible solution here is the solution that has a high quality after readjustment to the outcomes of the stochastic parameters. They replace the objective function by a so-called robust evaluation function that measures the robustness or flexibility of the solution. This function value for a given solution is calculated by repeatedly applying the solution to a sampling of the stochastic parameters and calculating the corresponding (deterministic) objective function values. In other words, they make a reorganization in order to achieve flexibility. Adaptation of that approach may be done to consider problems that are more complex.

Agra et al. (2013) presented robust vehicle routing problem (VRP) with time windows. The aim was to incorporate robustness frequent delays. They have extend two existing exact models – resource inequalities and path inequality models but added robust constraints. This constraints guarantee that model provides routes that are feasible for all values of travel durations in a predetermined uncertainty polytope.

There are known other approaches to manage uncertain elements in maritime transportation such as cutting off solution that are considered risky as in (Christiansen and Fagerholt 2002) and (Christiansen and Nygreen 2005). These approaches need more complex expression of robustness to improve the results.

In the articles above, related to robust PSVPP, there is no one, which is concerned with robust schedule construction, applicable for the large-size instances. We may conclude that for the problem observed in this thesis should be developed new approach. According to the complexity of the problem, it seems reasonable to develop metaheuristic approach for the problem with incorporation of the robustness, which is able to provide sufficient solutions in reasonable time.

4.0 Methodology

In this section, we describe two approaches, which were applied to find a sailing plan for the PSVPP without consideration of robustness and further, we provide two variant approaches to achieve robustness.

4.1 *Two-phase approach*

This approach was developed by (Halvorsen-Weare et al. 2012). It consists of two phases. At the first phase, they generated all shortest feasible candidate voyages. Then, those voyages, at the second phase, are used as input to solve with them voyage-based model. Let's consider these phases in more depth.

4.1.1 Voyage generation

At this phase, initially, authors identified all potential subsets of offshore installations that particular vessel may visit. Each subset is limited in size by the minimum and maximum number of installations to visit on a voyage and the available capacity on the supply vessel. After that, for each of the subsets, if it does not include night-closed installations is solved Travelling Salesman Problem (TSP). However, if the subset contains at least one night-closed installation, it is solved Travelling Salesman Problem with Multiple Time Window (TSPMTW). Together with candidate voyages in output of the model, they calculated sailing costs for each voyage. Sailing costs is the summation of total sailing distance multiplied by total fuel consumption rate and waiting time multiplied by consumption rate.

4.1.2 Voyage-based model

The purpose of voyage-based model is to solve the supply vessel planning problem by choosing the cheapest supply vessels and assigning them to the cheapest pregenerated voyages consistent with satisfaction the constraints.

In the beginning, we introduce the notation of the model. Let V be the set of all available vessels and N – the set of offshore installations. R_v is the set of voyages vessel $v \in V$ may sail. Let T be the set of days in the planning horizon, and L is a set of all possible voyage durations in days. Then subset $R_{vl} \subseteq R_v$ includes all candidate voyages that vessel $v \in V$ may sail of duration $l \in L$. The parameter C_v^{TC} is the weekly time charter cost for vessel $v \in V$, and parameter C_{vr}^{S} is sailing and service costs for voyage $r \in R_v$ sailed by vessel $v \in V$. Then F_v is the number of days vessel $v \in V$ can be used during planning horizon, the parameter S_i represents the required number of visits for installation $i \in N$. The parameter B_t is used to show the maximum number of supply vessels that may be serviced at the supply base on day $t \in T$ and the binary (data type that takes two values: 0 or 1) parameter A_{vir} is 1 if vessel $v \in V$ serves installation $i \in N$ during the voyage $r \in R_v$ and 0 otherwise. With purpose to provide the spread of departures there are additionally include following parameters: parameter $0 \le h_r \le |T|$ represents sub horizon for the installation with visit frequency $r \in F$, parameters $\underline{p}_r$ and $\overline{p}_r$ for minimum and maximum number of visits for an installation $i \in N_r$ during sub horizon h_r respectively. The decision variables are following: δ_v is 1 if vessel $v \in V$ is used, 0 otherwise, and x_{vrt} is 1 if vessel $v \in V$ sails voyage $r \in R_v$ starting on day $t \in T$, 0 otherwise.

$$\min \sum_{v \in V} C_v^{TC} \delta_v + \sum_{v \in V} \sum_{r \in R_v} \sum_{t \in T} C_{vr}^S x_{vrt}, \tag{4.1}$$

Subject to

$$\sum_{v \in V} \sum_{r \in R} \sum_{t \in T} A_{vir} x_{vrt} \ge s_i, \quad i \in N, \tag{4.2}$$

$$\sum_{r \in R_v} \sum_{t \in T} D_{vr} x_{vrt} - F_v \delta_v \le 0, \quad v \in V, \tag{4.3}$$

$$\sum_{v \in V} \sum_{r \in R_v} x_{vrt} \le B_t, \quad t \in T, \tag{4.4}$$

$$\sum_{r \in R_{vl}} x_{vrt} + \sum_{r \in R_v} \sum_{v=1} x_{vr,((t+v) \bmod |T|)} \le 1, \quad v \in V, \quad t \in T, \quad l \in L \tag{4.5}$$

$$\underline{p}_r \le \sum_{v \in V} \sum_{r \in R_v} \sum_{h0} a_{ijk} x_{vr,((t+h) \bmod |T|)} \le \overline{p}_r, \quad i \in N_r, \quad t \in T, \quad r \in F \tag{4.6}$$

$$\delta_v \in \{0,1\}, \quad v \in V, \tag{4.7}$$

$$x_{vrt} \in \{0,1\}, \quad v \in V, \quad r \in R_v, \quad t \in T. \tag{4.8}$$

The objective function (4.1) minimizes the sum of the time charter costs and costs for the sailing. The primary objective is to find the most cost-efficient fleet composition because time charter cost is much higher than the sailing costs. Constraints (4.2) guarantee that all installations have the required number of visits during the planning horizon. Constraints (4.3) provide that the total duration of all voyages sailed by a vessel does not exceed the maximum number of days that vessel may be used during planning horizon and this constraints ensure that if vessel is used the binary variable must be equal to 1. Constraints (4.4) insure that there are no more supply vessels at the supply base on day $t \in T$

than is available due to base capacity. Constrains (4.5) ensure that a vessel cannot starts on a new voyage before it returned to the base from the preceding. Constraints (4.6) set even spread between departures to each installation during planning horizon according to visit frequency. Finally, two last constraints (4.7) and (4.8) set the binary requirements for decision variables.

4.2 *Large Neighborhood search heuristics*

4.2.1 Heuristic summary

In this section, we provide an overview of the Large Neighborhood Search (LNS) algorithm that was proposed by (Shaw 1998) to solve vehicle routing problems and further implemented for PSVPP by (Shyshou et al. 2012).

Heuristic is applied for a certain number of restarts. At each restart, it randomly generates initial solution while maintaining feasibility. Then it applies a given number of LNS iterations. At each iteration, it defines the neighborhood $N(z)$ of a solution z as the set of all solutions achievable from z by using two following procedures. First procedure called “Remove visits” takes a fixed number of voyages (users defined), removes from them random number of visits and puts them into pool S of uninserted visits. The second procedure that is called “Insert visits”, insert visits from the set S, back into voyages (not obligatory into the same voyages from which they were taken) using a regret criterion. A transition from a solution z to its neighborhood solution z' is called a move. When it finds a feasible solution with the best relocation of removed visits, it applies a set of improvement operators while the cost of the solution goes down. After that, a post improvement procedure is implemented with purpose of reduction of the fleet size and LNS starts the next iteration. It may happen that after application of the post improvement procedure, number of voyages reduces below predefined lower bound for the number of vessels when a feasible solution cannot be achieved. If number of voyages is less than the lower bound at the beginning of the next iteration, the algorithm creates empty voyages in the schedule.

4.2.2 Construction of initial solution

Initial solution represents a set of supply vessels, each having a set of voyages with certain departure times. Initial feasible solution is generated at each restart. First, for each installation is randomly generated a feasible scenario of departure times, corresponding to visit frequency and spread of departure requirements. The result of this assignment is that for each day of the planning horizon we know a set of installations to which vessels must departure. Then, for each day installations are randomly assigned to voyages. The number of voyages for each day is defined depending on vessels capacity and maximum number of installation per voyage. For example, if maximum number of installations per voyage is 7, and the number of installations assigned to Monday is 9, than we have 2 voyages. When installations are assigned to voyages, heuristic reordering procedure is applied to optimize the sequence of installation to each voyage. Furthermore, it should be guaranteed that voyages of the same vessel cannot overlap in time and the number of voyages starting on each day cannot exceeds the capacity of the base. If after a certain number of iterations a feasible initial solution was not achieved, the algorithm stops and the fleet size is incremented by one vessel.

4.2.3 The LNS iteration

After initial solution is generated, the algorithm makes a move from the current solution to the solution in its neighborhood. The move to a neighborhood solution is performed by two procedures: «Remove visits» and «Insert visits». The removed visits procedure takes randomly several voyages and removes from each random number of visits (minimum one and maximum one less than the actual number), all removed visits are placed into pool S . In fact, “Remove visits” procedure partially destroys the schedule. Than “Insert visits” procedure repairs the schedule by reinserting visits from the set S back into the schedule. If after reinsertion attempt the pool S is not empty, the algorithms proceeds to the next iteration. If in the pool of uninserted visits there are some visits from the previous iteration and if the number of voyages in the schedule after post improvement procedure from the previous iteration is less than lower bound then, empty voyages are created. Empty voyages are created due to the following reasons. The first reason is that, creation of empty voyages provides feasibility of the schedule when all visits contain in the pool S can be reinserted back into schedule, illuminates possible infeasibility of the schedule. After this procedure, it is made attempts to insert removed visits to voyages using a regret-like heuristic. If after a certain number of attempts or a certain time spent there are no any voyages for insertion the LNS performs next iteration.

Then the pool S get empty (all visits are inserted), are applied local improvement procedures with the purpose to find the cheaper schedule. With this aim, it is made an attempt to reduce number of voyages. Visits from the shortest voyages are taken and tried to be reinserted to other voyages until some voyages become empty. Next procedure, called "Reassigning voyages to vessel schedule" is performed in order to try to reduce number of using vessels. Then it is made an attempt to reduce the total duration of all voyages. The purpose here is to expand the idle time of a vessel and further reassign voyages again for tighter packing. Last improvement procedure, called "Relocating visits between voyages" applied to reduce total sailing cost.

All local improvement procedures are applied while total cost decreases. After all local improvements are made, again is performed an attempt to reduce the fleet size. Visits from voyages of a vessel are fractionally reassigned to other voyages. Visits that were not reassigned are put to the pool S and vessel is denoted as "not used". If the number of voyages after remove procedure is below the lower bound, as it was mentioned above, empty voyages are created. At the end of each iteration feasible solution is stored and after all iterations are done, it is returned the cheapest solution.

4.2.4 Improvement procedures

Procedure 4.2.4.1. <u>Intra voyage optimization</u>

This procedure is repeatedly called during the algorithm. It is used to attempt to reduce the length of voyages by repetitive removing visits and inserting them to another places. The procedure is applied while improvements can be made.

Procedure 4.2.4.2. <u>Reducing the number of voyages</u>

The procedure tries to reduce the total number of voyages. It goes with following logic. First, select a voyage. Then remove a visit and insert it to another voyage. Repeat this step for all visits of the voyage. If succeeds to remove all visited, then accept the changes. Repeat whole procedure until further reduction the number of vessels cannot be made or it reached the lower bound.

Procedure 4.2.4.3. <u>Reassigning voyages to vessel</u>

The procedure tries to relocate voyages between vessels in order to get the schedule tighter to reduce the number of vessels that are used. The procedure is following: Select a vessel, try to reassigned voyages to other vessel (vessel can be not used now, but then it must be smaller than selected vessel). Changes are accepted only if all voyages of vessel were reassigned. Continue the procedure for all vessels.

Procedure 4.2.4.4. <u>Reduce total duration of voyages</u>

This procedure tries to reduce total voyage duration measured in days. It is caused by the fact that the supply base opens at 8.00 and if the vessel arrives at the base later its opening it may starts a new voyage only on the next day, so small reduction the duration in hours may lead to save the whole day for the voyage. The steps are following: select a voyage, evaluate all feasible relocations to another voyages so that the duration of the destination voyage in number of days not increase. Implement the best relocations in terms of the following lexicographic ordering: 1) number of possible relocations for a visit; 2) difference between the increase in time of the voyage in which we insert visits and decrease of the voyages from which we insert visits; 3) increase of the total costs.

It the duration reduces the schedule is stored. After evaluations for all visits of all voyages, relocation executive the smallest total costs increase is implemented. The procedure is performed until there are possible voyage relocations or voyage duration decreases by one day without increasing the duration of other voyages in days.

Procedure 4.2.4.5. Relocate visits to other voyage

The aim of this procedure is to reduce the total cost. It is done by relocation of all visits of all voyages keeping feasibility while the objective function can be improved.

4.3 *Approaches for dealing with uncertainty*

Very early planners realized that in many optimization problems, it is essential to take into account stochasticity in key parameters. In this section, we provide different approaches allowing to cope with uncertainty.

4.3.1 **Stochastic programming with recourse**

Robust linear optimization with recourse was developed by (Dantzig 1955) and (Beale 1955) separately. According to this approach, problem is divided into different stages, between which relevant information about key parameters is partially discovered. The simplest case includes two stages. In this case, second stage performs recourse actions, which are done to arrange plans to the performance of uncertainty. For example, in PSVPP with stochastic demand, recourse actions that are taken in order to arrange a-priory solution may be following: returning to the supply base when the capacity is exceeded, or complete rerouting for appearing customers etc. Recourse models are very difficult for implementation and significantly increase the complexity in the model formulation and solution procedure. There are two other approaches to control the uncertainty: chance constraint programming and robust optimization.

4.3.2 **Chance constrained programming**

Chance constrained programming (CCP) was proposed by (Charnes and Cooper 1959). In CCP it is supposed that uncertain parameters are unknown during planning but follow some known probability distributions. The main particularity that distinguish the chance constrained programming from the robust optimization is that in CCP is defined special parameter, that represents the confidence level of the constraint. In practice, it allows some constraints to be satisfied only with some predefined probability. According to our problem, we consider uncertainty in voyage duration caused by weather conditions. In order to have any statistical data about probability distribution, we need to take into account wave height on each physical point during a voyage and at each particular time unit. However, it is impossible to reflect probability distribution for voyage duration mathematically. The only way, to get required values is to proceed particular voyage in particular weather conditions in particular time period. Simulation modeling tool may provide the ability to check the performance of a voyage.

4.3.3 **Robust optimization**

Shen, Ordónez, and Dessouky (2009) identify as robust optimization approach which assumes that the values of uncertain parameters belong to a given limited uncertainty set (without any defined probability). The purpose of approach is to optimize the problem against the worst case that might arise by using a min-max objective. Robust solutions have the ability to be efficient in practice, since they usually are not far from the optimal solution of the deterministic case and essential outperform in the worst case of the deterministic optimal solution. As advantages of this approach is the two following: it is simple to incorporate robustness into modeling and robust model has the same complexity to the original problem formulation.

As regards to the approaches dealing with stochasticity with their advantages and disadvantages, robust optimization seems to be the most suitable in our case. In robust modeling, we need to perform planning against a worst-case performance. Chance-constraints is hard to implement since probability distribution of our stochastic parameters are unavailable, since they are dependent on the location of a vessel and any point of time. As regards stochastic programming with recourse, such approach cannot be applied to our problem due to high complexity and large size of our problem, as well multi-stage nature of information revelation (information related to wave height at any point in any time). In our problem, parameters with uncertainty are supposed to be the duration of a voyage and service time at an installation.

5.0 Research objective

Due to all abovementioned, we can formulate the research objective. The mail purpose of the research work is twofold. On the one hand, we need to develop an approach for incorporation of robustness into schedule, namely we have to define which factors should be considered when introducing a robustness measure to a voyage. In addition, we have to develop some dependence logic between robustness measures and these factors. On the other hand, we are going to develop a metaheuristics algorithm that is able to deal with PSVPP of large size and takes into account stochasticity of weather conditions. To summarize, we need to develop heuristic algorithm with incorporated mechanism ensuring robustness of a schedule.

6.0 Solution approach

6.1 *Robustness assumptions*

In this section, we provide the logic to further implementation of robust optimization methodology to the PSVPP.

Supply vessel weekly schedule is robust if there are sufficient slacks on sailing legs and on time at installations in all voyages of the schedule. These slacks guarantee robustness of schedule against violation of time windows at installations and violation of voyage time window and thus voyage overlap. In other words, extended duration of voyage with slacks may reduce the risk of not performing all visits within voyage time window.

We differentiate between two types of voyages: voyages without TWs (Figure 7) and without (Figure 8). The type of voyage will have a direct influence on the length of the total slack. If having TWs on a voyage, it will imply a longer slack compared to a voyage without TWs. For each installation with TW and for the supply base, it will be created a slack.

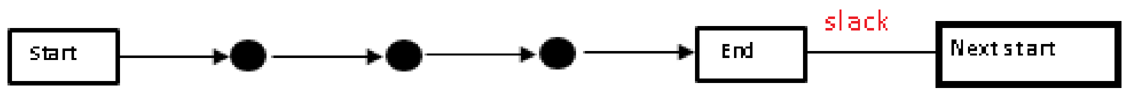

Figure 7 – Slack on a voyage that does not contain installation with TW

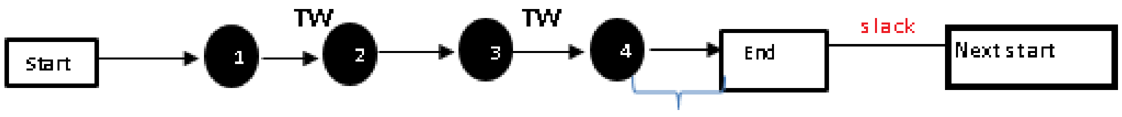

Figure 8 – Slack on a voyage that contains installations with TW

Longer travel time to an installation with TW means higher risk of not arriving on time due to higher uncertainty. Therefore it is required a longer slack before the latest start of service at the installation.

Another factor influencing the slack size on voyages with TWs is the number of installations. A great number of installations after a TW installation, means a greater impact on the later installations if not finishing the service on time at the TW installation. By adding more slack at the TW installation, it is possible to reduce or prevent that from happening.

The challenge is to define duration of the slacks. In order to find out possible duration, first we need to formulate main characteristics that influence to the potential violation of the schedule.

Characteristics influencing duration of slacks within voyage:

- Distances between installations and base
- Location of installations with respect to each other (clusters) and base
- Number of installations on voyage
- Lay time at installations
- Time windows at installations
- Location of installation(s) with TW on the voyage (first, second, or last)
- Start of next voyage of the vessel
- Season (month etc…)

The duration of slack on a leg depends on:

- Leg length. A longer leg would require more time to sail in case of bad weather (wave height increase) compared to a shorter leg.
- Geographical location of a leg (and as follows installations defining a leg). In different parts of sea, the weather behave variously.
- Season when a schedule is used. In different seasons, the weather behave variously.
- Base opening time (for the last voyage leg) – check if the natural slack at the end of voyage is sufficient enough for accommodate for possible delays along the voyage

We may assume that the weather it is constant within certain geographical areas (clusters) during a certain season. The wave height may be taken as an average (according to statistics) for a certain time period and within certain geographical area. As well, the wave height may be defined with some confidence interval (95%) by analyzing statistics; in this case, we are trying to construct a schedule, which is 95% robust against all weather conditions. During a voyage, it may occur that wave height becomes higher than 5 meters, than vessel's speed decreases almost to zero and service at installations is forbidden. In such a case, we do not have any restricted upper bound of the uncertainty set as these parameters probably may be with infinite duration. In order to bound uncertainty set, we define the upper bound that corresponds to the worst-case performance based on the experience.

The duration of slack for the lay time installation depends on:

- Service time at an installation
- Time window at installation
- Geographical location of an installation and the time of a year when the schedule is supposed to be used

Slack is calculated for each installation with TW (Figure 9) and between subsequent voyages of the same vessel. Slack for each installation with TW is dependent on the travel time to this installation from the beginning of this voyage.

$$s^{TW} = d_i\alpha + l_{ri}\delta \qquad (6.1.1)$$

where*:*

- d_i – travel time to installation *i* or to the depot (end) from the depot (start) or from previous installation with TW.
- l_{ir} - lay time of installation *i* of the voyage *r*.

Where α and δ are **user defined** coefficients

δ - Coefficient transforming lay time into slack, that may vary between [0,1] and is user defined

α - Coefficient transforming travel time into slack, that may vary between [0,1] and is defined by a user.

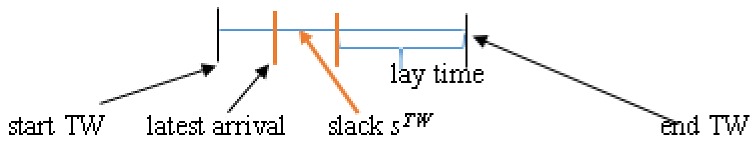

Figure 9 – Slack at installation with TW

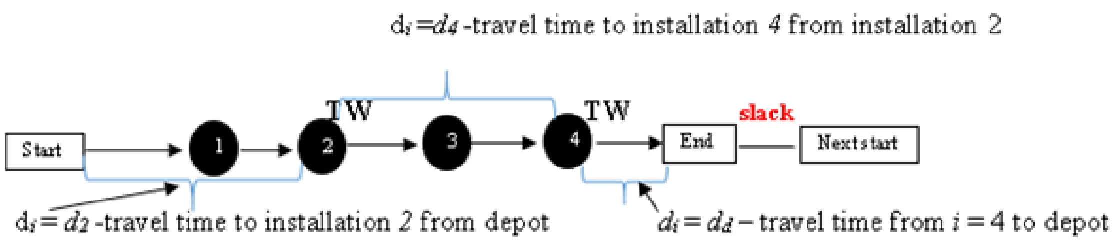

Figure 10 - Explanation of slacks' parameters

Explanation of parameters d_i *and* n_i is presented on Figure 10.

When there are no TWs on a voyage than robustness is provided by adding a slack at the end of a voyage. The slack depends on the voyage travel distance and lay time of installations. The slack is supposed to be a minimal time between end of the current voyage and start of the next.

l_{ir} - lay time of installation *i* of the voyage *r*.

C_{ij}^{r} –travel time between installations or depot and installation i and j on the voyage r

Then total slack *s* for voyage *r* may be calculated as:

$$s_r = \sum_{i\in I} l_{ri}\,\delta + \sum_{i\in I} C_{ij}^{r}\,\delta \qquad (6.1.2)$$

Where δ and α are user defined coefficients

The end of the voyage with slack is compared with start of the next voyage.

In order to increase the accuracy of the approach, the values all robustness coefficients are supposed to be dependent on their geographical location, in other words the

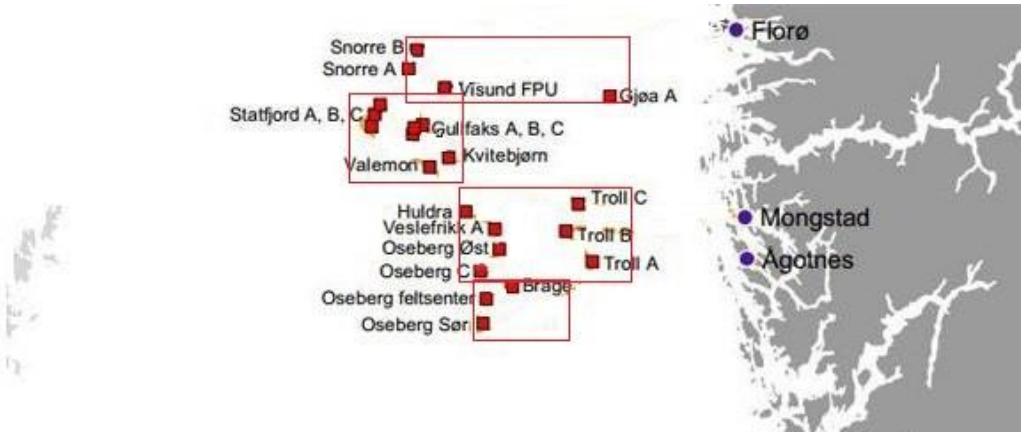

Figure 11 – Example of clusters

sea sector with installations supplied from Mongstad is subdivided into certain clusters. The number and geographical locations of these clusters are user-defined. The value of robustness coefficients are indicated for each cluster separately. It is worth because the wave height is different in different offshore points. The example of clusterization is presented in the Figure 11 below.

6.1.1 Schedule robustness assessment (robust measure)

Robustness of the schedule is assessed on several levels:

- Strategic level. All constraints with incorporated slack are satisfied/ not satisfied
- Tactical level. Assessment of the number of voyages in which robustness constraints are violated
    - $\sigma_1 = \frac{n^v}{\mathrm{n}}$, (6.1.1.1)

where n^v – number of voyages with violated constraints and *n* is the total number of voyages

- Operational level. Assessment of the degree of violation in terms of number of unserved installations
  - $\sigma_2 = \frac{i^n}{n^v},$ (6.1.1.2)

where i^n - number if unserved installations and n^v - total number of visits, σ_1 *and* σ_2 are user defined

6.1.2 Robustness summary

We have **two** user defined coefficients for calculation slacks. The value of each coefficient is user defined and should be determined based on experience. As well, the values may be adjusted after simulating the weather conditions for the constructed schedule.
Schedule robustness is maintained by controlling the coefficients σ_1 *and* σ_2 allowing for partial violation of some constraints. These coefficients are applied both during schedule construction by LNS heuristic (schedules satisfying the values of coefficients are stored for the subsequent analysis) and after simulation run for the assessment of the schedule with expected voyages' duration.

6.2 *Solution algorithm for the robust PSVPP*

In this section, we provide a heuristic algorithm based on the Large Neighborhood Search algorithm by (Shyshou et al. 2012). The main algorithm is similar to the LNS described above in section 4.2.1 with some modifications. All differences from the previous mentioned approach are documented in this section. The algorithm is developed using C# programming language.

6.2.1 Heuristics overview

The heuristics is run for a given number of restarts, pre-defined by a user. At each restart, this algorithm randomly generates a feasible initial solution, and executes a number of LNS iterations (pre-defined by user). At each iteration, the algorithm defines a neighborhood N(z) of a solution z. In other words, in order to find a better alternative, it is defined the area of solutions, that are achievable from the current solution z than we proceed a transition from z to neighborhood solution z'. This transition is called a move and is performed by two procedures. The first one is called "Remove visits" procedure (takes fixed number of voyages, removes from each a randomly generated number of visits and put them in a set S of uninserted visits). The second is called "Insert visits" (reinsert visits from set S back to the voyages in another places) using a regret criterion. After the move, we may have two cases, the set S may become an empty (all visits are reinserted back) or not empty (current solution is infeasible). If $S \neq \emptyset$, the algorithm goes to the next iteration. Otherwise, it performs a set of local improvement procedures. Improvements aim to reduce the size of vessels fleet, as this is a major costs component. It starts with an attempt to reduce the number of voyages (Procedure 4.2.4.2). Than it tries to reduce the number of vessels by trying to reassign voyages of some vessel to other vessels (Procedure 4.2.4.3). After that, the algorithm tries to reduce the total duration of the voyages by visit relocations between voyages (Procedure 4.2.4.4). Further, the heuristic again tries to repack voyages more tightly (Procedure 4.2.4.3).

The next procedure (Procedure 6.2.1), called "swap" mentioned by (Mili and Mili 2014) tries to assess all possible swap of visits between all voyages. The procedure search for any swap while the cost of the solution reduces.

The last procedure tries to relocate visits from each voyage to some other voyages with the objective of the cost reduction and the algorithm again tries to reduce the fleet size by procedure (Procedure 4.2.4.5);

Each time any procedure changes a voyage or several voyages, feasibility check takes place for the following constraints: voyage duration, voyages overlap, spread of departures and time windows (TW). Since we incorporated special coefficients for provision of slacks in potential bottlenecks, we check TW and voyage overlap constraints with incorporated (according to the described above logic) clacks.

After the last iteration, the algorithm returns the best found solution for all iterations. Pseudocode of the algorithm is presented below.

Algorithm 3.2 LNS

1:Set the cost of the best known solution $c *= \infty$;
2:**for** ρ restarts **do**
3: generate an initial solution z^0 (Section 4.2.2);
4: $z = z^0$;
5: $c(z) = cost\ of\ solution\ z$;
6: $S = \emptyset$;
7: **for** η iterations **do**
8: remove visits from some voyages in z (Section 4.2.3) and store them in array S;
9: **while** there exist feasible insertions of visits from S and $S \neq \emptyset$ **do**
10: insert visits into voyages in z (Section 4.2.3) and update S;
11: **end while**
12: **if** $S \neq \emptyset$ **then**
13: go to line 8;
14: **else**
15: **while** c(z) decreases **do**
16: reduce the number of voyages in z (Procedure 4.2.4.2);

reassign voyages to vessel schedules in z (Procedure 4.2.4.3);
reduce the total voyage duration in z (Procedure 4.2.4.4);
reassign voyages to vessel schedules in z (Procedure 4.2.4.3);
swap visits between voyages (Procedure 6.2.1);
reassign voyages to vessel schedules in z (Procedure 4.2.4.3);
relocate visits between voyages in z (Procedure 4.2.4.5);
reassign voyages to vessel schedules in z (Procedure 4.2.4.3);
end while
if $c(z) < c^*$ **then**
$z^* = z;$
$c^* = c(z^*);$
end if
end if
end for
end for
return z*;

6.2.2 Robust LNS

Below we provide the pseudocode of the algorithm for the search of the robust schedules. Before we proceed to the details, we have to describe the main logic of the robustness search. The major cost component in the schedule is vessel charter cost, and we have to identify a robust schedule with a minimum number of vessels. Operational costs (sailing and servicing) are minor, compared to the charter cost. Therefore, it would be logically correct to utilize the available fleet more efficiently, i.e. we can try to find some schedule for the given fleet size with maximal robustness. In such schedule, even slight increase of slacks would require increase of the fleet size.

The search for the maximal robustness for the given fleet size is provided using the binary search logic or half interval search. Realization of the algorithm that works for all arrays was developed by (Lehmer 1960). Binary search works by comparing some target value to the middle element of the list. If the target value is less or more than the middle element of the list, then the search proceeds respectively within lower or upper half of the list eliminating the other half of the list. In our case, we compare the number of vessels in the solution for different values of the robustness coefficients (α and δ). Initially we define minimal and maximal values for the coefficients. The minimal values are set to zero while maximal values are to be set sufficiently large so that the fleet size increases by one vessel compared to the solution with zero coefficients (schedule without incorporated robustness i.e. the cheapest schedule). The search is organized within min and max values.

Below we provide the pseudocode of the algorithm for the robust LNS for PSVPP. We assume that we search two robust schedules: one with minimal fleet size, and another with minimal fleet size plus one vessel. In some cases, weather conditions may be very harsh and the need of additional vessel may be required. Therefore, we find maximal robustness for the increased fleet.

Given the set of clusters K for which robustness coefficient are specified, $k \in K$. Coefficients α_k and δ_k. First, we find the solution with minimal number of vessels and for α_k and δ_k coefficients set to zero (line 2), and save the result (z^0 - schedule and n^0 – number of vessels). Then we run the algorithm for maximal values α_k and δ_k and save the solution (z^c - schedule and n^c – number of vessels with current robustness level). Then, according to the binary search logic, we gradually approach the schedule with maximal robustness. The algorithm makes η iterations, where at each iteration it adjusts the values of α_k and δ_k. First, maximal values of the coefficients are reduced half and the algorithm checks weather the fleet size equals to that minimal. If yes, the coefficients α_k and $\beta_k$increased by $\frac{\alpha_k^0}{2^i}$ and $\frac{\beta_k^0}{2^i}$ and the i^{th} iteration and procedure goes to the next iteration i+1. If the fleet size increased, then the coefficientsα_k and $\beta_k$reduced by $\frac{\alpha_k^0}{2^i}$ and $\frac{\beta_k^0}{2^i}$ and the i^{th} iteration and procedure goes to the next iteration. The algorithm tries to find the higher values of coefficients while keeping the fleets size to be minimal. After η iterations, the algorithm returns the last schedule (with maximal robustness) with minimal fleet size. The algorithm proceeds to search for the schedule with maximal robustness for the fleet with additional vessel.

Algorithm 3.2 Robust LNS

1: **Function** RoubustLNS(Lay slack α_k^0, Leg slack β_k^0, number of approximations η)
2: **run** LNS with $\alpha_k = 0$ and $\beta_k = 0$;
3: z^0 – Founded by LNS solution without incorporated robustness;
4: c(z^0) – Cost of solution z^0;
5: n^0- number of vessels without incorporated robustness;
6: $\alpha_k = \alpha_k^0$;
7: $\beta_k = b_k^0$;
8: $z_r = \emptyset$ robust solution where $n^c = n^0$
9: **for** $i = 0$ to η **do**
10: run **LNS** with α_k and β_k coefficient
11: z^c = current solution with α_k and β_k coefficient;
12: n^c = number of vessels in z^c;
13: **if** $n^c \leq n^0$ **then**
14: $z_r = z^c$;
15: $\beta_k = \beta_k + \frac{\beta_k^0}{2^i}$;
16: $\alpha_k = \alpha_k + \frac{\alpha_k^0}{2^i}$;
17: **else**

$\beta_k = \beta_k - \frac{\beta_k^0}{2^i}$;

$\alpha_k = \alpha_k - \frac{\alpha_k^0}{2^i}$;

End if

$i = i + 1$;

end for

$\alpha_k = \alpha_k^0$;

$\beta_k = \alpha_k^0$;

$z_{r+1} = \emptyset$ robust solution where $n^c = n^0+1$

for $i = 0$ to η **do**

Run **LNS** with α_k and β_k coefficient

z^c = solution with α_k and β_k coefficient;

n^c = number of vessels in z^c;

if $n^c \leq (n^0 + 1)$ **then**

$z_{r,1} = z^c$;

$\beta_k = \beta_k + \frac{\beta_k^0}{2^i}$;

$\alpha_k = \alpha_k + \frac{\alpha_k^0}{2^i}$;

else

$\beta_k = \beta_k - \frac{\beta_k^0}{2^i}$;

$\alpha_k = \alpha_k - \frac{\alpha_k^0}{2^i}$;

End if

$i = i + 1$;

end for

return $z^0, z_r, z_{r,1}$;

7.0 Computational Experiments

In this section, we provide results of the conducted experiments and their analysis. All the experiments were done on the computer with following characteristics: 3.5. GHz Intel core i5 and 8 GB RAM.

7.1 Experimental setup

We have an instance with 26 installations. Our experiments are divided into two phases. At the first phase, we generate schedules with different level of robustness. At the second phase, we simulate schedule with the aim to find service level.

First phase:

- Find robust schedules for the minimal number of vessels (found by algorithm) and for the fleet with one vessel more
- For each fleet size configuration we take three scenarios – with minimal robustness (zero coefficients with minimal fleet), with medium and with maximal robustness.

Second phase:

- We simulate weather conditions for each schedule, in order to define the level of its robustness.

7.2 *Results and Analysis*

We run ours robust LNS for 10 replications for each fleet size configuration (four and five vessels). At each replication robustness coefficients are adjusted by the algorithm. At the last replication the algorithm returns the schedules with minimum, medium and maximum robustness. As a result, we have three schedules for each fleet size configuration.

After that, we simulated weather for each schedule by a simulation tool. For simulation we used approach developed by (Maisiuk and Gribkovskaia 2014), where weather was incorporated in the following logic.

Norwegian Meteorological Institute (MET) provided data for modeling of statistical estimates of weather conditions. In our experiments it was used the statistical data, corresponds to January. Weather conditions are defined as four different weather states that may occur during execution of the schedule. The first weather state is when wave height is less than 2.5 meters; this state does not affect the service time and the sailing speed. Second state of the weather represents wave height between 2.5 and 3.5 meters, it does not affect sailing speed, but service time increases by 20%. In the third state, wave height lies between

3.5 and 4.5 meters, and lead to the reduction in sailing speed by 2 knot (one nautical mile per hour) and to 30% increase in the service time. The last state corresponds to wave height more than 4.5 meters, than the sailing speed reduces by 3 knot and service is forbidden, until new weather states appear.

The flowchart of the simulation process is shown at the Figure 12. From the figure, we may see that the new weather state is generated every three hours. We simulate the voyage and check the feasibility. If the voyage is infeasible, we remove a platform and simulate it again. If the voyage is feasible, we than check if we need more runs. If yes, we return to the voyage simulation process. If not, we calculate voyages and platforms sustainability.

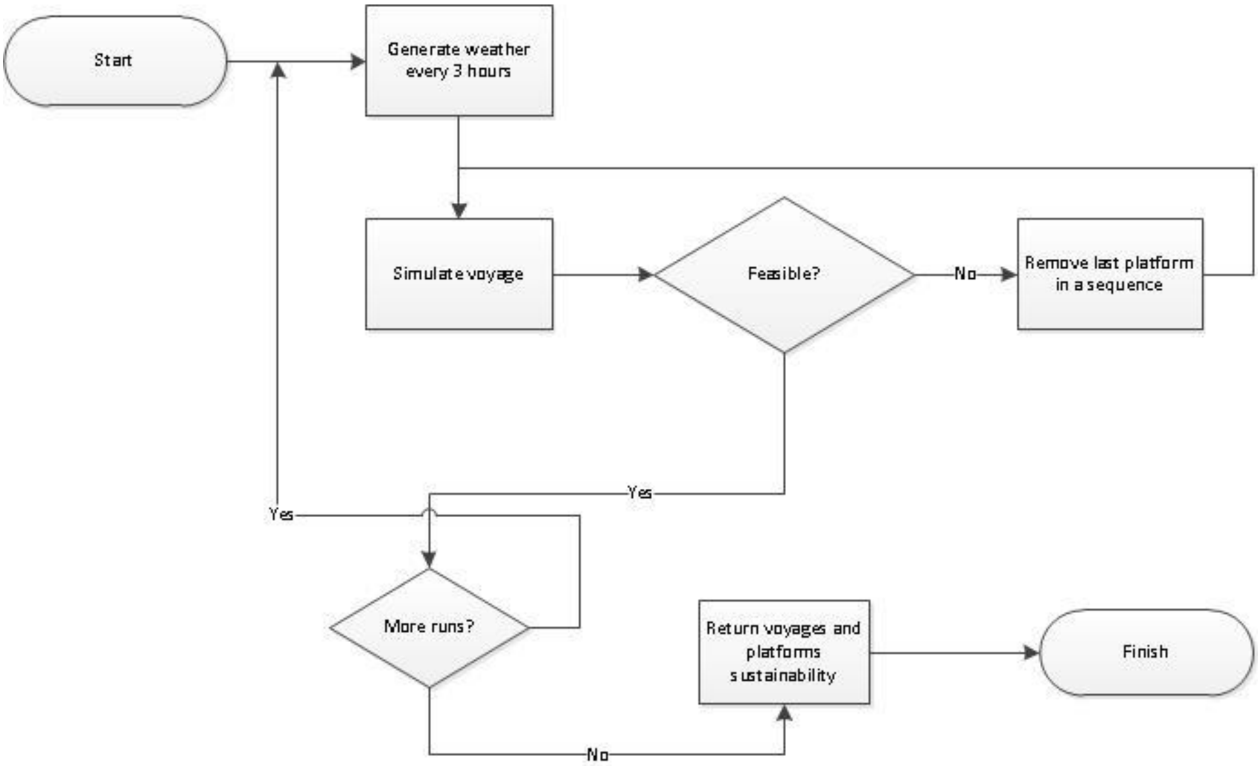

Figure 12 - Flowchart of the simulation model

Each schedule was run with 250 replications (see the appendix), with the aim to collect statistics on the service level. Table with output results is presented in Figure 13 below. Each row represents the output for a schedule with certain level of robustness (or values of robust coefficients). In the first column, we may see how many vessels are used in the particular schedule. In the bold columns describe the sustainability of the schedule in terms of the percentage of the number of voyages and platforms performed according to schedule. Columns 4 and 5 shows the average number of feasible and infeasible voyages in a schedule (average for 250 replications). Columns 7 and 8 represents the average number of served and unserved platforms according to schedule. The Values of robust coefficients are shown in the columns 9 and 10 as “lay slack” and “lag slack”. Column 11 contains the cost of each schedule and column 12 the gap from the minimal cost (without robustness). From the Figure 13 we may see that increase in the robust coefficients lead us to significant contribution to the stability while costs are approximately the same. For the convenience, we provide graphical representation of the dependence of the cost of a schedule on the service level.

	Robustness level	**Routes Sustainability**	Average number of feasible routes	Average number of not feasible routes	**Platforms Sustainability**	Average number of performed visits	Average number of not performed visits	Lay slack	Lag slack	Costs	gap
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
4 vessels	min	**0,840**	40,336	7,664	**0,969**	310,032	9,968			6 333 401	0,000
	medium	**0,843**	40,456	7,544	**0,970**	310,336	9,664	0,058594	0,058594	6 340 517	0,001
	max	**0,887**	42,588	5,412	**0,978**	312,896	7,104	0,062012	0,062012	6 352 862	0,003
5 vessels	min	**0,983**	47,168	0,832	**0,995**	318,252	1,748	0,125	0,125	7 751 430	0,224
	medium	**0,988**	47,436	0,564	**0,996**	318,684	1,316	0,214844	0,214844	7 764 458	0,226
	max	**0,990**	47,52	0,48	**0,997**	318,904	1,096	0,218262	0,218262	7 785 923	0,229

Figure 13 - Results of experiments

On the Figure 14 depicted routes sustainability. i.e. the percentage of the number of feasible routes depending on the robustness coefficients with corresponding schedules cost. On the Figure 15 depicted percentage of visits performed depending on the values of the robustness coefficients with corresponding schedules cost. The results of the simulation show that the service level, both in terms of routes and platforms sustainability, increases with the increase of robustness level. From the figure 13 we see that maximum routes sustainability for the schedule with four vessels corresponds to 88,7%. If we add one more vessel, routes sustainability jumps up to a 98,3% and maximal robustness for the fleet with 5 vessels is achieved up to 99.0%.

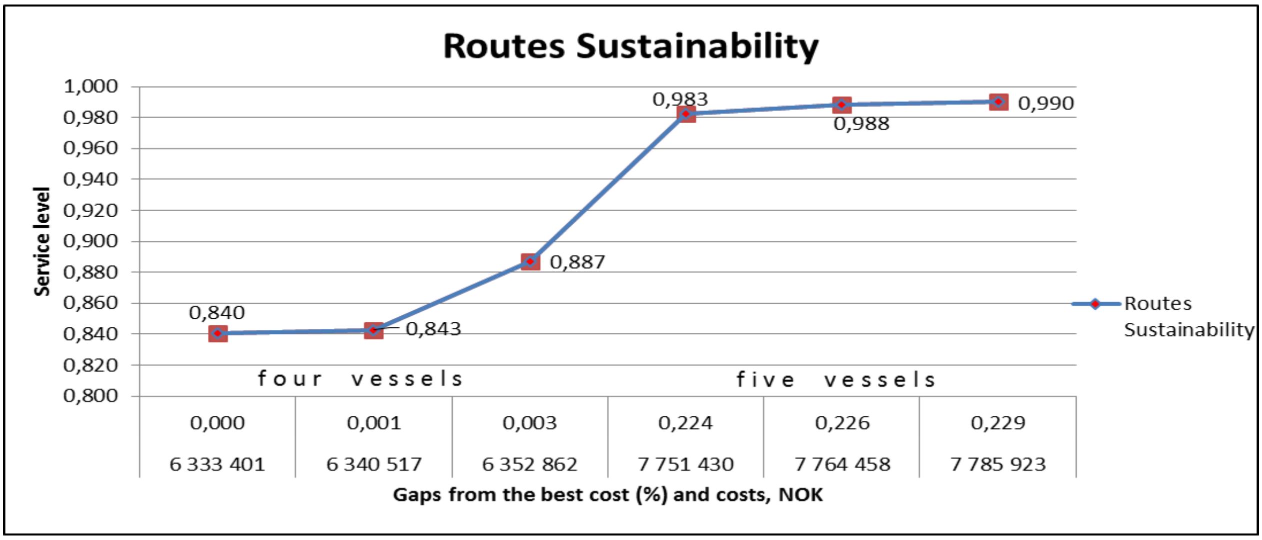

Figure 14 – Dependence between service level and costs

If we have a look at platform sustainability, we see that maximal robustness for the minimal fleet size corresponds to the 97.8%, while no robust solution is 96.9%. If we increase the fleet size by one vessel, then platform sustainability grows up to 99.5% and maximum is achieved at 99.7%.

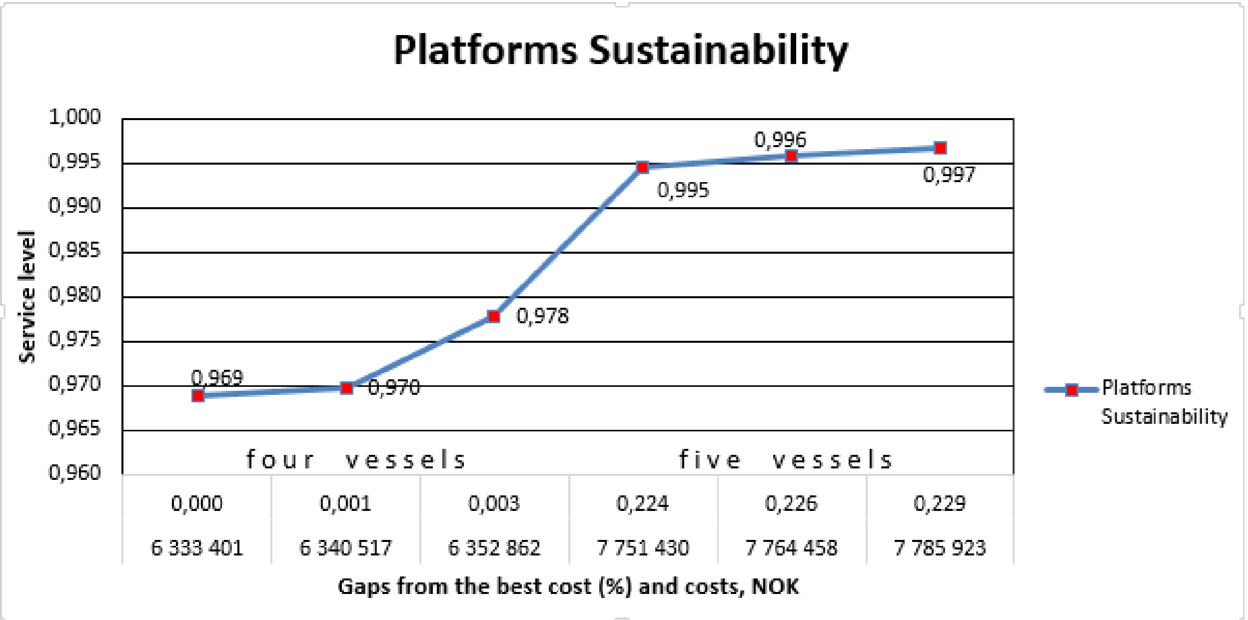

Figure 15 – Dependence between service level and costs

Here we describe the computational time required for each phase. It takes around 5.5 hours to find schedules with maximal robustness for the two fleet size configuration. The search procedure is relatively time consuming taking into account that we have to perform binary search for 20 runs of the algorithm. As regards simulation time, it takes in average 3 hours to run a schedule for 250 replications for statistics collection. We simulated six schedules, three for each fleet size configuration. In total, simulation took 9 hours. The whole procedure of both robust schedules construction and subsequent simulation took 15 hours. Since, the construction and the search for a robust schedule is more strategic task rather than tactical, we think that 15 hours are worth of that.

8.0 **Conclusions**

In the Periodic Supply Vessel Planning Problem (PSVPP), we are extremely interested to have a stable schedule that meet all the requirements under minimal costs. Cases where disruptions or delays occur result in downtime costs or the need for additional spot vessels. Both downtime cost and cost of a spot vessel costs are quite high. The major source of disruptions in upstream offshore supply is the weather. Bed weather is associated with high waves, when a vessel speed and service time at an installation as a result are reduced. In Norway weather condition are quite harsh and unpredictable, especially in winter. Therefore, delivery schedule should be constructed, taking into account possible disruptions and downtime.

In this thesis, we deal with an actual real life problem in the upstream offshore petroleum logistics, which represent the variant of PSVPP. Difference from the classical PSVPP is that we adjust the planning, by taking into account stochasticity of weather conditions in order to make the schedule more robust against weather uncertainty. Existing literature provides some methods of dealing with weather uncertainty in PSVPP or VRP (similar but simpler field). Such methods as chance-constraint programming and stochastic programming with recourse are inapplicable in our case due to high-complexity of the problem and due to impossibility of analytical expression of probability distribution for travel and service times. For this reason, we stopped our choice on robust planning. This approach assumes creation of a schedule for some worst-case scenario.

There are several contributions to PSVPP in our research. First, we developed an efficient metaheuristics algorithm, based on Large Neighbourhood Search (LNS) methodology, which is able to construct good solution for the PSVPP within relatively short time. Second, we developed a new concept for robustness incorporation into delivery schedule. As well, we introduced several approaches to robustness measurement on tactical and operational level. Finally, we developed approach enabling to find a schedule with maximal robustness for a given fleet size, which is based on binary search.

We conducted a set of experiments on a large size instance with the aim of testing of robust schedules. For all robust schedules, we simulated weather conditions and collected all the necessary statistics required for determination of the service level. The experiments show that the service level of a schedule increases with the increase of robustness requirements and maximal robustness criteria corresponds to the maximal service level.

For the future research, we propose further investigation of the robustness achievement. First, we have to examine the influence of the number of bottlenecks in a schedule on the service level. As well, we aim to incorporate dependence of the slacks of travel and service times on the number of installations in a voyage.

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Appendix

Output of the Simulation modelling for the PSVPP with different degree of robustness (Instance with 26 installations)

Table A.1: Output without robust requirements

	Number of vessels used=4	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,895833333	43	5	0,978125	313	7
2	0,9375	45	3	0,9875	316	4
3	0,916666667	44	4	0,9875	316	4
4	0,833333333	40	8	0,975	312	8
5	0,729166667	35	13	0,921875	295	25
6	0,791666667	38	10	0,934375	299	21
7	0,895833333	43	5	0,98125	314	6
8	0,791666667	38	10	0,9625	308	12
9	0,833333333	40	8	0,971875	311	9
10	0,833333333	40	8	0,971875	311	9
11	0,854166667	41	7	0,971875	311	9
12	0,770833333	37	11	0,9375	300	20
13	0,916666667	44	4	0,9875	316	4
14	0,895833333	43	5	0,98125	314	6
15	0,875	42	6	0,9625	308	12
16	0,8125	39	9	0,971875	311	9
17	0,791666667	38	10	0,965625	309	11
18	0,791666667	38	10	0,9625	308	12
19	0,770833333	37	11	0,95	304	16
20	0,895833333	43	5	0,984375	315	5
21	0,770833333	37	11	0,915625	293	27
22	0,770833333	37	11	0,959375	307	13
23	0,854166667	41	7	0,978125	313	7
24	0,895833333	43	5	0,984375	315	5
25	0,895833333	43	5	0,984375	315	5
26	0,833333333	40	8	0,971875	311	9
27	0,729166667	35	13	0,9375	300	20
28	0,75	36	12	0,95625	306	14
29	0,729166667	35	13	0,925	296	24
30	0,916666667	44	4	0,9875	316	4

31	0,75	36	12	0,91875	294	26
32	0,833333333	40	8	0,96875	310	10
33	0,8125	39	9	0,965625	309	11
34	0,791666667	38	10	0,95	304	16
35	0,791666667	38	10	0,95	304	16
36	0,875	42	6	0,978125	313	7
37	0,770833333	37	11	0,959375	307	13
38	0,791666667	38	10	0,946875	303	17
39	0,895833333	43	5	0,98125	314	6
40	0,854166667	41	7	0,978125	313	7
41	0,958333333	46	2	0,99375	318	2
42	0,958333333	46	2	0,99375	318	2
43	0,854166667	41	7	0,975	312	8
44	0,875	42	6	0,978125	313	7
45	0,791666667	38	10	0,96875	310	10
46	0,833333333	40	8	0,975	312	8
47	0,854166667	41	7	0,978125	313	7
48	0,875	42	6	0,98125	314	6
49	0,854166667	41	7	0,978125	313	7
50	0,8125	39	9	0,965625	309	11
51	0,875	42	6	0,98125	314	6
52	0,770833333	37	11	0,95	304	16
53	0,854166667	41	7	0,978125	313	7
54	0,833333333	40	8	0,975	312	8
55	0,875	42	6	0,971875	311	9
56	0,770833333	37	11	0,9625	308	12
57	0,770833333	37	11	0,925	296	24
58	0,916666667	44	4	0,9875	316	4
59	0,8125	39	9	0,971875	311	9
60	0,895833333	43	5	0,984375	315	5
61	0,958333333	46	2	0,99375	318	2
62	0,833333333	40	8	0,96875	310	10
63	0,875	42	6	0,98125	314	6
64	0,791666667	38	10	0,9625	308	12
65	0,895833333	43	5	0,984375	315	5
66	0,875	42	6	0,98125	314	6
67	0,770833333	37	11	0,965625	309	11
68	0,9375	45	3	0,990625	317	3
69	0,895833333	43	5	0,946875	303	17
70	0,833333333	40	8	0,96875	310	10
71	0,75	36	12	0,959375	307	13
72	0,770833333	37	11	0,921875	295	25
73	0,791666667	38	10	0,965625	309	11
74	0,875	42	6	0,98125	314	6
75	0,875	42	6	0,98125	314	6

76	0,9375	45	3	0,990625	317	3
77	0,8125	39	9	0,971875	311	9
78	0,833333333	40	8	0,971875	311	9
79	0,8125	39	9	0,9625	308	12
80	0,875	42	6	0,98125	314	6
81	0,791666667	38	10	0,95625	306	14
82	0,854166667	41	7	0,978125	313	7
83	0,875	42	6	0,971875	311	9
84	0,875	42	6	0,978125	313	7
85	0,9375	45	3	0,990625	317	3
86	0,770833333	37	11	0,921875	295	25
87	0,895833333	43	5	0,984375	315	5
88	0,854166667	41	7	0,971875	311	9
89	0,75	36	12	0,946875	303	17
90	0,9375	45	3	0,990625	317	3
91	0,833333333	40	8	0,975	312	8
92	0,916666667	44	4	0,9875	316	4
93	0,9375	45	3	0,990625	317	3
94	0,666666667	32	16	0,91875	294	26
95	0,833333333	40	8	0,975	312	8
96	0,770833333	37	11	0,91875	294	26
97	0,875	42	6	0,98125	314	6
98	0,875	42	6	0,98125	314	6
99	0,895833333	43	5	0,978125	313	7
100	0,854166667	41	7	0,95625	306	14
101	0,770833333	37	11	0,9625	308	12
102	0,854166667	41	7	0,975	312	8
103	0,916666667	44	4	0,9875	316	4
104	0,770833333	37	11	0,953125	305	15
105	0,9375	45	3	0,990625	317	3
106	0,854166667	41	7	0,971875	311	9
107	0,854166667	41	7	0,978125	313	7
108	0,8125	39	9	0,96875	310	10
109	0,895833333	43	5	0,984375	315	5
110	0,833333333	40	8	0,975	312	8
111	0,916666667	44	4	0,984375	315	5
112	0,875	42	6	0,978125	313	7
113	0,875	42	6	0,98125	314	6
114	0,75	36	12	0,940625	301	19
115	0,9375	45	3	0,990625	317	3
116	0,833333333	40	8	0,975	312	8
117	0,833333333	40	8	0,953125	305	15
118	0,854166667	41	7	0,975	312	8
119	0,875	42	6	0,98125	314	6
120	0,875	42	6	0,98125	314	6

121	0,854166667	41	7	0,975	312	8
122	0,916666667	44	4	0,9875	316	4
123	0,833333333	40	8	0,953125	305	15
124	0,791666667	38	10	0,95	304	16
125	0,854166667	41	7	0,975	312	8
126	0,833333333	40	8	0,95625	306	14
127	0,895833333	43	5	0,984375	315	5
128	0,791666667	38	10	0,96875	310	10
129	0,895833333	43	5	0,984375	315	5
130	0,8125	39	9	0,971875	311	9
131	0,833333333	40	8	0,975	312	8
132	0,854166667	41	7	0,975	312	8
133	0,8125	39	9	0,965625	309	11
134	0,895833333	43	5	0,984375	315	5
135	0,854166667	41	7	0,978125	313	7
136	0,770833333	37	11	0,95625	306	14
137	0,854166667	41	7	0,978125	313	7
138	0,791666667	38	10	0,965625	309	11
139	0,770833333	37	11	0,95625	306	14
140	0,770833333	37	11	0,928125	297	23
141	0,895833333	43	5	0,984375	315	5
142	0,8125	39	9	0,965625	309	11
143	0,729166667	35	13	0,95625	306	14
144	0,8125	39	9	0,959375	307	13
145	0,833333333	40	8	0,975	312	8
146	0,833333333	40	8	0,9625	308	12
147	0,854166667	41	7	0,959375	307	13
148	0,708333333	34	14	0,93125	298	22
149	0,854166667	41	7	0,971875	311	9
150	0,895833333	43	5	0,98125	314	6
151	0,791666667	38	10	0,93125	298	22
152	0,833333333	40	8	0,975	312	8
153	0,75	36	12	0,925	296	24
154	0,916666667	44	4	0,978125	313	7
155	0,833333333	40	8	0,971875	311	9
156	0,791666667	38	10	0,959375	307	13
157	0,791666667	38	10	0,93125	298	22
158	0,770833333	37	11	0,95	304	16
159	0,895833333	43	5	0,98125	314	6
160	0,8125	39	9	0,96875	310	10
161	0,708333333	34	14	0,95625	306	14
162	0,854166667	41	7	0,978125	313	7
163	0,791666667	38	10	0,9625	308	12
164	0,791666667	38	10	0,965625	309	11
165	0,958333333	46	2	0,99375	318	2

166	0,708333333	34	14	0,946875	303	17
167	0,75	36	12	0,9375	300	20
168	0,75	36	12	0,946875	303	17
169	0,875	42	6	0,971875	311	9
170	0,770833333	37	11	0,928125	297	23
171	0,854166667	41	7	0,978125	313	7
172	0,854166667	41	7	0,978125	313	7
173	0,833333333	40	8	0,940625	301	19
174	0,833333333	40	8	0,940625	301	19
175	0,958333333	46	2	0,99375	318	2
176	0,854166667	41	7	0,971875	311	9
177	0,770833333	37	11	0,965625	309	11
178	0,8125	39	9	0,965625	309	11
179	0,8125	39	9	0,959375	307	13
180	0,854166667	41	7	0,978125	313	7
181	0,75	36	12	0,959375	307	13
182	0,895833333	43	5	0,978125	313	7
183	0,854166667	41	7	0,978125	313	7
184	0,895833333	43	5	0,984375	315	5
185	0,854166667	41	7	0,978125	313	7
186	0,8125	39	9	0,9625	308	12
187	0,729166667	35	13	0,95	304	16
188	0,854166667	41	7	0,975	312	8
189	0,895833333	43	5	0,984375	315	5
190	0,8125	39	9	0,971875	311	9
191	0,875	42	6	0,98125	314	6
192	0,8125	39	9	0,953125	305	15
193	0,854166667	41	7	0,978125	313	7
194	0,916666667	44	4	0,9875	316	4
195	0,833333333	40	8	0,975	312	8
196	0,854166667	41	7	0,965625	309	11
197	0,854166667	41	7	0,978125	313	7
198	0,875	42	6	0,975	312	8
199	0,791666667	38	10	0,96875	310	10
200	0,854166667	41	7	0,978125	313	7
201	0,895833333	43	5	0,984375	315	5
202	0,8125	39	9	0,96875	310	10
203	0,9375	45	3	0,990625	317	3
204	0,895833333	43	5	0,98125	314	6
205	0,875	42	6	0,978125	313	7
206	0,6875	33	15	0,9125	292	28
207	0,916666667	44	4	0,9875	316	4
208	0,75	36	12	0,946875	303	17
209	0,958333333	46	2	0,99375	318	2
210	0,895833333	43	5	0,984375	315	5

211	0,791666667	38	10	0,953125	305	15
212	0,770833333	37	11	0,959375	307	13
213	0,833333333	40	8	0,971875	311	9
214	0,833333333	40	8	0,96875	310	10
215	0,8125	39	9	0,965625	309	11
216	0,895833333	43	5	0,98125	314	6
217	0,895833333	43	5	0,984375	315	5
218	0,833333333	40	8	0,975	312	8
219	0,854166667	41	7	0,978125	313	7
220	0,875	42	6	0,98125	314	6
221	0,895833333	43	5	0,984375	315	5
222	0,9375	45	3	0,990625	317	3
223	0,875	42	6	0,98125	314	6
224	0,916666667	44	4	0,9875	316	4
225	0,666666667	32	16	0,95	304	16
226	0,875	42	6	0,98125	314	6
227	0,9375	45	3	0,990625	317	3
228	0,8125	39	9	0,971875	311	9
229	0,8125	39	9	0,96875	310	10
230	0,833333333	40	8	0,975	312	8
231	0,791666667	38	10	0,95	304	16
232	0,895833333	43	5	0,984375	315	5
233	0,916666667	44	4	0,9875	316	4
234	0,8125	39	9	0,96875	310	10
235	0,708333333	34	14	0,925	296	24
236	0,770833333	37	11	0,94375	302	18
237	0,791666667	38	10	0,96875	310	10
238	0,895833333	43	5	0,984375	315	5
239	0,875	42	6	0,98125	314	6
240	0,8125	39	9	0,959375	307	13
241	0,8125	39	9	0,95625	306	14
242	0,958333333	46	2	0,99375	318	2
243	0,833333333	40	8	0,959375	307	13
244	0,875	42	6	0,98125	314	6
245	0,9375	45	3	0,990625	317	3
246	0,833333333	40	8	0,965625	309	11
247	0,854166667	41	7	0,978125	313	7
248	0,729166667	35	13	0,95625	306	14
249	0,833333333	40	8	0,96875	310	10
250	0,875	42	6	0,98125	314	6
AVERAGE:	**0,840333333**	**40,336**	**7,664**	**0,96885**	**310,032**	**9,968**

Table A.2: Output for minimal fleet with intermediate robust coefficients

	Number of vessels used=4	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,875	42	6	0,971875	311	9
2	0,875	42	6	0,98125	314	6
3	0,895833333	43	5	0,984375	315	5
4	0,854166667	41	7	0,978125	313	7
5	0,729166667	35	13	0,93125	298	22
6	0,791666667	38	10	0,940625	301	19
7	0,875	42	6	0,98125	314	6
8	0,895833333	43	5	0,971875	311	9
9	0,854166667	41	7	0,978125	313	7
10	0,875	42	6	0,98125	314	6
11	0,854166667	41	7	0,965625	309	11
12	0,833333333	40	8	0,95625	306	14
13	0,895833333	43	5	0,984375	315	5
14	0,854166667	41	7	0,978125	313	7
15	0,8125	39	9	0,946875	303	17
16	0,875	42	6	0,98125	314	6
17	0,854166667	41	7	0,978125	313	7
18	0,833333333	40	8	0,971875	311	9
19	0,770833333	37	11	0,934375	299	21
20	0,875	42	6	0,98125	314	6
21	0,729166667	35	13	0,91875	294	26
22	0,791666667	38	10	0,959375	307	13
23	0,854166667	41	7	0,978125	313	7
24	0,895833333	43	5	0,98125	314	6
25	0,895833333	43	5	0,98125	314	6
26	0,875	42	6	0,978125	313	7
27	0,75	36	12	0,94375	302	18
28	0,8125	39	9	0,971875	311	9
29	0,770833333	37	11	0,9375	300	20
30	0,916666667	44	4	0,984375	315	5
31	0,770833333	37	11	0,921875	295	25
32	0,833333333	40	8	0,971875	311	9
33	0,854166667	41	7	0,975	312	8
34	0,833333333	40	8	0,971875	311	9
35	0,770833333	37	11	0,946875	303	17
36	0,833333333	40	8	0,975	312	8
37	0,8125	39	9	0,96875	310	10
38	0,75	36	12	0,946875	303	17
39	0,833333333	40	8	0,975	312	8
40	0,895833333	43	5	0,984375	315	5

41	0,875	42	6	0,98125	314	6
42	0,854166667	41	7	0,978125	313	7
43	0,854166667	41	7	0,978125	313	7
44	0,854166667	41	7	0,975	312	8
45	0,833333333	40	8	0,975	312	8
46	0,854166667	41	7	0,975	312	8
47	0,854166667	41	7	0,978125	313	7
48	0,875	42	6	0,98125	314	6
49	0,895833333	43	5	0,984375	315	5
50	0,770833333	37	11	0,959375	307	13
51	0,875	42	6	0,978125	313	7
52	0,770833333	37	11	0,953125	305	15
53	0,833333333	40	8	0,975	312	8
54	0,875	42	6	0,98125	314	6
55	0,8125	39	9	0,94375	302	18
56	0,8125	39	9	0,96875	310	10
57	0,833333333	40	8	0,940625	301	19
58	0,854166667	41	7	0,978125	313	7
59	0,833333333	40	8	0,975	312	8
60	0,833333333	40	8	0,975	312	8
61	0,916666667	44	4	0,9875	316	4
62	0,854166667	41	7	0,975	312	8
63	0,895833333	43	5	0,984375	315	5
64	0,854166667	41	7	0,978125	313	7
65	0,895833333	43	5	0,984375	315	5
66	0,854166667	41	7	0,978125	313	7
67	0,854166667	41	7	0,975	312	8
68	0,916666667	44	4	0,9875	316	4
69	0,8125	39	9	0,946875	303	17
70	0,75	36	12	0,95625	306	14
71	0,770833333	37	11	0,959375	307	13
72	0,833333333	40	8	0,940625	301	19
73	0,791666667	38	10	0,9625	308	12
74	0,875	42	6	0,98125	314	6
75	0,833333333	40	8	0,975	312	8
76	0,916666667	44	4	0,9875	316	4
77	0,791666667	38	10	0,96875	310	10
78	0,854166667	41	7	0,975	312	8
79	0,854166667	41	7	0,96875	310	10
80	0,875	42	6	0,98125	314	6
81	0,8125	39	9	0,965625	309	11
82	0,875	42	6	0,98125	314	6
83	0,791666667	38	10	0,9625	308	12
84	0,875	42	6	0,978125	313	7
85	0,895833333	43	5	0,984375	315	5

86	0,791666667	38	10	0,9125	292	28
87	0,895833333	43	5	0,984375	315	5
88	0,875	42	6	0,98125	314	6
89	0,770833333	37	11	0,95625	306	14
90	0,916666667	44	4	0,9875	316	4
91	0,875	42	6	0,98125	314	6
92	0,916666667	44	4	0,9875	316	4
93	0,916666667	44	4	0,9875	316	4
94	0,625	30	18	0,903125	289	31
95	0,854166667	41	7	0,978125	313	7
96	0,708333333	34	14	0,896875	287	33
97	0,895833333	43	5	0,98125	314	6
98	0,833333333	40	8	0,975	312	8
99	0,833333333	40	8	0,9625	308	12
100	0,833333333	40	8	0,96875	310	10
101	0,8125	39	9	0,965625	309	11
102	0,833333333	40	8	0,975	312	8
103	0,916666667	44	4	0,9875	316	4
104	0,791666667	38	10	0,953125	305	15
105	0,895833333	43	5	0,984375	315	5
106	0,854166667	41	7	0,975	312	8
107	0,875	42	6	0,98125	314	6
108	0,833333333	40	8	0,975	312	8
109	0,854166667	41	7	0,975	312	8
110	0,854166667	41	7	0,978125	313	7
111	0,916666667	44	4	0,9875	316	4
112	0,895833333	43	5	0,984375	315	5
113	0,875	42	6	0,98125	314	6
114	0,75	36	12	0,928125	297	23
115	0,895833333	43	5	0,984375	315	5
116	0,895833333	43	5	0,984375	315	5
117	0,833333333	40	8	0,946875	303	17
118	0,833333333	40	8	0,975	312	8
119	0,854166667	41	7	0,978125	313	7
120	0,895833333	43	5	0,984375	315	5
121	0,916666667	44	4	0,9875	316	4
122	0,895833333	43	5	0,984375	315	5
123	0,8125	39	9	0,94375	302	18
124	0,729166667	35	13	0,928125	297	23
125	0,854166667	41	7	0,975	312	8
126	0,854166667	41	7	0,9625	308	12
127	0,916666667	44	4	0,9875	316	4
128	0,791666667	38	10	0,95625	306	14
129	0,875	42	6	0,98125	314	6
130	0,875	42	6	0,978125	313	7

131	0,833333333	40	8	0,965625	309	11
132	0,854166667	41	7	0,978125	313	7
133	0,875	42	6	0,978125	313	7
134	0,916666667	44	4	0,9875	316	4
135	0,916666667	44	4	0,9875	316	4
136	0,770833333	37	11	0,965625	309	11
137	0,791666667	38	10	0,959375	307	13
138	0,833333333	40	8	0,96875	310	10
139	0,770833333	37	11	0,953125	305	15
140	0,770833333	37	11	0,9375	300	20
141	0,770833333	37	11	0,965625	309	11
142	0,8125	39	9	0,971875	311	9
143	0,875	42	6	0,978125	313	7
144	0,791666667	38	10	0,95625	306	14
145	0,875	42	6	0,978125	313	7
146	0,8125	39	9	0,96875	310	10
147	0,854166667	41	7	0,971875	311	9
148	0,770833333	37	11	0,95625	306	14
149	0,833333333	40	8	0,975	312	8
150	0,875	42	6	0,978125	313	7
151	0,8125	39	9	0,946875	303	17
152	0,854166667	41	7	0,978125	313	7
153	0,75	36	12	0,9375	300	20
154	0,875	42	6	0,953125	305	15
155	0,833333333	40	8	0,971875	311	9
156	0,833333333	40	8	0,971875	311	9
157	0,8125	39	9	0,94375	302	18
158	0,833333333	40	8	0,9625	308	12
159	0,916666667	44	4	0,9875	316	4
160	0,854166667	41	7	0,975	312	8
161	0,75	36	12	0,959375	307	13
162	0,833333333	40	8	0,971875	311	9
163	0,8125	39	9	0,971875	311	9
164	0,791666667	38	10	0,96875	310	10
165	0,916666667	44	4	0,9875	316	4
166	0,770833333	37	11	0,965625	309	11
167	0,770833333	37	11	0,95625	306	14
168	0,770833333	37	11	0,9625	308	12
169	0,875	42	6	0,98125	314	6
170	0,770833333	37	11	0,9375	300	20
171	0,833333333	40	8	0,975	312	8
172	0,875	42	6	0,98125	314	6
173	0,8125	39	9	0,94375	302	18
174	0,833333333	40	8	0,946875	303	17
175	0,916666667	44	4	0,9875	316	4

176	0,8125	39	9	0,959375	307	13
177	0,791666667	38	10	0,965625	309	11
178	0,833333333	40	8	0,971875	311	9
179	0,791666667	38	10	0,953125	305	15
180	0,854166667	41	7	0,978125	313	7
181	0,791666667	38	10	0,96875	310	10
182	0,833333333	40	8	0,971875	311	9
183	0,854166667	41	7	0,96875	310	10
184	0,895833333	43	5	0,984375	315	5
185	0,854166667	41	7	0,978125	313	7
186	0,833333333	40	8	0,965625	309	11
187	0,729166667	35	13	0,95625	306	14
188	0,854166667	41	7	0,965625	309	11
189	0,875	42	6	0,98125	314	6
190	0,854166667	41	7	0,96875	310	10
191	0,895833333	43	5	0,984375	315	5
192	0,791666667	38	10	0,959375	307	13
193	0,854166667	41	7	0,975	312	8
194	0,916666667	44	4	0,9875	316	4
195	0,875	42	6	0,98125	314	6
196	0,8125	39	9	0,9625	308	12
197	0,833333333	40	8	0,971875	311	9
198	0,854166667	41	7	0,975	312	8
199	0,854166667	41	7	0,978125	313	7
200	0,833333333	40	8	0,971875	311	9
201	0,875	42	6	0,98125	314	6
202	0,770833333	37	11	0,959375	307	13
203	0,916666667	44	4	0,9875	316	4
204	0,875	42	6	0,98125	314	6
205	0,854166667	41	7	0,978125	313	7
206	0,75	36	12	0,928125	297	23
207	0,875	42	6	0,98125	314	6
208	0,6875	33	15	0,940625	301	19
209	0,916666667	44	4	0,9875	316	4
210	0,895833333	43	5	0,984375	315	5
211	0,8125	39	9	0,96875	310	10
212	0,770833333	37	11	0,953125	305	15
213	0,8125	39	9	0,9625	308	12
214	0,833333333	40	8	0,975	312	8
215	0,833333333	40	8	0,965625	309	11
216	0,916666667	44	4	0,9875	316	4
217	0,875	42	6	0,978125	313	7
218	0,895833333	43	5	0,984375	315	5
219	0,895833333	43	5	0,98125	314	6
220	0,875	42	6	0,98125	314	6

221	0,854166667	41	7	0,978125	313	7
222	0,895833333	43	5	0,984375	315	5
223	0,854166667	41	7	0,96875	310	10
224	0,854166667	41	7	0,978125	313	7
225	0,770833333	37	11	0,959375	307	13
226	0,916666667	44	4	0,984375	315	5
227	0,895833333	43	5	0,984375	315	5
228	0,875	42	6	0,98125	314	6
229	0,833333333	40	8	0,975	312	8
230	0,875	42	6	0,98125	314	6
231	0,8125	39	9	0,95625	306	14
232	0,916666667	44	4	0,9875	316	4
233	0,895833333	43	5	0,984375	315	5
234	0,833333333	40	8	0,975	312	8
235	0,791666667	38	10	0,946875	303	17
236	0,833333333	40	8	0,946875	303	17
237	0,875	42	6	0,98125	314	6
238	0,875	42	6	0,978125	313	7
239	0,8125	39	9	0,971875	311	9
240	0,875	42	6	0,96875	310	10
241	0,833333333	40	8	0,95625	306	14
242	0,875	42	6	0,98125	314	6
243	0,854166667	41	7	0,959375	307	13
244	0,875	42	6	0,978125	313	7
245	0,916666667	44	4	0,9875	316	4
246	0,833333333	40	8	0,96875	310	10
247	0,875	42	6	0,98125	314	6
248	0,75	36	12	0,95625	306	14
249	0,875	42	6	0,978125	313	7
250	0,854166667	41	7	0,971875	311	9
AVERAGE:	**0,842833333**	**40,456**	**7,544**	**0,9698**	**310,336**	**9,664**

Table A.3: Output for minimal fleet with maximal robust coefficients

	Number of vessels used=4	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,9375	45	3	0,98125	314	6
2	0,916666667	44	4	0,9875	316	4
3	0,9375	45	3	0,990625	317	3
4	0,875	42	6	0,98125	314	6
5	0,770833333	37	11	0,93125	298	22
6	0,854166667	41	7	0,94375	302	18
7	0,895833333	43	5	0,984375	315	5
8	0,854166667	41	7	0,971875	311	9
9	0,9375	45	3	0,990625	317	3
10	0,895833333	43	5	0,984375	315	5
11	0,895833333	43	5	0,975	312	8
12	0,833333333	40	8	0,95	304	16
13	0,979166667	47	1	0,996875	319	1
14	0,875	42	6	0,98125	314	6
15	0,833333333	40	8	0,95625	306	14
16	0,958333333	46	2	0,99375	318	2
17	0,875	42	6	0,98125	314	6
18	0,854166667	41	7	0,975	312	8
19	0,833333333	40	8	0,9625	308	12
20	0,9375	45	3	0,990625	317	3
21	0,729166667	35	13	0,921875	295	25
22	0,8125	39	9	0,96875	310	10
23	0,875	42	6	0,98125	314	6
24	0,9375	45	3	0,990625	317	3
25	0,9375	45	3	0,990625	317	3
26	0,895833333	43	5	0,984375	315	5
27	0,770833333	37	11	0,95625	306	14
28	0,833333333	40	8	0,975	312	8
29	0,854166667	41	7	0,94375	302	18
30	0,916666667	44	4	0,9875	316	4
31	0,833333333	40	8	0,934375	299	21
32	0,916666667	44	4	0,9875	316	4
33	0,8125	39	9	0,96875	310	10
34	0,875	42	6	0,978125	313	7
35	0,8125	39	9	0,95625	306	14
36	0,958333333	46	2	0,99375	318	2
37	0,8125	39	9	0,96875	310	10
38	0,8125	39	9	0,9625	308	12
39	0,895833333	43	5	0,984375	315	5
40	0,979166667	47	1	0,996875	319	1

41	1	48	0	1	320	0
42	0,9375	45	3	0,990625	317	3
43	0,9375	45	3	0,990625	317	3
44	0,854166667	41	7	0,975	312	8
45	0,916666667	44	4	0,9875	316	4
46	0,854166667	41	7	0,978125	313	7
47	0,916666667	44	4	0,9875	316	4
48	0,9375	45	3	0,990625	317	3
49	0,958333333	46	2	0,99375	318	2
50	0,833333333	40	8	0,975	312	8
51	0,833333333	40	8	0,975	312	8
52	0,8125	39	9	0,965625	309	11
53	0,895833333	43	5	0,984375	315	5
54	0,875	42	6	0,98125	314	6
55	0,854166667	41	7	0,96875	310	10
56	0,8125	39	9	0,96875	310	10
57	0,833333333	40	8	0,940625	301	19
58	0,916666667	44	4	0,9875	316	4
59	0,854166667	41	7	0,978125	313	7
60	0,895833333	43	5	0,984375	315	5
61	1	48	0	1	320	0
62	0,854166667	41	7	0,978125	313	7
63	0,958333333	46	2	0,99375	318	2
64	0,916666667	44	4	0,9875	316	4
65	0,9375	45	3	0,990625	317	3
66	0,854166667	41	7	0,978125	313	7
67	0,895833333	43	5	0,984375	315	5
68	0,958333333	46	2	0,99375	318	2
69	0,895833333	43	5	0,95	304	16
70	0,833333333	40	8	0,971875	311	9
71	0,8125	39	9	0,9625	308	12
72	0,833333333	40	8	0,940625	301	19
73	0,854166667	41	7	0,975	312	8
74	0,9375	45	3	0,990625	317	3
75	0,9375	45	3	0,990625	317	3
76	0,958333333	46	2	0,99375	318	2
77	0,875	42	6	0,98125	314	6
78	0,833333333	40	8	0,975	312	8
79	0,854166667	41	7	0,96875	310	10
80	0,9375	45	3	0,990625	317	3
81	0,854166667	41	7	0,975	312	8
82	0,875	42	6	0,98125	314	6
83	0,875	42	6	0,978125	313	7
84	0,9375	45	3	0,9875	316	4
85	0,958333333	46	2	0,99375	318	2

86	0,8125	39	9	0,928125	297	23
87	0,958333333	46	2	0,99375	318	2
88	0,958333333	46	2	0,99375	318	2
89	0,791666667	38	10	0,959375	307	13
90	0,979166667	47	1	0,996875	319	1
91	0,958333333	46	2	0,99375	318	2
92	1	48	0	1	320	0
93	0,958333333	46	2	0,99375	318	2
94	0,604166667	29	19	0,921875	295	25
95	0,895833333	43	5	0,984375	315	5
96	0,770833333	37	11	0,928125	297	23
97	0,958333333	46	2	0,990625	317	3
98	0,958333333	46	2	0,99375	318	2
99	0,916666667	44	4	0,975	312	8
100	0,895833333	43	5	0,965625	309	11
101	0,770833333	37	11	0,965625	309	11
102	0,895833333	43	5	0,984375	315	5
103	0,9375	45	3	0,990625	317	3
104	0,833333333	40	8	0,965625	309	11
105	0,979166667	47	1	0,996875	319	1
106	0,833333333	40	8	0,975	312	8
107	0,958333333	46	2	0,99375	318	2
108	0,875	42	6	0,98125	314	6
109	0,916666667	44	4	0,9875	316	4
110	0,958333333	46	2	0,99375	318	2
111	0,958333333	46	2	0,99375	318	2
112	0,916666667	44	4	0,9875	316	4
113	0,979166667	47	1	0,996875	319	1
114	0,729166667	35	13	0,9375	300	20
115	1	48	0	1	320	0
116	0,9375	45	3	0,990625	317	3
117	0,791666667	38	10	0,95	304	16
118	0,895833333	43	5	0,984375	315	5
119	0,895833333	43	5	0,98125	314	6
120	0,916666667	44	4	0,9875	316	4
121	0,9375	45	3	0,990625	317	3
122	0,958333333	46	2	0,99375	318	2
123	0,875	42	6	0,9625	308	12
124	0,791666667	38	10	0,953125	305	15
125	0,854166667	41	7	0,978125	313	7
126	0,9375	45	3	0,978125	313	7
127	0,895833333	43	5	0,984375	315	5
128	0,791666667	38	10	0,96875	310	10
129	0,958333333	46	2	0,99375	318	2
130	0,875	42	6	0,98125	314	6

131	0,833333333	40	8	0,971875	311	9
132	0,916666667	44	4	0,9875	316	4
133	0,875	42	6	0,98125	314	6
134	0,916666667	44	4	0,9875	316	4
135	0,979166667	47	1	0,996875	319	1
136	0,854166667	41	7	0,978125	313	7
137	0,854166667	41	7	0,978125	313	7
138	0,875	42	6	0,971875	311	9
139	0,770833333	37	11	0,959375	307	13
140	0,791666667	38	10	0,93125	298	22
141	0,875	42	6	0,98125	314	6
142	0,895833333	43	5	0,984375	315	5
143	0,875	42	6	0,98125	314	6
144	0,854166667	41	7	0,965625	309	11
145	0,895833333	43	5	0,984375	315	5
146	0,895833333	43	5	0,98125	314	6
147	0,916666667	44	4	0,978125	313	7
148	0,8125	39	9	0,95625	306	14
149	0,895833333	43	5	0,984375	315	5
150	0,916666667	44	4	0,984375	315	5
151	0,875	42	6	0,946875	303	17
152	0,875	42	6	0,978125	313	7
153	0,770833333	37	11	0,93125	298	22
154	0,958333333	46	2	0,984375	315	5
155	0,875	42	6	0,98125	314	6
156	0,854166667	41	7	0,975	312	8
157	0,791666667	38	10	0,934375	299	21
158	0,916666667	44	4	0,975	312	8
159	0,958333333	46	2	0,99375	318	2
160	0,854166667	41	7	0,978125	313	7
161	0,8125	39	9	0,971875	311	9
162	0,895833333	43	5	0,984375	315	5
163	0,875	42	6	0,98125	314	6
164	0,875	42	6	0,98125	314	6
165	1	48	0	1	320	0
166	0,75	36	12	0,9625	308	12
167	0,833333333	40	8	0,959375	307	13
168	0,8125	39	9	0,96875	310	10
169	0,875	42	6	0,98125	314	6
170	0,770833333	37	11	0,93125	298	22
171	0,895833333	43	5	0,984375	315	5
172	0,875	42	6	0,98125	314	6
173	0,854166667	41	7	0,94375	302	18
174	0,854166667	41	7	0,94375	302	18
175	0,958333333	46	2	0,99375	318	2

176	0,854166667	41	7	0,971875	311	9
177	0,854166667	41	7	0,978125	313	7
178	0,895833333	43	5	0,984375	315	5
179	0,8125	39	9	0,9625	308	12
180	0,9375	45	3	0,990625	317	3
181	0,854166667	41	7	0,978125	313	7
182	0,895833333	43	5	0,984375	315	5
183	0,854166667	41	7	0,978125	313	7
184	0,916666667	44	4	0,9875	316	4
185	0,875	42	6	0,98125	314	6
186	0,854166667	41	7	0,971875	311	9
187	0,770833333	37	11	0,965625	309	11
188	0,895833333	43	5	0,975	312	8
189	0,9375	45	3	0,990625	317	3
190	0,854166667	41	7	0,978125	313	7
191	0,9375	45	3	0,990625	317	3
192	0,854166667	41	7	0,96875	310	10
193	0,895833333	43	5	0,984375	315	5
194	0,958333333	46	2	0,99375	318	2
195	0,895833333	43	5	0,984375	315	5
196	0,875	42	6	0,975	312	8
197	0,9375	45	3	0,990625	317	3
198	0,916666667	44	4	0,984375	315	5
199	0,875	42	6	0,978125	313	7
200	0,875	42	6	0,98125	314	6
201	0,916666667	44	4	0,9875	316	4
202	0,833333333	40	8	0,975	312	8
203	1	48	0	1	320	0
204	0,916666667	44	4	0,9875	316	4
205	0,875	42	6	0,98125	314	6
206	0,791666667	38	10	0,934375	299	21
207	0,958333333	46	2	0,99375	318	2
208	0,708333333	34	14	0,95	304	16
209	1	48	0	1	320	0
210	1	48	0	1	320	0
211	0,875	42	6	0,978125	313	7
212	0,8125	39	9	0,965625	309	11
213	0,854166667	41	7	0,971875	311	9
214	0,916666667	44	4	0,9875	316	4
215	0,895833333	43	5	0,975	312	8
216	0,958333333	46	2	0,99375	318	2
217	0,979166667	47	1	0,996875	319	1
218	0,958333333	46	2	0,99375	318	2
219	0,895833333	43	5	0,984375	315	5
220	0,916666667	44	4	0,9875	316	4

221	0,9375	45	3	0,990625	317	3
222	0,979166667	47	1	0,996875	319	1
223	0,854166667	41	7	0,978125	313	7
224	0,9375	45	3	0,990625	317	3
225	0,833333333	40	8	0,975	312	8
226	0,9375	45	3	0,990625	317	3
227	0,979166667	47	1	0,996875	319	1
228	0,895833333	43	5	0,984375	315	5
229	0,833333333	40	8	0,975	312	8
230	0,895833333	43	5	0,984375	315	5
231	0,791666667	38	10	0,95625	306	14
232	0,979166667	47	1	0,996875	319	1
233	1	48	0	1	320	0
234	0,833333333	40	8	0,975	312	8
235	0,770833333	37	11	0,9375	300	20
236	0,875	42	6	0,9625	308	12
237	0,854166667	41	7	0,978125	313	7
238	0,958333333	46	2	0,9875	316	4
239	0,854166667	41	7	0,978125	313	7
240	0,895833333	43	5	0,971875	311	9
241	0,854166667	41	7	0,965625	309	11
242	1	48	0	1	320	0
243	0,9375	45	3	0,96875	310	10
244	0,9375	45	3	0,990625	317	3
245	1	48	0	1	320	0
246	0,895833333	43	5	0,98125	314	6
247	0,9375	45	3	0,990625	317	3
248	0,729166667	35	13	0,95	304	16
249	0,9375	45	3	0,990625	317	3
250	0,916666667	44	4	0,978125	313	7
AVERAGE:	**0,88725**	**42,588**	**5,412**	**0,9778**	**312,896**	**7,104**

Table A.4: Output for the fleet increased by one vessel with minimal robust coefficients

	Number of vessels used=5	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,979166667	47	1	0,99375	318	2
2	1	48	0	1	320	0
3	1	48	0	1	320	0
4	0,979166667	47	1	0,996875	319	1
5	0,9375	45	3	0,971875	311	9
6	0,958333333	46	2	0,971875	311	9
7	1	48	0	1	320	0
8	0,979166667	47	1	0,99375	318	2
9	1	48	0	1	320	0
10	1	48	0	1	320	0
11	0,979166667	47	1	0,99375	318	2
12	0,958333333	46	2	0,984375	315	5
13	1	48	0	1	320	0
14	0,979166667	47	1	0,996875	319	1
15	0,9375	45	3	0,984375	315	5
16	1	48	0	1	320	0
17	1	48	0	1	320	0
18	0,979166667	47	1	0,996875	319	1
19	0,979166667	47	1	0,9875	316	4
20	1	48	0	1	320	0
21	0,875	42	6	0,9625	308	12
22	0,979166667	47	1	0,996875	319	1
23	1	48	0	1	320	0
24	1	48	0	1	320	0
25	1	48	0	1	320	0
26	1	48	0	1	320	0
27	0,979166667	47	1	0,99375	318	2
28	1	48	0	1	320	0
29	0,958333333	46	2	0,971875	311	9
30	1	48	0	1	320	0
31	0,916666667	44	4	0,9625	308	12
32	0,979166667	47	1	0,996875	319	1
33	0,979166667	47	1	0,996875	319	1
34	0,958333333	46	2	0,99375	318	2
35	0,958333333	46	2	0,978125	313	7
36	1	48	0	1	320	0
37	1	48	0	1	320	0
38	0,958333333	46	2	0,984375	315	5
39	1	48	0	1	320	0

40	1	48	0	1	320	0
41	1	48	0	1	320	0
42	1	48	0	1	320	0
43	1	48	0	1	320	0
44	1	48	0	1	320	0
45	1	48	0	1	320	0
46	0,979166667	47	1	0,996875	319	1
47	0,979166667	47	1	0,996875	319	1
48	1	48	0	1	320	0
49	1	48	0	1	320	0
50	0,979166667	47	1	0,996875	319	1
51	1	48	0	1	320	0
52	0,958333333	46	2	0,984375	315	5
53	0,979166667	47	1	0,996875	319	1
54	0,979166667	47	1	0,996875	319	1
55	0,979166667	47	1	0,9875	316	4
56	0,979166667	47	1	0,996875	319	1
57	0,958333333	46	2	0,971875	311	9
58	1	48	0	1	320	0
59	0,979166667	47	1	0,996875	319	1
60	0,979166667	47	1	0,996875	319	1
61	1	48	0	1	320	0
62	1	48	0	1	320	0
63	1	48	0	1	320	0
64	0,958333333	46	2	0,99375	318	2
65	1	48	0	1	320	0
66	0,979166667	47	1	0,996875	319	1
67	1	48	0	1	320	0
68	1	48	0	1	320	0
69	0,9375	45	3	0,96875	310	10
70	1	48	0	1	320	0
71	1	48	0	1	320	0
72	0,958333333	46	2	0,971875	311	9
73	1	48	0	1	320	0
74	1	48	0	1	320	0
75	1	48	0	1	320	0
76	1	48	0	1	320	0
77	1	48	0	1	320	0
78	0,958333333	46	2	0,99375	318	2
79	0,979166667	47	1	0,99375	318	2
80	1	48	0	1	320	0
81	0,979166667	47	1	0,996875	319	1
82	1	48	0	1	320	0
83	0,958333333	46	2	0,99375	318	2
84	1	48	0	1	320	0

85	1	48	0	1	320	0
86	0,9375	45	3	0,959375	307	13
87	1	48	0	1	320	0
88	1	48	0	1	320	0
89	0,958333333	46	2	0,9875	316	4
90	1	48	0	1	320	0
91	1	48	0	1	320	0
92	1	48	0	1	320	0
93	1	48	0	1	320	0
94	0,895833333	43	5	0,9625	308	12
95	1	48	0	1	320	0
96	0,916666667	44	4	0,965625	309	11
97	1	48	0	1	320	0
98	1	48	0	1	320	0
99	0,979166667	47	1	0,99375	318	2
100	0,979166667	47	1	0,984375	315	5
101	1	48	0	1	320	0
102	1	48	0	1	320	0
103	1	48	0	1	320	0
104	0,958333333	46	2	0,990625	317	3
105	1	48	0	1	320	0
106	1	48	0	1	320	0
107	1	48	0	1	320	0
108	1	48	0	1	320	0
109	1	48	0	1	320	0
110	1	48	0	1	320	0
111	1	48	0	1	320	0
112	1	48	0	1	320	0
113	1	48	0	1	320	0
114	0,916666667	44	4	0,98125	314	6
115	1	48	0	1	320	0
116	1	48	0	1	320	0
117	0,9375	45	3	0,984375	315	5
118	1	48	0	1	320	0
119	0,979166667	47	1	0,996875	319	1
120	1	48	0	1	320	0
121	1	48	0	1	320	0
122	1	48	0	1	320	0
123	0,9375	45	3	0,984375	315	5
124	0,9375	45	3	0,98125	314	6
125	1	48	0	1	320	0
126	0,958333333	46	2	0,98125	314	6
127	1	48	0	1	320	0
128	0,9375	45	3	0,990625	317	3
129	1	48	0	1	320	0

130	1	48	0	1	320	0
131	0,9375	45	3	0,9875	316	4
132	0,979166667	47	1	0,996875	319	1
133	0,979166667	47	1	0,996875	319	1
134	1	48	0	1	320	0
135	1	48	0	1	320	0
136	0,979166667	47	1	0,996875	319	1
137	0,958333333	46	2	0,99375	318	2
138	0,958333333	46	2	0,99375	318	2
139	0,958333333	46	2	0,990625	317	3
140	0,9375	45	3	0,96875	310	10
141	1	48	0	1	320	0
142	1	48	0	1	320	0
143	1	48	0	1	320	0
144	0,979166667	47	1	0,99375	318	2
145	1	48	0	1	320	0
146	1	48	0	1	320	0
147	0,979166667	47	1	0,990625	317	3
148	0,979166667	47	1	0,990625	317	3
149	1	48	0	1	320	0
150	1	48	0	1	320	0
151	0,9375	45	3	0,96875	310	10
152	0,979166667	47	1	0,996875	319	1
153	0,916666667	44	4	0,96875	310	10
154	0,979166667	47	1	0,9875	316	4
155	1	48	0	1	320	0
156	1	48	0	1	320	0
157	0,958333333	46	2	0,971875	311	9
158	0,979166667	47	1	0,99375	318	2
159	1	48	0	1	320	0
160	1	48	0	1	320	0
161	0,979166667	47	1	0,996875	319	1
162	1	48	0	1	320	0
163	0,979166667	47	1	0,996875	319	1
164	1	48	0	1	320	0
165	1	48	0	1	320	0
166	0,979166667	47	1	0,996875	319	1
167	0,979166667	47	1	0,990625	317	3
168	0,958333333	46	2	0,99375	318	2
169	0,979166667	47	1	0,996875	319	1
170	0,916666667	44	4	0,965625	309	11
171	0,979166667	47	1	0,996875	319	1
172	1	48	0	1	320	0
173	0,958333333	46	2	0,971875	311	9
174	0,958333333	46	2	0,971875	311	9

175	1	48	0	1	320	0
176	0,9375	45	3	0,98125	314	6
177	0,979166667	47	1	0,996875	319	1
178	1	48	0	1	320	0
179	0,979166667	47	1	0,996875	319	1
180	1	48	0	1	320	0
181	0,979166667	47	1	0,996875	319	1
182	0,979166667	47	1	0,996875	319	1
183	0,958333333	46	2	0,99375	318	2
184	1	48	0	1	320	0
185	1	48	0	1	320	0
186	0,958333333	46	2	0,990625	317	3
187	0,958333333	46	2	0,99375	318	2
188	0,9375	45	3	0,984375	315	5
189	1	48	0	1	320	0
190	0,958333333	46	2	0,99375	318	2
191	1	48	0	1	320	0
192	0,979166667	47	1	0,990625	317	3
193	1	48	0	1	320	0
194	1	48	0	1	320	0
195	0,979166667	47	1	0,996875	319	1
196	0,958333333	46	2	0,984375	315	5
197	1	48	0	1	320	0
198	0,979166667	47	1	0,996875	319	1
199	1	48	0	1	320	0
200	1	48	0	1	320	0
201	1	48	0	1	320	0
202	0,979166667	47	1	0,996875	319	1
203	1	48	0	1	320	0
204	1	48	0	1	320	0
205	1	48	0	1	320	0
206	0,958333333	46	2	0,971875	311	9
207	1	48	0	1	320	0
208	0,916666667	44	4	0,984375	315	5
209	1	48	0	1	320	0
210	1	48	0	1	320	0
211	1	48	0	1	320	0
212	0,9375	45	3	0,9875	316	4
213	0,958333333	46	2	0,990625	317	3
214	0,979166667	47	1	0,996875	319	1
215	0,979166667	47	1	0,99375	318	2
216	1	48	0	1	320	0
217	1	48	0	1	320	0
218	1	48	0	1	320	0
219	1	48	0	1	320	0

220	1	48	0	1	320	0
221	1	48	0	1	320	0
222	1	48	0	1	320	0
223	0,958333333	46	2	0,99375	318	2
224	1	48	0	1	320	0
225	0,979166667	47	1	0,996875	319	1
226	1	48	0	1	320	0
227	1	48	0	1	320	0
228	1	48	0	1	320	0
229	1	48	0	1	320	0
230	1	48	0	1	320	0
231	0,958333333	46	2	0,98125	314	6
232	1	48	0	1	320	0
233	1	48	0	1	320	0
234	1	48	0	1	320	0
235	0,958333333	46	2	0,978125	313	7
236	0,9375	45	3	0,984375	315	5
237	1	48	0	1	320	0
238	0,979166667	47	1	0,996875	319	1
239	0,979166667	47	1	0,996875	319	1
240	0,979166667	47	1	0,99375	318	2
241	0,916666667	44	4	0,975	312	8
242	1	48	0	1	320	0
243	0,958333333	46	2	0,984375	315	5
244	1	48	0	1	320	0
245	1	48	0	1	320	0
246	0,979166667	47	1	0,996875	319	1
247	1	48	0	1	320	0
248	1	48	0	1	320	0
249	0,979166667	47	1	0,996875	319	1
250	0,979166667	47	1	0,996875	319	1
AVERAGE:	**0,982666667**	**47,168**	**0,832**	**0,9945375**	**318,252**	**1,748**

Table A.5: Output for the fleet increased by one vessel with intermediate robust coefficients

	Number of vessels used=5	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,97916667	47	1	0,996875	319	1
2	1	48	0	1	320	0
3	1	48	0	1	320	0
4	1	48	0	1	320	0
5	0,91666667	44	4	0,971875	311	9
6	0,91666667	44	4	0,971875	311	9
7	1	48	0	1	320	0
8	0,97916667	47	1	0,99375	318	2
9	1	48	0	1	320	0
10	1	48	0	1	320	0
11	0,97916667	47	1	0,996875	319	1
12	0,9375	45	3	0,98125	314	6
13	1	48	0	1	320	0
14	1	48	0	1	320	0
15	0,95833333	46	2	0,984375	315	5
16	1	48	0	1	320	0
17	1	48	0	1	320	0
18	0,97916667	47	1	0,996875	319	1
19	0,97916667	47	1	0,984375	315	5
20	1	48	0	1	320	0
21	0,9375	45	3	0,971875	311	9
22	1	48	0	1	320	0
23	1	48	0	1	320	0
24	1	48	0	1	320	0
25	1	48	0	1	320	0
26	1	48	0	1	320	0
27	0,97916667	47	1	0,99375	318	2
28	1	48	0	1	320	0
29	0,91666667	44	4	0,971875	311	9
30	1	48	0	1	320	0
31	0,89583333	43	5	0,95625	306	14
32	1	48	0	1	320	0
33	0,97916667	47	1	0,996875	319	1
34	1	48	0	1	320	0
35	0,9375	45	3	0,978125	313	7
36	1	48	0	1	320	0
37	0,97916667	47	1	0,996875	319	1
38	0,97916667	47	1	0,996875	319	1
39	1	48	0	1	320	0

40	1	48	0	1	320	0
41	1	48	0	1	320	0
42	1	48	0	1	320	0
43	1	48	0	1	320	0
44	1	48	0	1	320	0
45	1	48	0	1	320	0
46	1	48	0	1	320	0
47	1	48	0	1	320	0
48	1	48	0	1	320	0
49	1	48	0	1	320	0
50	1	48	0	1	320	0
51	1	48	0	1	320	0
52	0,97916667	47	1	0,996875	319	1
53	1	48	0	1	320	0
54	1	48	0	1	320	0
55	0,97916667	47	1	0,984375	315	5
56	1	48	0	1	320	0
57	0,91666667	44	4	0,9625	308	12
58	1	48	0	1	320	0
59	1	48	0	1	320	0
60	1	48	0	1	320	0
61	1	48	0	1	320	0
62	1	48	0	1	320	0
63	1	48	0	1	320	0
64	1	48	0	1	320	0
65	1	48	0	1	320	0
66	1	48	0	1	320	0
67	1	48	0	1	320	0
68	1	48	0	1	320	0
69	0,95833333	46	2	0,975	312	8
70	1	48	0	1	320	0
71	0,97916667	47	1	0,996875	319	1
72	0,91666667	44	4	0,9625	308	12
73	1	48	0	1	320	0
74	1	48	0	1	320	0
75	1	48	0	1	320	0
76	1	48	0	1	320	0
77	1	48	0	1	320	0
78	1	48	0	1	320	0
79	0,97916667	47	1	0,996875	319	1
80	1	48	0	1	320	0
81	1	48	0	1	320	0
82	1	48	0	1	320	0
83	1	48	0	1	320	0
84	1	48	0	1	320	0

85	1	48	0	1	320	0
86	0,89583333	43	5	0,95625	306	14
87	1	48	0	1	320	0
88	1	48	0	1	320	0
89	0,97916667	47	1	0,996875	319	1
90	1	48	0	1	320	0
91	1	48	0	1	320	0
92	1	48	0	1	320	0
93	1	48	0	1	320	0
94	0,95833333	46	2	0,98125	314	6
95	1	48	0	1	320	0
96	0,91666667	44	4	0,96875	310	10
97	1	48	0	1	320	0
98	1	48	0	1	320	0
99	0,95833333	46	2	0,99375	318	2
100	0,95833333	46	2	0,98125	314	6
101	1	48	0	1	320	0
102	1	48	0	1	320	0
103	1	48	0	1	320	0
104	0,97916667	47	1	0,99375	318	2
105	1	48	0	1	320	0
106	1	48	0	1	320	0
107	1	48	0	1	320	0
108	1	48	0	1	320	0
109	1	48	0	1	320	0
110	1	48	0	1	320	0
111	1	48	0	1	320	0
112	1	48	0	1	320	0
113	1	48	0	1	320	0
114	0,91666667	44	4	0,975	312	8
115	1	48	0	1	320	0
116	1	48	0	1	320	0
117	0,95833333	46	2	0,9875	316	4
118	1	48	0	1	320	0
119	1	48	0	1	320	0
120	1	48	0	1	320	0
121	1	48	0	1	320	0
122	1	48	0	1	320	0
123	0,95833333	46	2	0,984375	315	5
124	0,95833333	46	2	0,98125	314	6
125	1	48	0	1	320	0
126	0,97916667	47	1	0,996875	319	1
127	1	48	0	1	320	0
128	1	48	0	1	320	0
129	1	48	0	1	320	0

130	1	48	0	1	320	0
131	0,97916667	47	1	0,996875	319	1
132	1	48	0	1	320	0
133	1	48	0	1	320	0
134	1	48	0	1	320	0
135	1	48	0	1	320	0
136	1	48	0	1	320	0
137	1	48	0	1	320	0
138	0,97916667	47	1	0,996875	319	1
139	0,97916667	47	1	0,99375	318	2
140	0,95833333	46	2	0,975	312	8
141	1	48	0	1	320	0
142	1	48	0	1	320	0
143	1	48	0	1	320	0
144	0,95833333	46	2	0,99375	318	2
145	1	48	0	1	320	0
146	1	48	0	1	320	0
147	0,97916667	47	1	0,990625	317	3
148	0,97916667	47	1	0,9875	316	4
149	1	48	0	1	320	0
150	1	48	0	1	320	0
151	0,95833333	46	2	0,975	312	8
152	1	48	0	1	320	0
153	0,95833333	46	2	0,975	312	8
154	0,97916667	47	1	0,984375	315	5
155	1	48	0	1	320	0
156	1	48	0	1	320	0
157	0,91666667	44	4	0,971875	311	9
158	0,95833333	46	2	0,99375	318	2
159	1	48	0	1	320	0
160	1	48	0	1	320	0
161	1	48	0	1	320	0
162	1	48	0	1	320	0
163	1	48	0	1	320	0
164	1	48	0	1	320	0
165	1	48	0	1	320	0
166	1	48	0	1	320	0
167	0,97916667	47	1	0,9875	316	4
168	1	48	0	1	320	0
169	1	48	0	1	320	0
170	0,9375	45	3	0,971875	311	9
171	1	48	0	1	320	0
172	1	48	0	1	320	0
173	0,91666667	44	4	0,971875	311	9
174	0,91666667	44	4	0,971875	311	9

175	1	48	0	1	320	0
176	0,97916667	47	1	0,99375	318	2
177	1	48	0	1	320	0
178	1	48	0	1	320	0
179	0,97916667	47	1	0,99375	318	2
180	1	48	0	1	320	0
181	1	48	0	1	320	0
182	1	48	0	1	320	0
183	1	48	0	1	320	0
184	1	48	0	1	320	0
185	1	48	0	1	320	0
186	0,97916667	47	1	0,99375	318	2
187	1	48	0	1	320	0
188	0,97916667	47	1	0,99375	318	2
189	1	48	0	1	320	0
190	1	48	0	1	320	0
191	1	48	0	1	320	0
192	0,97916667	47	1	0,99375	318	2
193	1	48	0	1	320	0
194	1	48	0	1	320	0
195	1	48	0	1	320	0
196	0,97916667	47	1	0,996875	319	1
197	1	48	0	1	320	0
198	0,97916667	47	1	0,996875	319	1
199	1	48	0	1	320	0
200	1	48	0	1	320	0
201	1	48	0	1	320	0
202	1	48	0	1	320	0
203	1	48	0	1	320	0
204	1	48	0	1	320	0
205	1	48	0	1	320	0
206	0,91666667	44	4	0,9625	308	12
207	1	48	0	1	320	0
208	0,97916667	47	1	0,99375	318	2
209	1	48	0	1	320	0
210	1	48	0	1	320	0
211	1	48	0	1	320	0
212	0,97916667	47	1	0,99375	318	2
213	0,97916667	47	1	0,99375	318	2
214	1	48	0	1	320	0
215	0,97916667	47	1	0,996875	319	1
216	1	48	0	1	320	0
217	1	48	0	1	320	0
218	1	48	0	1	320	0
219	1	48	0	1	320	0

220	1	48	0	1	320	0
221	1	48	0	1	320	0
222	1	48	0	1	320	0
223	1	48	0	1	320	0
224	1	48	0	1	320	0
225	1	48	0	1	320	0
226	1	48	0	1	320	0
227	1	48	0	1	320	0
228	1	48	0	1	320	0
229	1	48	0	1	320	0
230	1	48	0	1	320	0
231	0,97916667	47	1	0,996875	319	1
232	1	48	0	1	320	0
233	1	48	0	1	320	0
234	1	48	0	1	320	0
235	0,95833333	46	2	0,98125	314	6
236	0,95833333	46	2	0,984375	315	5
237	1	48	0	1	320	0
238	0,97916667	47	1	0,996875	319	1
239	1	48	0	1	320	0
240	0,95833333	46	2	0,99375	318	2
241	0,95833333	46	2	0,990625	317	3
242	1	48	0	1	320	0
243	0,9375	45	3	0,984375	315	5
244	1	48	0	1	320	0
245	1	48	0	1	320	0
246	1	48	0	1	320	0
247	1	48	0	1	320	0
248	0,97916667	47	1	0,99375	318	2
249	1	48	0	1	320	0
250	0,97916667	47	1	0,996875	319	1
AVERAGE:	**0,98825**	**47,436**	**0,564**	**0,9958875**	**318,684**	**1,316**

Table A.6: Output for the fleet increased by one vessel with maximal robust coefficients

	Number of vessels used=5	Number of routes schedules =48		Number of visits scheduled =320		
	Routes sustainability	Number of feasible routes	Number of not feasible routes	Platforms Sustainability	Number of completed visits	Number of visits missed
1	0,979166667	47	1	0,99375	318	2
2	1	48	0	1	320	0
3	1	48	0	1	320	0
4	1	48	0	1	320	0
5	0,958333333	46	2	0,9875	316	4
6	0,9375	45	3	0,984375	315	5
7	1	48	0	1	320	0
8	0,979166667	47	1	0,99375	318	2
9	1	48	0	1	320	0
10	1	48	0	1	320	0
11	0,979166667	47	1	0,99375	318	2
12	0,9375	45	3	0,975	312	8
13	1	48	0	1	320	0
14	1	48	0	1	320	0
15	0,958333333	46	2	0,98125	314	6
16	1	48	0	1	320	0
17	1	48	0	1	320	0
18	0,979166667	47	1	0,996875	319	1
19	0,979166667	47	1	0,9875	316	4
20	1	48	0	1	320	0
21	0,9375	45	3	0,96875	310	10
22	1	48	0	1	320	0
23	1	48	0	1	320	0
24	1	48	0	1	320	0
25	1	48	0	1	320	0
26	1	48	0	1	320	0
27	0,979166667	47	1	0,99375	318	2
28	1	48	0	1	320	0
29	0,9375	45	3	0,984375	315	5
30	1	48	0	1	320	0
31	0,895833333	43	5	0,96875	310	10
32	1	48	0	1	320	0
33	0,979166667	47	1	0,990625	317	3
34	1	48	0	1	320	0
35	0,979166667	47	1	0,99375	318	2
36	1	48	0	1	320	0
37	0,979166667	47	1	0,990625	317	3
38	1	48	0	1	320	0
39	1	48	0	1	320	0

40	1	48	0	1	320	0
41	1	48	0	1	320	0
42	1	48	0	1	320	0
43	1	48	0	1	320	0
44	1	48	0	1	320	0
45	1	48	0	1	320	0
46	1	48	0	1	320	0
47	1	48	0	1	320	0
48	1	48	0	1	320	0
49	1	48	0	1	320	0
50	1	48	0	1	320	0
51	1	48	0	1	320	0
52	1	48	0	1	320	0
53	1	48	0	1	320	0
54	1	48	0	1	320	0
55	0,979166667	47	1	0,9875	316	4
56	1	48	0	1	320	0
57	0,916666667	44	4	0,975	312	8
58	1	48	0	1	320	0
59	1	48	0	1	320	0
60	1	48	0	1	320	0
61	1	48	0	1	320	0
62	1	48	0	1	320	0
63	1	48	0	1	320	0
64	1	48	0	1	320	0
65	1	48	0	1	320	0
66	1	48	0	1	320	0
67	1	48	0	1	320	0
68	1	48	0	1	320	0
69	0,958333333	46	2	0,98125	314	6
70	0,979166667	47	1	0,996875	319	1
71	1	48	0	1	320	0
72	0,916666667	44	4	0,975	312	8
73	0,979166667	47	1	0,996875	319	1
74	1	48	0	1	320	0
75	1	48	0	1	320	0
76	1	48	0	1	320	0
77	1	48	0	1	320	0
78	1	48	0	1	320	0
79	0,979166667	47	1	0,99375	318	2
80	1	48	0	1	320	0
81	1	48	0	1	320	0
82	1	48	0	1	320	0
83	1	48	0	1	320	0
84	0,979166667	47	1	0,996875	319	1

85	1	48	0	1	320	0
86	0,916666667	44	4	0,971875	311	9
87	1	48	0	1	320	0
88	1	48	0	1	320	0
89	0,979166667	47	1	0,99375	318	2
90	1	48	0	1	320	0
91	1	48	0	1	320	0
92	1	48	0	1	320	0
93	1	48	0	1	320	0
94	0,979166667	47	1	0,9875	316	4
95	1	48	0	1	320	0
96	0,9375	45	3	0,971875	311	9
97	1	48	0	1	320	0
98	1	48	0	1	320	0
99	0,958333333	46	2	0,9875	316	4
100	0,979166667	47	1	0,990625	317	3
101	1	48	0	1	320	0
102	1	48	0	1	320	0
103	1	48	0	1	320	0
104	0,979166667	47	1	0,99375	318	2
105	1	48	0	1	320	0
106	1	48	0	1	320	0
107	1	48	0	1	320	0
108	1	48	0	1	320	0
109	1	48	0	1	320	0
110	1	48	0	1	320	0
111	1	48	0	1	320	0
112	1	48	0	1	320	0
113	1	48	0	1	320	0
114	0,916666667	44	4	0,978125	313	7
115	1	48	0	1	320	0
116	1	48	0	1	320	0
117	0,958333333	46	2	0,978125	313	7
118	1	48	0	1	320	0
119	0,979166667	47	1	0,996875	319	1
120	1	48	0	1	320	0
121	1	48	0	1	320	0
122	1	48	0	1	320	0
123	0,958333333	46	2	0,978125	313	7
124	0,979166667	47	1	0,9875	316	4
125	1	48	0	1	320	0
126	1	48	0	1	320	0
127	1	48	0	1	320	0
128	1	48	0	1	320	0
129	1	48	0	1	320	0

130	1	48	0	1	320	0
131	0,979166667	47	1	0,99375	318	2
132	1	48	0	1	320	0
133	1	48	0	1	320	0
134	1	48	0	1	320	0
135	1	48	0	1	320	0
136	1	48	0	1	320	0
137	1	48	0	1	320	0
138	1	48	0	1	320	0
139	0,979166667	47	1	0,99375	318	2
140	0,958333333	46	2	0,98125	314	6
141	1	48	0	1	320	0
142	1	48	0	1	320	0
143	1	48	0	1	320	0
144	0,958333333	46	2	0,984375	315	5
145	1	48	0	1	320	0
146	1	48	0	1	320	0
147	0,979166667	47	1	0,99375	318	2
148	0,979166667	47	1	0,990625	317	3
149	1	48	0	1	320	0
150	1	48	0	1	320	0
151	0,9375	45	3	0,978125	313	7
152	1	48	0	1	320	0
153	0,958333333	46	2	0,98125	314	6
154	0,979166667	47	1	0,9875	316	4
155	1	48	0	1	320	0
156	1	48	0	1	320	0
157	0,9375	45	3	0,984375	315	5
158	0,958333333	46	2	0,984375	315	5
159	1	48	0	1	320	0
160	1	48	0	1	320	0
161	1	48	0	1	320	0
162	1	48	0	1	320	0
163	1	48	0	1	320	0
164	1	48	0	1	320	0
165	1	48	0	1	320	0
166	1	48	0	1	320	0
167	0,979166667	47	1	0,990625	317	3
168	1	48	0	1	320	0
169	1	48	0	1	320	0
170	0,958333333	46	2	0,98125	314	6
171	1	48	0	1	320	0
172	1	48	0	1	320	0
173	0,9375	45	3	0,984375	315	5
174	0,9375	45	3	0,984375	315	5

175	1	48	0	1	320	0
176	0,958333333	46	2	0,990625	317	3
177	1	48	0	1	320	0
178	1	48	0	1	320	0
179	0,979166667	47	1	0,99375	318	2
180	1	48	0	1	320	0
181	1	48	0	1	320	0
182	1	48	0	1	320	0
183	1	48	0	1	320	0
184	1	48	0	1	320	0
185	1	48	0	1	320	0
186	0,979166667	47	1	0,99375	318	2
187	1	48	0	1	320	0
188	0,979166667	47	1	0,99375	318	2
189	1	48	0	1	320	0
190	1	48	0	1	320	0
191	1	48	0	1	320	0
192	0,979166667	47	1	0,990625	317	3
193	1	48	0	1	320	0
194	1	48	0	1	320	0
195	1	48	0	1	320	0
196	1	48	0	1	320	0
197	1	48	0	1	320	0
198	0,979166667	47	1	0,990625	317	3
199	1	48	0	1	320	0
200	1	48	0	1	320	0
201	1	48	0	1	320	0
202	1	48	0	1	320	0
203	1	48	0	1	320	0
204	1	48	0	1	320	0
205	1	48	0	1	320	0
206	0,916666667	44	4	0,975	312	8
207	1	48	0	1	320	0
208	0,979166667	47	1	0,996875	319	1
209	1	48	0	1	320	0
210	1	48	0	1	320	0
211	1	48	0	1	320	0
212	0,979166667	47	1	0,99375	318	2
213	0,979166667	47	1	0,996875	319	1
214	1	48	0	1	320	0
215	0,979166667	47	1	0,99375	318	2
216	1	48	0	1	320	0
217	1	48	0	1	320	0
218	1	48	0	1	320	0
219	1	48	0	1	320	0

220	1	48	0	1	320	0
221	1	48	0	1	320	0
222	1	48	0	1	320	0
223	1	48	0	1	320	0
224	1	48	0	1	320	0
225	1	48	0	1	320	0
226	1	48	0	1	320	0
227	1	48	0	1	320	0
228	1	48	0	1	320	0
229	1	48	0	1	320	0
230	1	48	0	1	320	0
231	1	48	0	1	320	0
232	1	48	0	1	320	0
233	1	48	0	1	320	0
234	1	48	0	1	320	0
235	0,958333333	46	2	0,9875	316	4
236	0,958333333	46	2	0,978125	313	7
237	1	48	0	1	320	0
238	1	48	0	1	320	0
239	1	48	0	1	320	0
240	0,958333333	46	2	0,984375	315	5
241	0,979166667	47	1	0,99375	318	2
242	1	48	0	1	320	0
243	0,979166667	47	1	0,996875	319	1
244	1	48	0	1	320	0
245	1	48	0	1	320	0
246	1	48	0	1	320	0
247	1	48	0	1	320	0
248	0,979166667	47	1	0,996875	319	1
249	1	48	0	1	320	0
250	1	48	0	1	320	0
AVERAGE:	**0,99**	**47,52**	**0,48**	**0,996575**	**318,904**	**1,096**