University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program / Specialization: Industrial Economics/ Project Management	Fall semester, 2013 Restricted access
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Title of thesis: Optimal offshore supply vessel planning: A case study of a Chinese offshore oil and gas production area.	
Credits (ECTS): 30 ETCS	
Key words: offshore supply vessel planning; optimization; bin-packing problem ; traveling salesman problem; genetic algorithm ;	Pages: 50 Beijing, May 2014

Acknowledgement

I would like to give my sincere gratitude to my supervisor, Professor Ove Tobias Gudmestad, for giving me good instructions and comments during the process of writing this thesis. He help me to collect valuable references and bring me step by step to reach qualify academic level to concludes the master degree in Industrial Economics at University of Stavanger.

I would also like to thank Professor Tore. Markeset , Professor Ove Tobias Gudmestad, as well as other Professors of University of Stavanger, for their instructions and help in my study, as both my teachers and friends.

I would also like to take the chance to express my appreciation to University of Stavanger, who give me such a precious chance to study in Norway, and also to express my thanks to Mr. Li, Yong and Mr. Zi, Silong who on behalf of the company COSL to sponsor my graduate study in University of Stavanger, without their good faith and deeds for the youth of their company, I could not finish the study in good wellbeing freely.

I would also like to thank my family members who encouraged and supported me to go ahead, not only in studying in Norway, but also in writing the thesis.

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Abbreviations

BPP	Bin-Packing Problem
COSL	China Oilfield Services Limited
GA	Genetic Algorithm
PSV	Platform Supply Vessel
MTVRSP	Multi-trip Vehicle Routing and Scheduling Problem
TSP	Traveling Salesman Problem
VRP	Vehicle Routing Problem
VRPSPD	Vehicle Routing Problem with simultaneous pick-up and delivery

Abstract

In the offshore oil and gas industry, the drilling or production installations scattered in the offshore oilfields require supplies from onshore depots. These supply services are performed specially by the offshore supply vessel fleets shuttling between offshore installations and onshore depots. In practice, the offshore supply vessels owned by a service company are normally under time charter and their operations are arranged by their charterer, the oil company. The planning of the supply service under many real-life constraints is a problem faced by every offshore oil company. Considering the time charter and the fuel costs being so costly, a cost-efficient supply service planning can achieve considerable cost-saving for the operators. So, how to optimize the composition, supply route, and voyage schedule of the fleets, to minimize their operational cost, is an important and worthwhile problem. Fortunately, there are already some successful solutions for this optimization problem. Many logistics and maritime transportation methods can be introduced to realize the optimal and robust solution. In this thesis, the main objective is to discuss these methods, apply one of these methods, combined with the case of the offshore supply vessel fleet of COSL, to try to find out an optimal cost-efficient supply vessel planning for a specific offshore oil and gas production area.

Chapter 1. Introduction

1.1 Industrial background

In the offshore oil and gas industry, the oil and gas offshore installations not only require regular supplies of commodities from onshore depots, but need collecting cargo or waste to land as well. These cargo delivery and pickup services are performed by the offshore supply vessels. In terms of logistics, this transportation between offshore installations and onshore depots is known as upstream logistics, which is critical to support the offshore drilling and production operations.

This offshore supply chain consists of onshore depots, offshore installations, supply vessels, cargoes, and service performances: Onshore depots are where companies store or receive the supply or returned goods. Offshore installations which mainly include drilling rigs and production platforms require transportation services to ensure their smooth drilling or production operations. Offshore supply vessels are chartered to perform the transportation service. They visit offshore installations to perform deliveries or pickups at certain intervals. The cargoes are divided into two basic categories: deck cargo, such as containers, baskets in different kinds, sizes, and weights; dry or liquid bulk, like cement, drilling mud, or water that stored in tanks. The transportation services performance consist of delivery supply goods and pickup return cargoes. These supply services are planned by the oil company, who charter the supply vessels to satisfy the supply demands of offshore operations.

In the real-life, the offshore supply services are subject to many constraints and uncertainties. **Constraints**: the operating time window of production platforms and onshore depots; the limited loading and storing capability of the supply vessels and offshore installations; the limited sailing distance of the supply vessels; the limited service capacity of the onshore depots; the demands volume of cargoes from offshore operation. **Uncertainties:** the stochastic requirements for operating materials; the varying size of free space for storing on an offshore installation; the dynamic weather conditions; some unpredictable accidents.

In this logistics chain, the operation of supply vessels is a costly element. The cost of renting and operating a supply vessel per day is approximately 200,000RMB in China. On the other hand, bad supply services may cause unacceptable delay or close down the drilling or production operations, which means great economic losses for the oil company. Hence, in order to satisfy the demands from the offshore operations, the offshore oil company input enormous money in these supply services.

1.2 Problem description and Objectives

In view of the dynamic demands volume of offshore operations and the real-life constrains and uncertainties, the supply service planning faced by every offshore oil company is a very complex problem which needs careful planning. This planning problem consists of determining the fleet size of supply vessels and their corresponding supply routes and schedules from an onshore supply depot to offshore installations. It mainly concerns two aspects: how to design the fleet size and configuration, according to the supply demands volume and supply vessel's transport capacity; how to arrange supply vessels' supply period and routing with pickups and deliveries, under many constraints. At present, in most oil companies, the planning of the offshore installations' supply services is decided almost only manually without any application of optimization methods. Hence, considering the high cost of the supply service, substantial cost-savings may be realized by improving the planning, through introducing some optimization tool to develop a cost-efficient solution.

Actually, in other industries, the optimization methods have been applied widely. The introduction of optimization algorithm in solving the vehicle routing problem and the limited resources allocation problem in other fields has been explored for decades. This type of offshore supply logistics planning problem is often regarded as a special vehicle routing problem. So, it is reasonable to believe that the application of optimization algorithm can be also introduced in the upstream logistics of offshore oil and gas industry. In recent years, many researches have learnt to use optimization algorithms in optimizing offshore supply logistics planning. Some classic optimization algorithms, e.g. genetic algorithm, heuristic algorithm, neural network algorithm, have already been introduced to solve the optimization problem of offshore supply service planning. The solution is mainly realized by developing mathematic model from the operation researches, and then by applying some optimization algorithm on powerful optimization softwares, such as Matlab, Lingo, Cplex and Excel, to solve this mathematic model.

At present, in China, little research has been conducted in this area. So, the objective of this thesis is to learn and discuss some the successful developed optimization solutions of this problem, and apply one of these methods to build a mathematical model, combined with the case of the offshore supply vessel fleet of COSL, to try to find out an optimal fleet composition, routing and schedule planning for this fleet.

The optimization tool will be developed to answer these two questions in this thesis:

- What is the best size and composition of a supply vessel fleet to service a specific oil and gas field, so that the charter cost is minimal?
- What sequence of installations to be visited by each supply vessel in this fleet, what periodic schedule of the supply vessels in this fleet to go forth and back between depots and offshore installations, so that the supply services are performed at lowest cost while satisfying the various operational constraints and with respect to the stochastic factors?

1.3 Limitation

However, due to the dynamic, stochastic and unpredictable factors in this industry, it is unpractical to obtain an exact optimal solution for this supply service planning and it is hard to establish a fixed schedule and routing planning. The developed solution is not only similar to the optimization, but also subject to update and adjustments. Besides, it is also unpractical to prove the solution of the planning in real-life operation at present.

1.4 Relevant literature

1.4.1 Literature review for the vehicle routing problem (VRP).

Brandao and Mercer (1997) present a novel tabu search heuristic for the multi-trip vehicle routing and scheduling problem (MTVRSP).

An exact algorithm for the VRP with time windows and multiple uses of vehicles can be found in Azi et al. (2010). The authors introduce a branch-and-price approach to address this problem.

A new exact algorithm to solve the multi-trip vehicle routing problem with time windows and limited duration can be found in Hernandez et al. (2012). The authors provide an exact two-phase algorithm to solve this problem.

Shuguang Liu et al. (2009) introduce an effective genetic algorithm for the fleet size and mix vehicle routing problems, they design and implement a genetic algorithm (GA) based heuristic method to find one best solution for the fleet size and mix vehicle routing problem.

1.4.2 Literature review for the supply vessel planning problems.

The role of supply vessels in the offshore logistics chain is discussed by Aas et al. (2009). The authors present the elements of the upstream logistics in the oil and gas industry. The focus of the paper is on the design of the supply vessel fleet, searching for the best fleet configuration and size by analyzing the carrying capacity of supply vessels.

The routing of supply vessels to petroleum installations is studied by Gribkovskaia et al. (2008) where a simplified version of the real-life routing problem for one supply vessel is formulated as a mixed integer linear programming model that contains constraints reflecting the storage requirements problem. The goal is to explore how the offshore installations' limited storage capacity affects the routing of the supply vessels aiming towards creating efficient routes.

Halvorsen-Weare et al. (2012) develop a voyage-based solution method for the supply vessel planning problem, including both fleet composition and periodic routing planning. The voyage-based model solves this problem by choosing the most cost-effective supply vessels and picking the best of the pre-generated voyages that in combination fulfill the constraints. Their solution method has been tested on actual problems based on a real supply vessel planning problem faced by Statoil.

The rest of this thesis is organized as follows: First, introduce the offshore supply planning problem and develop the mathematic model. Then the Genetic Algorithm optimization algorithms and the Genetic Algorithm based software are discussed. Next, one Genetic Algorithm based software will be introduced to solve these mathematic models. And a pilot study will be conducted to develop an optimization method for the offshore vessel planning problem. Thereafter, we present a real case of the offshore supply vessel planning, including an offshore supply vessel fleet of COSL and the specific offshore oil and gas fields they are servicing. The optimization method developed in the pilot study is introduced to optimize the service planning of this supply vessel fleet. Finally, in the last section, a conclusion is given and some suggestions for further research are presented.

Chapter 2. The offshore supply vessel planning optimization problem and a Mathematical model

2.1 Offshore supply chain

The offshore supply chain in the upstream logistics of the offshore oil industry mainly consists of onshore depots, supply vessels, offshore installations, cargoes, and service performances, which play their respective roles in this supply chain. Their characteristics and functions are introduced as below.

2.1.1 Onshore depots

Onshore depots are where companies store or receive the supply or returned goods. They have opening hours, (e.g. 0830-1730), for unloading and loading of supply vessels, and also have limited berth for alongside access.

2.1.2 Supply vessels

Offshore supply vessels are chartered by oil companies to perform the transportation service. They are capable of carrying deck cargo, bulk cargo, as well as liquid cargo. They shuttle between onshore depots and offshore installations to perform deliveries or pickups at certain intervals. A supply vessel has a designed deck and bulk capacity, sailing speed, sailing endurance and dead loading capability. The deck area for loading of deck cargo vary from about 400 to 600 m^2, deck loading tonnage is between 600t to 900t. The bulk capacity is about 170 m^3. The liquid carrying capability is between 2000 m^3 to 4000 m^3. The dead loading capability, which is the upper bound of the loading capability, is varying from about 1800t to 2500t. The maximum sailing speed is about 15kn, economic sailing speed is about 12kn. Their sailing endurance, the maximum sailing capability of a vessel, is varying from 7000 n miles to 10000 n miles. The offshore supply vessels are the most costly element in this supply chain. Their daily charter rate is about 100,000RMB in China, more or less, depending on their function. Their daily operation cost, including fuel consumption cost, port surcharge, and so on, is about 10,000RMB.

2.1.3 Offshore installations

Offshore installations mainly include drilling rigs and production platforms, which are scattered in the offshore oil field, requiring transportation services to ensure their smooth drilling or production operations. The production platform normally have opening time, 0700-1900, whereas the drilling rigs are open for handling cargo all 24 hours. Their deck or tank storage capabilities are also limited, depending on their size.

Their demand for cargo depends on their production or drilling operation, fluctuating around a year.

2.1.4 Cargoes

The cargoes are divided into two basic categories: deck cargo, such as containers, baskets of different kinds, sizes, and weights; dry or liquid bulk, like cement, drilling mud, or water that is stored in tanks.

2.1.5 Supply services performance and Offshore supply planning

In the offshore supply chain, the transportation services in one planning cycle are performed as below:

The information regarding the cargo that is demanded by a set of offshore installations in next week or several days ahead will be sent to the marine department of the oil company in advance. According to this information, the marine department makes a plan for the supply service, including the visit sequence (supply route), the number of vessels needed, the time schedule of the following voyages in next week or several days. Then this plan will be sent to the depot, ship companies, and captains, to request them to arrange the supply. Finally, being guided by the supply service plan, the assigned offshore supply vessels will come back to depots to load and unload cargo, and then sail to offshore installations, to delivery supply goods and pickup return cargoes during the opening time of the offshore installations.

2.2 The offshore supply vessel planning optimization problem

The offshore supply vessel planning optimization problem studied in this thesis is to optimize the offshore supply plan mentioned above. The objective is minimizing the costs, while satisfying the real life constraints and supply demands. This is achieved mainly by optimizing the composition of supply fleet to minimize the charter cost of supply vessels needed, and by optimizing the routes of the supply voyage to minimize the total sailing distance.
The following assumptions apply in this study:

- The route starts and ends at the same depot.
- The deck loading capability of a vessel is measured by the area of the deck loading zone.
- The demanded or pick-up cargoes from one installation seem as one cargo unit in the cargo area.
- Each offshore installation is visited exactly once in each supply voyage.
- The pick-up and delivery should be performed at the same visit.

- Split delivery is not permitted.
- One vessel only sails in one of the designed routes.
- The delivery is performed before the pick-up at each installation.
- The cargoes demanded by installation i should be delivery to installation i only.

2.3 Mathematical model of the supply vessel planning optimization problem

The offshore supply vessel planning optimization problem is a special kind of vehicle routing problem, which can be abstracted to be a combination of the **bin-packing problem (BPP)**, for optimizing the composition of supply fleet and the **vehicle routing problem (or Travelling salesman problem, if the number of vehicle needed is one) with simultaneous pick-up and delivery (VRPSPD)**, for optimizing supply routing planning. By applying operation research models, mathematic models can be developed to describe these two optimization problems. These two mathematic models are built as follow:

2.3.1 Minimizing the charter cost of needed supply vessels

In view of the costly time charter of one offshore supply vessel, cost-saving achieved by reducing the number of the needed supply vessels is much higher than by sailing the shortest supply distance. So, optimizing the composition of supply fleet to minimize the charter cost of supply vessels in the supply chain is the primary objective of this optimization problem. The bin-packing problem in the operation research is introduced to solve this problem.

2.3.1.1 Bin-packing problem (BPP)

In this part, the work is to find out the minimum number of vessels needed to perform supply services in a planning cycle, given the volume of cargo demanded and the loading capability of vessels. This is similar to the bin-packing problem in operation research. In the bin packing problem, objects of different volumes must be packed into a finite number of bins or containers with given volume V in a way that minimizes the number of bins used. In the case of supply planning, the bins are the supply vessels with designed capabilities, and the objects are the cargo units (the demanded or pick-up cargoes from one platform are counted as one cargo unit here). The aim is to find the way that a minimum number of vessels are used to load all the demanded cargoes, without violating the vessels' loading capability. **The difference** is that: the measurement parameters are the area of cargo units and vessels' decks, instead of their volumes or weights. Because, in practice, even though the deck of a supply vessel is full of cargoes, except some extraordinary heavy items, the total loading weights used to be still within the vessel' maximum loading capacity. So, the maximum loading area of one vessel's deck is regarded as the maximum loading capacity in this case. And the bin packing problem studied here is a simple 1D packing problem, not a 2D or 3D packing problem.

2.3.1.2 Mathematical model

Refer to the Genetic Algorithms and Engineering Optimization, Gen and Cheng, (2003), the mathematical model for minimizing the number of vessels needed is developed as:

Set:
n: the number of cargo units
a: the area of one cargo unit
cap: the loading capability of one vessel (the area of deck)
V: the number of vessel used

Minimize:

$$\mathrm{V} = \sum_{j=1}^{\mathrm{n}} \mathrm{y}_j \tag{1}$$

Subject to: $$\sum_{i=1}^{n} a_i x_{ij} \leq \mathrm{cap} \times y_j\,, \quad \forall i \in N = \{1,2,\cdots,n\} \tag{2}$$

$$y_j = 0 \text{ or}1, \qquad \forall\, i \in \mathrm{N} \tag{3}$$

$$x_{ij} = 0 \text{ or } 1, \qquad \forall i\,, j \in \mathrm{N} \tag{4}$$

Remark: x_{ij} = 1 means that packing unit *i* into vessel *j*; Otherwise, x_{ij} = 0.
y_j = 1 means that vessel *j* be used; Otherwise y_j = 0.
The constraint requires that the total area of the cargo unit that is packed into vessel *j* must not exceed the capacity of the vessel *j*.

2.3.2 Minimizing the total sailed distance

Once the optimal composition of supply fleet has been determined by the solution of the mathematic model above, the next objective is to find the optimal supply routes planning with the shortest total sailing distance for them. This is realized by applying the vehicle routing problem with simultaneous pick-up and delivery.

2.3.2.1 The vehicle routing problem with simultaneous pick-up and delivery (VRPSPD)

In this section, the objective is to minimize the total sailed distance by a fleet of supply vessels to serve offshore installations. The offshore supply routing optimization is similar to the vehicle routing problem, in which, vehicles start from one depot to visit a set of customers in a set of routes, to delivery and pickup cargoes, one vehicle only travel in one route, visiting all of the customers and returning to their starting point in the shortest total travelling distance. In our case, the supply vessels act as the vehicles depart from the depot to visit a set of offshore installations and then return to depot in their respective routes. Our goal is also to find a set of routes which minimizes the total travelling distance of these vessels. **The difference** is that the number of vessels is determined by the bin-packing problem, instead of being decided by the number of routes in the solution, as the method presented by Serdar Tasan and Gen (2011), in which the optimal solution consists of five routes and hence five vehicles are needed to perform the serves.

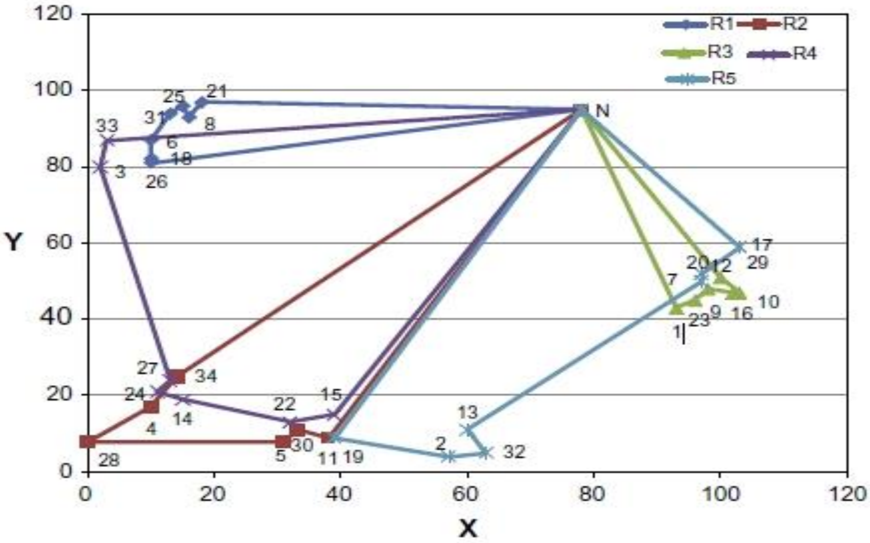


Figure 1 Example of vehicle routing problem (Serdar Tasan and Gen, 2011).

2.3.2.2 Mathematical model

Based on the mathematical model developed by Toth and Vigo, (2011), a mathematical model for minimizing of the total sailed distance by a fleet of supply vessels is built as follow:

Sets:

V: set of supply vessels used in one voyage

I: set of offshore installations

N: set of all nodes including depot

Parameters:

v: number of vessels in one voyage, $v \in V$

n: number of nodes, $n \in N$; n=0 denotes the depot

d: supply vessel sailing distance

cap: vessel carrying capacity.

d_{ij}: distance between nodes *i* and *j* *i*, *j*∈N, *i*≠*j*.

d_i: cargo amount demanded by installation *i* , *i*∈I.
p_i: cargo amount picked up from installation *i* , *i*∈I.

Decision Variables:
D_{ijv} : The remaining cargo to be delivered by the *v*-th vehicle when departing from node *i* to *j*
P_{ijv} : The cumulative cargo picked up by the *v*-th vehicle when departing from node *i* to j
u_{ijv}: The cargo of the v-th vehicle when departing from node *i* to *j*
x_{ijv}: Binary decision variable that indicates whether the *v*-th vehicle travels from *i* to *j*.
x_{ijv} = 1, if the vehicle travels directly from *i* to *j*
= 0, otherwise

Minimize:

$$\sum_{i=0}^{i=N}\sum_{j=0}^{j=N}\sum_{v=1}^{v=V} d_{ij}\ x_{ijv} \tag{1}$$

Subject to:

$$\sum_{j=1}^{j=N}\sum_{v=1}^{v=V} x_{ijv} = \sum_{j=1}^{j=N}\sum_{v=1}^{v=V} x_{jiv} = V \qquad i = 0, j \in N, v \in V \tag{2}$$

$$\sum_{i=0}^{i=N}\sum_{v=1}^{v=V} x_{ijv} = 1 \qquad \forall i \in N, v \in V \tag{3}$$

$$\sum_{j=0}^{j=N}\sum_{v=1}^{v=V} x_{ijv} = 1 \qquad \forall j \in N, v \in V \tag{4}$$

$$\sum_{j\in N} x_{ijv} = \sum_{j\in N} x_{jiv} = 1 \qquad i = 0, j \in N, v \in V \tag{5}$$

$$\sum_{j=1}^{j=N} D_{0jv} = \sum_{i=0}^{i=N}\sum_{j=0}^{j=N} x_{ijv} d_i \qquad \forall v \in V, i \neq j \tag{6}$$

$$\sum_{i=1}^{i=N} P_{i0v} = \sum_{i=0}^{i=N} \sum_{j=0}^{j=N} x_{ijv} p_i \qquad \forall v \in V, i \neq j \qquad (7)$$

$$\sum_{j=1}^{j=N} D_{0jv} \leq cap \qquad \forall i, j \in N, v \in V \qquad (8)$$

$$\sum_{i=1}^{i=N} P_{i0v} \leq cap \qquad \forall i, j \in N, v \in V \qquad (9)$$

$$u_{ijv} \leq x_{ijv} \times cap \qquad (10)$$

$$D_{ijv} \geq 0 \qquad P_{ijv} \geq 0 \qquad (11)$$

$$u_{iv} - u_{jv} + cap \times x_{ijv} \leq C - d_j \qquad \forall i, j \in N, v \in V, i \neq j$$

$$d_i \leq u_{iv} \leq cap \qquad (12)$$

$$x_{ijv} \in \{0,1\} \text{ and integer} \qquad \forall i, j \in N \qquad (13)$$

The objective function (1) minimizes the total sailed distance by a fleet of supply vessels. Constraint (2) ensures that the number of the vehicles which start from the depot and go back to depot is V. Constraints (3), (4) represent that each customer can only be served by one vehicle. Further, constraint (5) means all the vehicles which start from the depot go back to the depot. Equation (6) means that the initial loading cargo amount at the depot equal to the sum of the cargo amount demanded by all installations. Equation (7) means that the cumulative load picked up by the v-th vehicle when departing from node i to depot. Constraints (8) and (9) are transit load constraints. Constraint (10) ensures that no matter where the vehicle is, the load cannot exceed the vehicle's capacity. Constraint (11) maintains non-negativity of D_{ijv} and P_{ijv}. Constraint (12) is the subtour elimination constrains, e.g. when $x_{ijv} = 1$, $u_{jv} \geq u_{iv} + d_j$. x_{ijv} is a binary decision variable as in (13).

These two problems are both belonging to a type of combinatorial optimization problem, which can be solved by many optimization algorithms, such as Genetic Algorithm, Simulate Anneal Arithmetic, and Tabu search Algorithm, introduced by Wang, et al. (2006). In next chapter, the Genetic Algorithm will be discussed.

Chapter 3. The Genetic Algorithm

The Genetic Algorithm (GA) is known as an artificial intelligent optimization method developed by Holland and his students at the University of Michigan in the early 1970s, according to Wang, et al. (2006). In the following decades, the algorithm has been improved gradually and can be used to solve various optimization problems in lots of fields, such as vehicle routing problems, shortest path problems, and assignment problems. For its excellent optimization-searching performance, it becomes the most widespread and successful optimization algorithm in the theory of artificial intelligent optimization methods. In the works of Wang, et al. (2006) and Gen and Cheng, (2003), the genetic algorithm is introduced as below:

3.1 The general principle of Genetic Algorithm

3.1.1 Basic idea

The basic idea of the GA is that: an initial set of *chromosomes* (solutions) is generated as a *population* and subject to evaluation of the *fitness function* (scaled from the objective function). *Chromosomes* with relatively good fitness levels are more likely to survive and reproduce. They are selected as *parent chromosomes* to reproduce *offspring chromosomes,* while the ones with bad fitness values are removed. After *crossover* and *mutation* of couples of parent chromosomes, offspring chromosomes are produced and compose a new generation with not only improved genes, but also some of the characteristics of their parents. Again the *chromosomes* with relatively good fitness levels survive and reproduce in a new reproductive process. The reproductive and evolutive process repeats during several generations, in which chromosomes evolving to high-quality offspring and the population size is decreasing, until a chromosome with the best fitness is found. This chromosome with the best fitness is the right optimal solution that is searched.

3.1.2 Key elements

- Population and size

The initial population is generated by randomly choosing feasible solutions of the problem. Chromosomes are encoded to represent solutions. One chromosome represents one solution. The initial set of chromosomes composes the initial population. The number of chromosomes decides the size of population. Generally, the bigger size is better. However, considering that the increasing size takes more time to calculate, the population size is set from 100 to 1000.

- Encoding scheme

Developing a good chromosome representation of solutions to the problem is critical to find a good solution in a Genetic Algorithm based model. The chromosome consists of genes which should be encoded in a way that it be capable of representing a solution of the targeted problem. The encoding scheme, which is also called gene representation, mainly divides into: *binary encoding* (e.g. 01101101) and *real-number encoding* (e.g. 26413587).

- Fitness function

The fitness function (F_x) is scaled from the objective function (f_x). It is designed to evaluate the fitness value of individuals. In the minimization problem: $F_x = -minf_x$, (Wang, et al., 2006), if the objective function of a solution is smaller, the fitness value of this solution is higher. Individuals with high fitness value are more likely to survive in the selection.

- Selection policy

The selection policy is the method of choosing chromosomes with better fitness to reproduce, to ensure that the excellent genes been inherited by the next generations. It primarily covers two selection methods: Roulette wheel selection and Tournament selection.

Roulette wheel selection (proportional selection): this is the most popular selection policy, in which, the probability of chromosome being selected is related to the proportion of its fitness value in the whole population. The selection probability of individual *i* in a population can be descripted as:

$$P_i = \frac{F_i}{\sum_{i=1}^{i=N} F_i}$$

F_i = fitness valve of individual *i*

N = population size

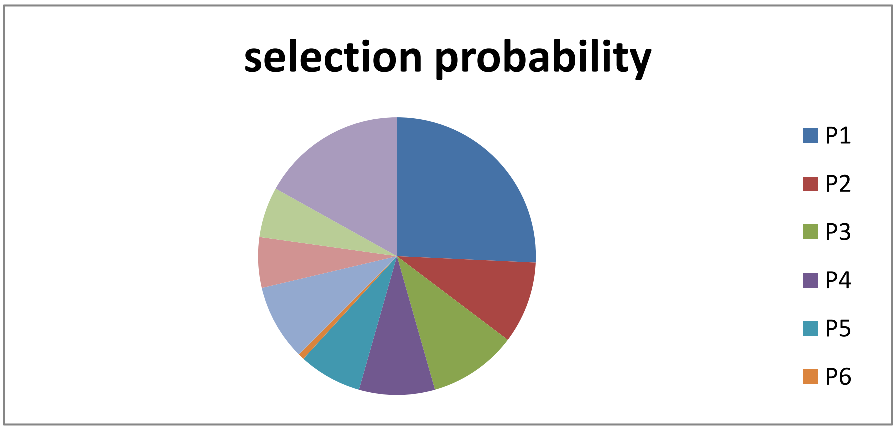


Figure 2 An example of Roulette wheel selection

As what is show in the above chart, Figure 2, the probability of individual 1 being selected to reproduce is high, due to its high fitness value, while the individual 6 with low fitness value has smaller chance to be selected.

Tournament selection: this method involves holding a tournament among “s” individuals (competitors), chosen randomly from the population. The winner of the tournament is the individual with the highest fitness value among the s competitors. And then the winner is selected into a mating population, which is comprised of tournament winners. This mating population has a higher fitness value than the average population. This fitness difference creates selection pressure, which drive the improvement of the fitness of the new generation. The higher selection pressure, the more the better individuals are favored.

- Genetic operators

Genetic operators include *crossover* and *mutation*. They simulate the reproductive process of the selected parent chromosomes evolving to offspring ones.

Crossover: Exchange certain parts between two parent chromosomes to generate offspring. The offspring inherit some of the characteristics of the parents and by this way the characteristics are passed onto the future generations. It mainly includes “one cutting crossovers” and “two cutting crossovers”, see below.

In a “one cutting crossover”, one cutting is selected randomly in each parent chromosome, and then the right side genes of the cutting between parents are exchanged to generate two offspring. For example:
P1= 001¦ 110   crossover   O1=001¦ 001
P2= 110¦ 001   O2=110¦ 110
cutting   cutting

In a “two cutting crossover”, two cuttings are selected randomly in each parent chromosome, and then the genes between cutting are exchanged. For instance:
P1= 001¦ 110¦ 00   crossover   O1= 001¦ 001¦ 00
P2= 110¦ 001¦ 10   O2=110¦ 110 ¦10
cutting cutting   cutting   cutting

However, not all the selected parent chromosomes join in the crossover, but only P_c percent of them have chance to take part in crossover. The P_c is called the crossover rate, which is appropriate to be designed as a big number, e.g. 0.9. Through crossover, the offspring inherit some characteristics of their parents and the characteristics are passed onto the future generations.

- Mutation:

A certain probability (P_m) number of genes of individuals in the population are picked out randomly and change. For instances: in binary encoding
P1= 001 1**1**0 00 mutation O1= 001 1**0**0 00

The mutation rate P_m is normally small number, e.g. 0.03. The mutation causes some random change to the genes of individuals and creates new characteristics to the future generations.

- Stop rules/criterion

The Stop rules decide when the reproductive process is over. The maximum number of generations is often set as the stop criterion, e.g. if the maximum generation is designed as 100, the reproductive process will iterate 100 times.

3.1.3 Processing steps

The processing steps of GA are illustrated as below in Figure 3:

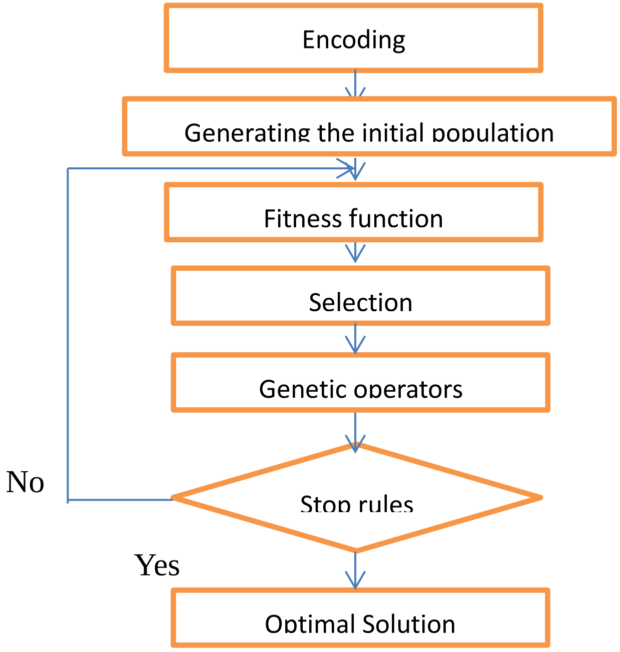


Figure 3 The processing steps of the Genetic Algorithm

The genetic algorithm is a very complex intelligent optimization algorithm indeed. It is based on the Darwin‘s theory of evolution, which states that evolution is selecting the superior ones while eliminating the inferior ones, and the survival of the good fitness. The general principle of GA is not difficult to understand, but the detailed methods and processes in solving optimization problems by GA are very complicated. In this thesis, the main objective is by applying Genetic Algorithm to solve offshore supply planning optimization problem, instead of studying the GA itself, so a powerful software, Matlab or Excel, is introduced to conduct the calculation of searching an optimal solution for the GA based approach.

3.2 The strength and weakness of Genetic Algorithm

This algorithm is very good in searching global optimizations. It can be used to solve some very complex optimization problems efficiently in real life. However, although widely applied, there are still some shortages, such as weakness in searching local optimizations, premature convergence, and its solution is influenced by the experience-based parameter settings.

3.3 The application of Genetic Algorithm

Based on the introduction from Gen and Cheng, (2003), the Genetic Algorithm is effective in solving some optimization problems as below:

Combinatorial optimization, which mainly aims to realize the maximum productivity by utilizing limited resources, while satisfying many other constraints, e.g. bin-packing problem, vehicle routing problem, and airline crew scheduling problem.
Multi-objective optimization, whose primary purpose is to find the optimal solution for several conflicting objectives under some constraints, such as multiple-objective transportation problem, capacitated plant location problem.

3.4 Genetic Algorithm based solution of combinatorial optimization

The optimization problems studied in this thesis belong to the combinatorial optimization, in which the objective function should be realized while several constraints need being satisfied. In a Genetic Algorithm based solution, the process of achieving the objective function, the optimal solution, is briefly discussed above. However, how to satisfying the constraints during this processing? Referring to the introduction of Gen and Cheng, (2003), it is known that the *penalty method* is the most popular method for handling the constraints in a Genetic Algorithm based approach. It is descripted as:

$$Fitness_i = fitness_i \pm P_i$$

$$\mathrm{P_i} \text{ is the penalty function of individual i}$$
$$\text{if i is under constraints}, \mathrm{P_i} = 0, \text{otherwise}, \ \mathrm{P_i} \neq 0$$

In this method, a penalty function is designed to ensure the solution is in the feasible region. The key aspect of the penalty function approach is to find appropriate penalty parameters needed to guide the search towards the constrained optimum.

3.5 Genetic Algorithm based software packages

3.5.1 Evolutionary Solver in Excel 2010

Referring to the introduction by Albright and Winston, (2012), it is known that: Genetic Algorithms have been implemented in several software packages. However, they have been available as Excel add-in only recently. In the Solver of Excel 2010, the Evolutionary Solver which applies GAs to obtain the optimal solution is developed to solve optimization problems. This software can help us to realize the complex computational process of GAs. What we need to do is to set the parameters, such as mutation rate, population sized, and calculation time (stop rule), as well as input the data, e.g. objective cell, changing cell, and constraints. This software is powerful but not perfect. The Evolutionary Solver can help us find a good solution, however, there is no guarantee that it will find the best solution, and it cannot handle constraints very well. Sometimes, a numeric penalty is set to penalize a violation of constraints, as the penalty function mentioned above. This software package will be applied to solve optimization problem in this thesis.

3.5.2 Sheffield GA toolbox in Matlab

Sheffield Genetic Algorithm toolbox is developed by the University of Sheffield, based on Matlab, (Shi Feng, et al. 2010). This toolbox applies the Matlab language to compute each part of the Genetic Algorithm as an M document. The computation of the Genetic Algorithm is conducted by invoking the functions in these M documents. And hence the whole computation process can be realized by applying this toolbox in Matlab.

Chapter 4. The application of a Genetic Algorithm based software package in solving an offshore supply vessel planning optimization problem

As what is introduced in Chapter 2, the offshore supply vessel planning optimization problem can be abstracted to be a combination of the bin-packing problem (BPP), for optimizing the composition of the supply fleet and the vehicle routing problem (or the Travelling salesman problem, if the number of vehicles needed is one) with simultaneous pick-up and delivery (VRPSPD), for optimizing the supply routing planning. In this chapter, a simple example, a pilot study, is conducted to illustrate the application of the Genetic Algorithm based software package in solving the offshore supply planning optimization problem. First, the bin-packing problem is solved to obtain optimal supply fleet composition, i.e. achieve the minimum charter cost, which is also the primary objective of the offshore supply planning. Once the supply vessels and their respective customers have been decided, the second step is optimizing the supply routing planning to find the shortest supply routing for them. This is realized by solving the vehicle routing problem.

4.1 Genetic Algorithm based solution of bin-packing problem

4.1.1 Illustrative example and Mathematical model settings

In one offshore supply cycle, 14 units of cargoes demanded by offshore installations (1-14) are planned to be packed in several vessels with different deck loading areas, while the backward cargoes of these 14 installations should be picked up by the same servicing vessel. The delivery and pick up operations are assumed conducted during the same visit. The backload cargo volume of each installation is not necessary less than the demanded. The objective is to find the minimum charter cost of chartering vessels needed to load these cargoes, while satisfying the installations' demand and without violating the vessels' deck loading capacity. The area of 14 unit cargoes and deck loading areas of available vessels and their respective charter rate are given as follow in Tables 1 and 2:

Table 1 Cargo demanded by the 1-14 installations

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Cargo (unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	total
Area(m^2)/delivery	28	110	66	28	74	32	83	97	101	142	135	146	184	169	1395
Area (m^2)/pick- up	75	22	12	76	23	28	36	116	64	176	26	42	165	112	973

Table 2 Deck loading area and charter rate of available vessels

Vessel available for charter	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Deck loading area (m^2)	380	380	380	380	450	450	450	450	320	320	320	500	500	500
Charter rate (10.000RMB/day)	9	9	9	9	10	10	10	10	8	8	8	12	12	12

The mathematical model is introduced from Chapter 2, 2.3.1.2 Mathematical model.

Set:
the total charter cost: C
the vessel i charter rate: r_i

Minimize:

$$\mathrm{C} = \sum_{j=1}^{\mathrm{n}} r_i \mathrm{y}_j \tag{1}$$

Subject to: $$\sum_{i=1}^{n} a_i x_{ij} \le \text{cap} \times y_j\,, \quad \forall i \in N = \{1,2,\cdots,n\} \tag{2}$$

$$y_j = 0 \text{ or } 1, \qquad \forall\, i \in \mathrm{N} \tag{3}$$

$$x_{ij} = 0 \text{ or } 1, \qquad \forall i\,, j \in \mathrm{N} \tag{4}$$

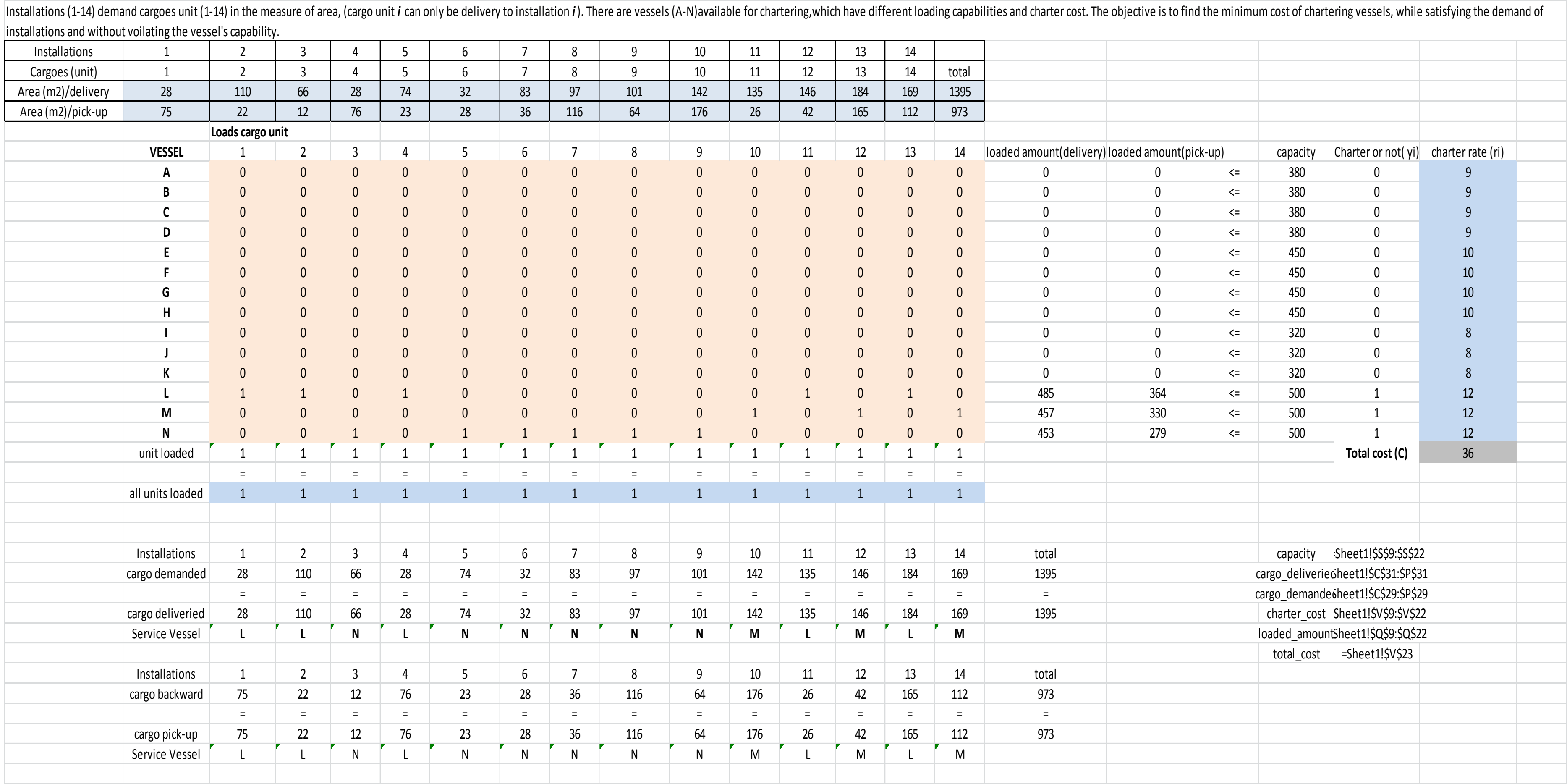
Remark: x_{ij} = 1 means that packing unit *i* into vessel *j*; Otherwise, x_{ij} = 0.
y_j = 1 means that vessel *j* be used; Otherwise y_j = 0.
The constraint requires that the total area of the cargo unit that is packed into vessel *j* must not exceed the capacity of the vessel *j*.

4.1.2 Excel 2010 solution

A spreadsheet model is built to solve this bin-packing problem example in the Excel 2010 software, as is shown in Fig.4. The solution is obtained by applying the Evolutionary Solver. The solution is illustrated in Fig.4. The minimum total cost of chartering vessels is 360,000RMB/day. To achieve this minimum total cost, 3 vessels, vessel L, M, and N, are chartered to perform the supply service. Vessel L is arranged to service installations 1, 2, 4, 11, and 13; Vessel M sail to installations 10, 12, and 14; Vessel N services installations 3, 5, 6, 7, 8, and 9. The demanded cargoes and backward cargoes of each installation are both satisfied without violating the vessel's capacity. In this supply cycle, the optimal supply vessel fleet is a compromise of three of the same type vessels, L, M, and N, whose deck loading area is $500m^2$, charter rate is 120,000 RMB/day.

Solution of the supply fleet composition planning:

The optimal composition of the supply fleet in this supply cycle is: Vessels L, M, and N. their service customers are listed as below:
Vessel L: services installations 1, 2, 4, 11, 13
Vessel M: services installations 10, 12, 14
Vessel N: services installations 3, 5, 6, 7, 8, 9



Installations (1-14) demand cargoes unit (1-14) in the measure of area, (cargo unit ***i*** can only be delivery to installation ***i***). There are vessels (A-N)available for chartering,which have different loading capabilities and charter cost. The objective is to find the minimum cost of chartering vessels, while satisfying the demand of installations and without voilating the vessel's capability.

Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Cargoes (unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	total
Area (m2)/delivery	28	110	66	28	74	32	83	97	101	142	135	146	184	169	1395
Area (m2)/pick-up	75	22	12	76	23	28	36	116	64	176	26	42	165	112	973

	Loads cargo unit																			
VESSEL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	loaded amount(delivery)	loaded amount(pick-up)		capacity	Charter or not(yi)	charter rate (ri)
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	380	0	9
B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	380	0	9
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	380	0	9
D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	380	0	9
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	10
F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	10
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	10
H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	10
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	320	0	8
J	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	320	0	8
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	320	0	8
L	1	1	0	1	0	0	0	0	0	0	1	0	1	0	485	364	<=	500	1	12
M	0	0	0	0	0	0	0	0	0	1	0	1	0	1	457	330	<=	500	1	12
N	0	0	1	0	1	1	1	1	1	0	0	0	0	0	453	279	<=	500	1	12
unit loaded	1	1	1	1	1	1	1	1	1	1	1	1	1	1					**Total cost (C)**	36
	=	=	=	=	=	=	=	=	=	=	=	=	=	=						
all units loaded	1	1	1	1	1	1	1	1	1	1	1	1	1	1						

Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	total		
cargo demanded	28	110	66	28	74	32	83	97	101	142	135	146	184	169	1395	capacity	Sheet1!$S$9:$S$22
	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	cargo_deliverie	Sheet1!$C$31:$P$31
cargo delivered	28	110	66	28	74	32	83	97	101	142	135	146	184	169	1395	cargo_demande	Sheet1!$C$29:$P$29
Service Vessel	**L**	**L**	**N**	**L**	**N**	**N**	**N**	**N**	**N**	**M**	**L**	**M**	**L**	**M**		charter_cost	Sheet1!$V$9:$V$22
																loaded_amount	Sheet1!$Q$9:$Q$22
																total_cost	=Sheet1!$V$23
Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	total		
cargo backward	75	22	12	76	23	28	36	116	64	176	26	42	165	112	973		
	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=		
cargo pick-up	75	22	12	76	23	28	36	116	64	176	26	42	165	112	973		
Service Vessel	L	L	N	L	N	N	N	N	N	M	L	M	L	M			

Figure 4 Spreadsheet model in Excel 2010 software for the bin-packing problem example

4.2 Genetic Algorithm based solution of vehicle routing problem

In the part above, the supply vessels (Vessels L, M, and N) and their service customers have been decided. The next work is to find their respective shortest supply routes. This will be realized by solving the vehicle routing problem, which can be seen as be consisting of three travelling salesman problems here. Hence, in this part, the objective is to find the shortest supply routes for vessels L, M, and N respectively. For realizing each of them, we need to solve a traveling salesman problem (TSP).

4.2.1 Illustrative example and Mathematical model settings

Continue the same example in this part. As what the solution above shows, vessels L, M, and N, will be chartered in this supply cycle and they will act as traveling salesman to service their customers. The supply service arrangement, position of depot and installations, and the distance matrixes are assumed as in Tables 3 to 7 and Figure 5 below:

Table 3 Supply vessels and their servicing installations

“Salesman”	“Customer”
Vessel L	Installations 1, 2, 4, 11, 13
Vessel M	Installations 10, 12, 14
Vessel N	Installations 3, 5, 6, 7, 8, 9

Table 4 Position of installations

	depot	1	2	3	4	5	6	7	8	9	10	11	12	13	14
x	12	1.8	2.6	3.8	8.5	8.9	10.5	11.5	10	0.1	0.5	1.5	2.5	0.5	4
y	12	3.2	0.8	1.1	0.2	1.3	2.3	1.3	4.2	11	8.8	10	2	7.5	4

Table 5 Distance Matrix of Vessel L’ s supply route

Distance (n mile)	Depot	Installation 1	Installation 2	Installation 4	Installation 11	Installation 13
Depot	0	13	15	12	11	12
Installation 1	13	0	3	7	7	4
Installation 2	15	3	0	6	9	7
Installation 4	12	7	6	0	12	11
Installation 11	11	7	9	12	0	3
Installation 13	12	4	7	11	3	0

Table 6 Distance Matrix of Vessel M’ s supply route

Distance (n mile)	Depot	Installation 10	Installation 12	Installation 14
Depot	0	12	14	11
Installation 10	12	0	7	6
Installation 12	14	7	0	3
Installation 14	11	6	3	0

Table 7 Distance Matrix of Vessel N's supply route

Distance (n mile)	Depot	Installation 3	Installation 5	Installation 6	Installation 7	Installation 8	Installation9
Depot	0	14	11	10	11	8	12
Installation 3	14	0	5	7	8	7	11
Installation 5	11	5	0	2	3	3	13
Installation 6	10	7	2	0	1	2	14
Installation 7	11	8	3	1	0	3	15
Installation 8	8	7	3	2	3	0	12
Installation 9	12	11	13	14	15	12	0

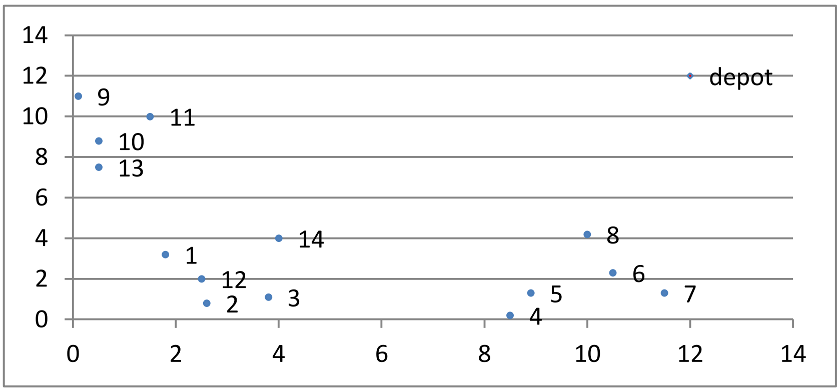


Figure 5 Location of depot and installations

The mathematical model of the TSP is introduced in Chapter 2 and we are referring to Toth and Vigo, (2011). It is somewhat different from the model of the vehicle routing problem in Chapter 2, 2.3.2.2 Mathematical model, as the number of vehicle *v* equals 1 in each subset problem and different sub-tour elimination constrains are used.

Minimize:

$$\sum_{i=0}^{i=N} \sum_{j=0}^{j=N} d_{ij} \; x_{ij} \tag{1}$$

Subject to:

$$\sum_{i=0}^{i=N} x_{ij} = 1 \qquad \forall i \in N$$

(2)

$$\sum_{j=0}^{j=N} x_{ij} = 1 \qquad \forall j \in N$$

(3)

$$\sum_{i=0}^{i=N}\sum_{j=0}^{j=N} x_{ij} \leq |S| - 1, \qquad \forall S \in N, 2 \leq |S| \leq n-2$$

(4)

$x_{ijv} \in \{0,1\}$ and integer $\qquad \forall i, j \in N$

(5)

Remark: $x_{ij} = 1$ means the line between customer i to j is on the shortest route;

Otherwise, $x_{ij} = 0$.

The constraints (2), (3) represent that each customer can only be served once. Constraint (4) is the sub-tour elimination constrains.

4.2.2 Excel 2010 solution

Referring to the spreadsheet model developed by Albright and Winston, (2012), a spreadsheet model is built to solve these three TSP problem examples in the Excel 2010 software, as what is shown in Figs. 7, 8, and 9. The solution is also achieved by applying the Evolutionary Solver. The shortest supply routes for Vessel L, M, and N are found, as what Fig. 6 illustrates. These three vessels service 14 offshore installations, with total distance 102 n miles. The distances of their supply routes are 39, 33, and 30 n miles respectively.

Solution of supply routing planning:

The shortest supply routes of these three vessels are given as below:
The supply route of Vessel L is: depot-4-2-1-13-11-depot, total distance is 39 n miles.
The supply route of Vessel M is: depot-10-12-14-depot, total distance is 33 n miles.
The supply route of Vessel N is: depot-8-6-7-5-3-9-depot, total distance is 30 n miles.

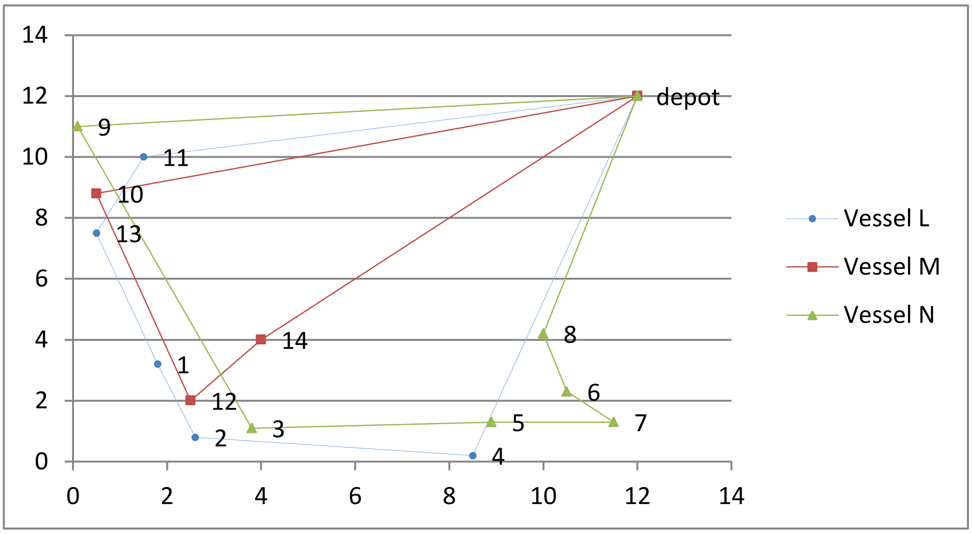
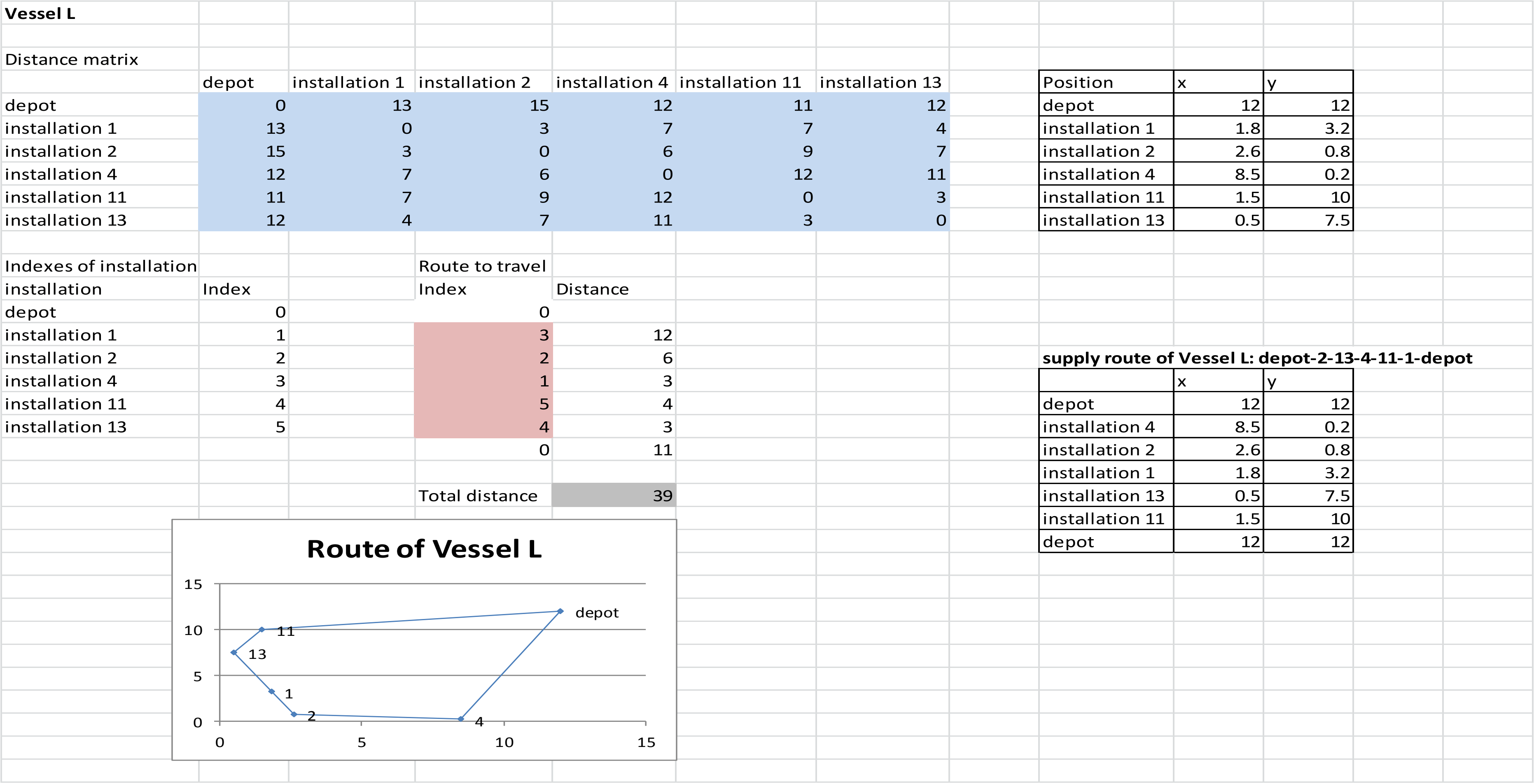


Figure 6 Supply routes of Vessel L, M, and N



Vessel L

Distance matrix

	depot	installation 1	installation 2	installation 4	installation 11	installation 13
depot	0	13	15	12	11	12
installation 1	13	0	3	7	7	4
installation 2	15	3	0	6	9	7
installation 4	12	7	6	0	12	11
installation 11	11	7	9	12	0	3
installation 13	12	4	7	11	3	0

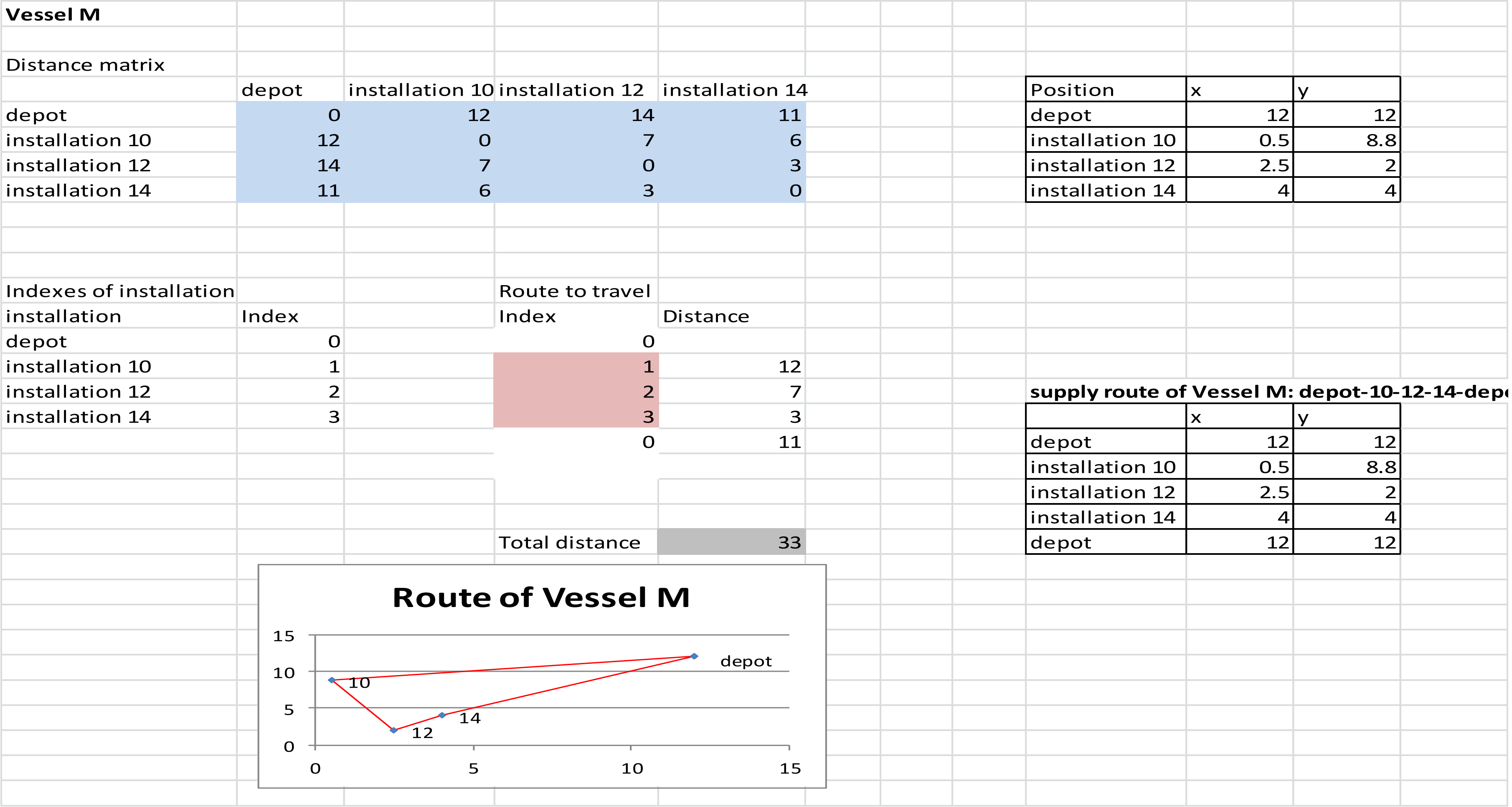
Position	x	y
depot	12	12
installation 1	1.8	3.2
installation 2	2.6	0.8
installation 4	8.5	0.2
installation 11	1.5	10
installation 13	0.5	7.5

Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 1	1		3	12
installation 2	2		2	6
installation 4	3		1	3
installation 11	4		5	4
installation 13	5		4	3
			0	11
			Total distance	39

supply route of Vessel L: depot-2-13-4-11-1-depot

	x	y
depot	12	12
installation 4	8.5	0.2
installation 2	2.6	0.8
installation 1	1.8	3.2
installation 13	0.5	7.5
installation 11	1.5	10
depot	12	12

Figure 7 Spreadsheet model in Excel 2010 for Vessel L' TSP



Vessel M

Distance matrix

	depot	installation 10	installation 12	installation 14
depot	0	12	14	11
installation 10	12	0	7	6
installation 12	14	7	0	3
installation 14	11	6	3	0

Position	x	y
depot	12	12
installation 10	0.5	8.8
installation 12	2.5	2
installation 14	4	4

Indexes of installation

installation	Index
depot	0
installation 10	1
installation 12	2
installation 14	3

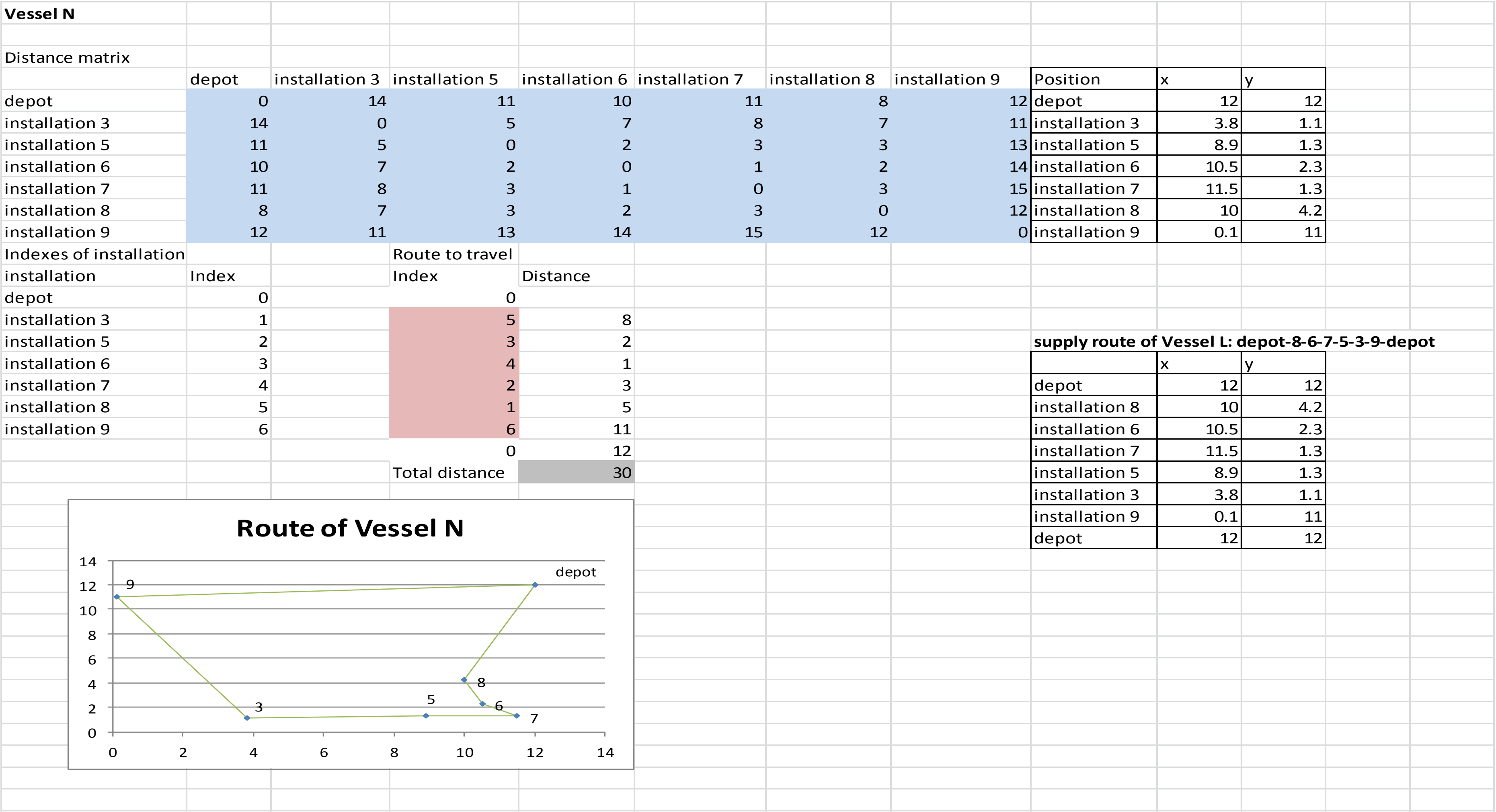
Route to travel

Index	Distance
0	
1	12
2	7
3	3
0	11
Total distance	33

supply route of Vessel M: depot-10-12-14-depo

	x	y
depot	12	12
installation 10	0.5	8.8
installation 12	2.5	2
installation 14	4	4
depot	12	12

Figure 8 Spreadsheet model in Excel 2010 for Vessel M’ TSP



Vessel N

Distance matrix

	depot	installation 3	installation 5	installation 6	installation 7	installation 8	installation 9
depot	0	14	11	10	11	8	12
installation 3	14	0	5	7	8	7	11
installation 5	11	5	0	2	3	3	13
installation 6	10	7	2	0	1	2	14
installation 7	11	8	3	1	0	3	15
installation 8	8	7	3	2	3	0	12
installation 9	12	11	13	14	15	12	0

Position	x	y
depot	12	12
installation 3	3.8	1.1
installation 5	8.9	1.3
installation 6	10.5	2.3
installation 7	11.5	1.3
installation 8	10	4.2
installation 9	0.1	11

Indexes of installation

installation	Index
depot	0
installation 3	1
installation 5	2
installation 6	3
installation 7	4
installation 8	5
installation 9	6

Route to travel

Index	Distance
0	
5	8
3	2
4	1
2	3
1	5
6	11
0	12
Total distance	30

supply route of Vessel L: depot-8-6-7-5-3-9-depot

	x	y
depot	12	12
installation 8	10	4.2
installation 6	10.5	2.3
installation 7	11.5	1.3
installation 5	8.9	1.3
installation 3	3.8	1.1
installation 9	0.1	11
depot	12	12

Figure 9 Spreadsheet model in Excel 2010 for Vessel N' TSP

Chapter 5. A real case study of optimizing the offshore supply vessel planning

In practice, the offshore supply vessel planning problem is more complex than the sample example studied in the previous chapter. There is not only many other real life factors that need to be taken into account, but also many uncertainties. In this study, the real life problem is simplified and is just limited to a typical planning cycle, which is similar to the case in the pilot study. In this chapter, the optimization methods developed in the pilot study will be applied to optimize a real offshore vessel operation for a specific offshore oil and gas production area.

5.1 The real case description

5.1.1 The introduction of a specific offshore oil and gas production area.

The BoHai Bay is the most important offshore oil and gas production area in China. There are about 20 oilfields scattered in this Bay. They are serviced by several supply fleets from three supply depots, Tanggu, Longkou, and Hulu Island. In this case, the supply vessel planning of the Tanggu supply depot for its 16 serviced installations are studied. The distance matrix of these 16 installations and the Tanggu depot is given as follows in Tables 8:

Table 8 Distance matrix of the 16 installations serviced by the Tanggu depot

Distance (n mile)	depot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
depot	0	146	101	98	99	79	23	46	124	62	75	146	151	162	177	180	214
Installation 1	146	0	46	48	49	63	125	100	88	104	100	144	128	139	148	157	188
Installation 2	101	46	0	5	12	20	80	54	72	63	60	118	111	124	131	144	174
Installation 3	98	48	5	0	6	21	79	54	66	59	56	113	106	119	127	139	170
Installation 4	99	49	12	6	0	25	81	57	60	56	52	107	100	112	120	133	164
Installation 5	79	63	20	21	25	0	61	35	79	52	53	119	117	130	137	150	181
Installation 6	23	125	80	79	81	61	0	26	114	51	64	128	141	153	166	171	202
Installation 7	46	100	54	54	57	35	26	0	98	44	54	123	130	143	155	161	194
Installation 8	124	88	72	66	60	79	114	98	0	65	52	57	40	53	60	73	105
Installation 9	62	104	63	59	56	52	51	44	65	0	14	79	90	102	114	120	152
Installation 10	75	100	60	56	52	53	64	54	52	14	0	69	77	90	100	108	140
Installation 11	146	144	118	113	107	119	128	123	57	79	69	0	33	37	48	46	74
Installation 12	151	128	111	106	100	117	141	130	40	90	77	33	0	13	24	33	65
Installation 13	162	139	124	119	112	130	153	143	53	102	90	37	13	0	13	20	52
Installation 14	177	148	131	127	120	137	166	155	60	114	100	48	24	13	0	14	45
Installation 15	180	157	144	139	133	150	171	161	73	120	108	46	33	20	14	0	32
Installation 16	214	188	174	170	164	181	202	194	105	152	140	74	65	52	45	32	0

5.1.2 The offshore supply vessel planning problem of the Tanggu depot

In one offshore supply cycle, the period is normally about 7 to 10 days, the number of visits the 1-16 installations require varies from 3 to 8 and the area for the demanded cargo for each installation vary from 100 to $800m^2$, depending on the need from the operations on installations. These demands are then divided by the number of visits an installation requires during a cycle to get the demands for each visit. These again vary from 20 to $200m^2$. The demanded cargo for one visit of the installations will be loaded on supply vessels planned to service these installations in their new supply voyages. The supply services for these 16 offshore installations are performed by supply fleets, which are composed of platform supply vessels (PSV) with different capacities. The vessels' loading capacities vary from 380 to $600m^2$. The time charter rates for all vessels vary from 70,000 to 120,000RMB per day. The rates vary, depending on the loading capacity of the vessel. The PSV with higher loading capacity always have higher charter costs.

The 16 units of cargoes demanded by the offshore installations (1-16) in one typical supply voyage are planned to be packed on several vessels with different deck loading areas, while the return cargoes from these 16 installations should be picked up by the same servicing vessel. The delivery and pick up operations are assumed conducted during the same visit. The return cargo volume of each installation is not necessary less than the demanded. The objective is to find the minimum charter cost of the chartering vessels needed to load these cargoes, while satisfying the installations' demand and without violating the vessels' deck loading capacity. The demanded cargo volume in this supply cycle and the supply vessel fleet' main facts are given as follow in Tables 9 and 10:

Table 9 Cargo demanded by the 1-16 installations in one supply planning voyage

Installation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Cargo (unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	total
Area(m^2)/delivery	36	54	118	96	78	63	55	125	141	84	129	152	85	166	98	103	1583
Area (m2)/pick- up	35	20	85	188	34	92	21	88	62	119	64	77	115	103	42	86	1231

Table 10 Deck loading area and charter rate of available platform supply vessels (PSV)

Vessel available for charter	A	B	C	D	E	F	G	H	I	J	K
Deck loading area (m^2)	380	450	450	450	480	480	500	500	500	600	600
Charter rate (10.000RMB/day)	7	9	9	9	10	10	11	11	11	13	13

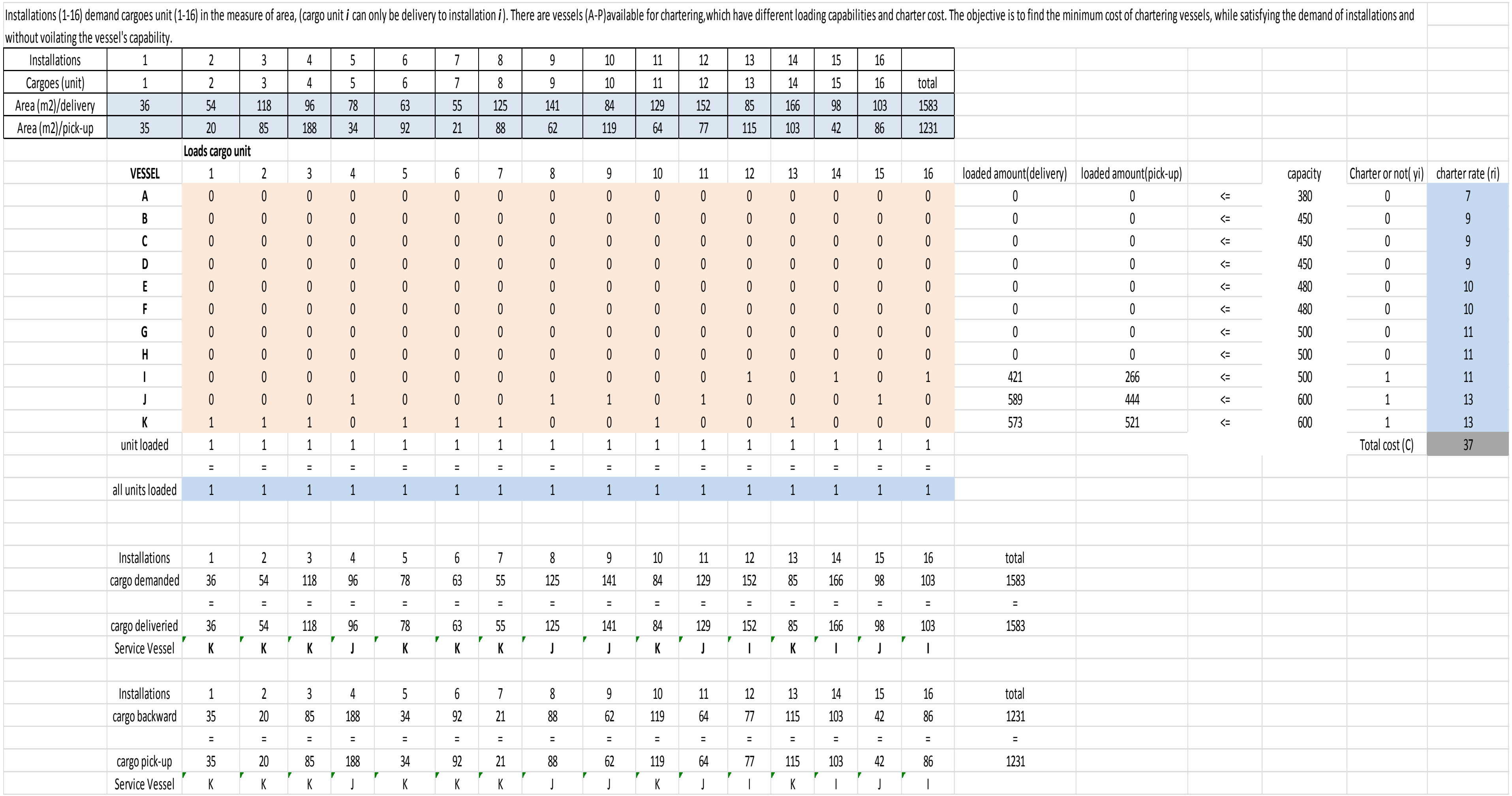
5.2 The optimization of the offshore supply vessel planning of the Tanggu depot

The optimization method developed in the pilot study in previous chapter will be introduced to solve this optimization problem, which applies the Genetic Algorithm based software package, Evolutionary Solver in Excel 2010, in solving the offshore supply planning optimization problem. First, the bin-packing problem is also solved to obtain the optimal supply fleet composition. Once the supply vessels and their respective customers have been decided, the second step is to solve the TSP to optimize the supply routing planning to find the shortest supply routing for them.

5.2.1 Excel 2010 solution of optimal supply fleet composition planning

A spreadsheet model is built to solve this bin-packing problem example in the Excel 2010 software, as is shown in Fig.10. The solution is obtained by applying the Evolutionary Solver. The solution is illustrated in Fig.10. The minimum total cost of chartering vessels is 370,000RMB/day. To achieve this minimum total cost, 3 vessels, vessels I, J, and K, are chartered to perform the supply service. Vessel I is arranged to service installations 12, 14, and 16; Vessel J sails to installations 4, 8, 9, 11 and 15; Vessel K services installations 1, 2, 3, 5, 6, 7, 10, and 13. The demanded cargoes and return cargoes of each installation are both satisfied without violating the vessel's capacity. In this supply cycle, the best fleet size is three vessels and the optimal supply vessel fleet is a compromise of two types of vessels, they are vessels I, J, and K, whose deck loading area are $500m^2$, $600m^2$, $600m^2$, charter rates are 110,000 RMB/day, 130,000 RMB/day, 130,000 RMB/day, respectively.

Solution of the supply fleet composition planning:
The optimal composition of the supply fleet in this supply cycle is: Vessels I, J, and K. Their service customers are listed as below:
Vessel I: services installations 12, 14, 16
Vessel J: services installations 4, 8, 9, 11, 15
Vessel K: services installations 1, 2, 3, 5, 6, 7, 10, 13



Installations (1-16) demand cargoes unit (1-16) in the measure of area, (cargo unit ***i*** can only be delivery to installation ***i***). There are vessels (A-P)available for chartering,which have different loading capabilities and charter cost. The objective is to find the minimum cost of chartering vessels, while satisfying the demand of installations and without voilating the vessel's capability.

Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Cargoes (unit)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	total
Area (m2)/delivery	36	54	118	96	78	63	55	125	141	84	129	152	85	166	98	103	1583
Area (m2)/pick-up	35	20	85	188	34	92	21	88	62	119	64	77	115	103	42	86	1231

Loads cargo unit

VESSEL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	loaded amount(delivery)	loaded amount(pick-up)		capacity	Charter or not(yi)	charter rate (ri)
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	380	0	7
B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	9
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	9
D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	450	0	9
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	480	0	10
F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	480	0	10
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	500	0	11
H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	500	0	11
I	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	421	266	<=	500	1	11
J	0	0	0	1	0	0	0	1	1	0	1	0	0	0	1	0	589	444	<=	600	1	13
K	1	1	1	0	1	1	1	0	0	1	0	0	1	0	0	0	573	521	<=	600	1	13
unit loaded	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1					Total cost (C)	37
	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=						
all units loaded	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1						

Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	total
cargo demanded	36	54	118	96	78	63	55	125	141	84	129	152	85	166	98	103	1583
	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
cargo deliveried	36	54	118	96	78	63	55	125	141	84	129	152	85	166	98	103	1583
Service Vessel	**K**	**K**	**K**	**J**	**K**	**K**	**K**	**J**	**J**	**K**	**J**	**I**	**K**	**I**	**J**	**I**	

Installations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	total
cargo backward	35	20	85	188	34	92	21	88	62	119	64	77	115	103	42	86	1231
	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
cargo pick-up	35	20	85	188	34	92	21	88	62	119	64	77	115	103	42	86	1231
Service Vessel	K	K	K	J	K	K	K	J	J	K	J	I	K	I	J	I	

Figure 10 Spreadsheet model in Excel 2010 software for the supply fleet composition planning of the Tanggu depot

5.2.2 Excel 2010 solution of optimal supply routing planning

A spreadsheet model is built to solve these three TSP problem examples in the Excel 2010 software. The shortest supply routes for Vessels I, J, and K are found by applying the Evolutionary Solver, as is shown in Figs. 11, 12, and 13. These three vessels service 16 offshore installations in this supply voyage, with total distance of 1313 n miles. The distances of their supply routes are 434, 419, and 460 n miles respectively.

Solution of supply routing planning:

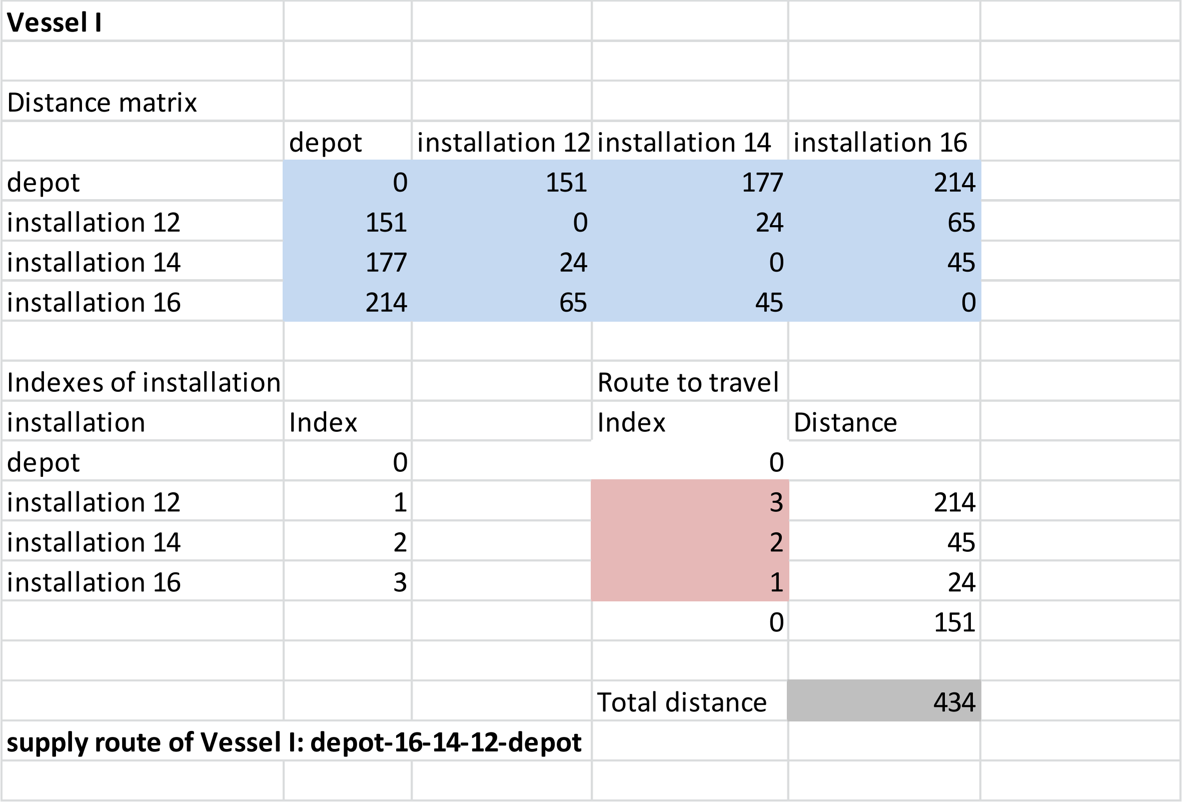
The shortest supply routes (the optimal sequence of installations to be visited) of these three vessels are given as below:

The supply route of Vessel I is: depot-16-14-12-depot, total distance is 434 n miles, Figure 11.

The supply route of Vessel J is: depot-9-11-15-8-4-depot, total distance is 419 n miles, Figure 12.

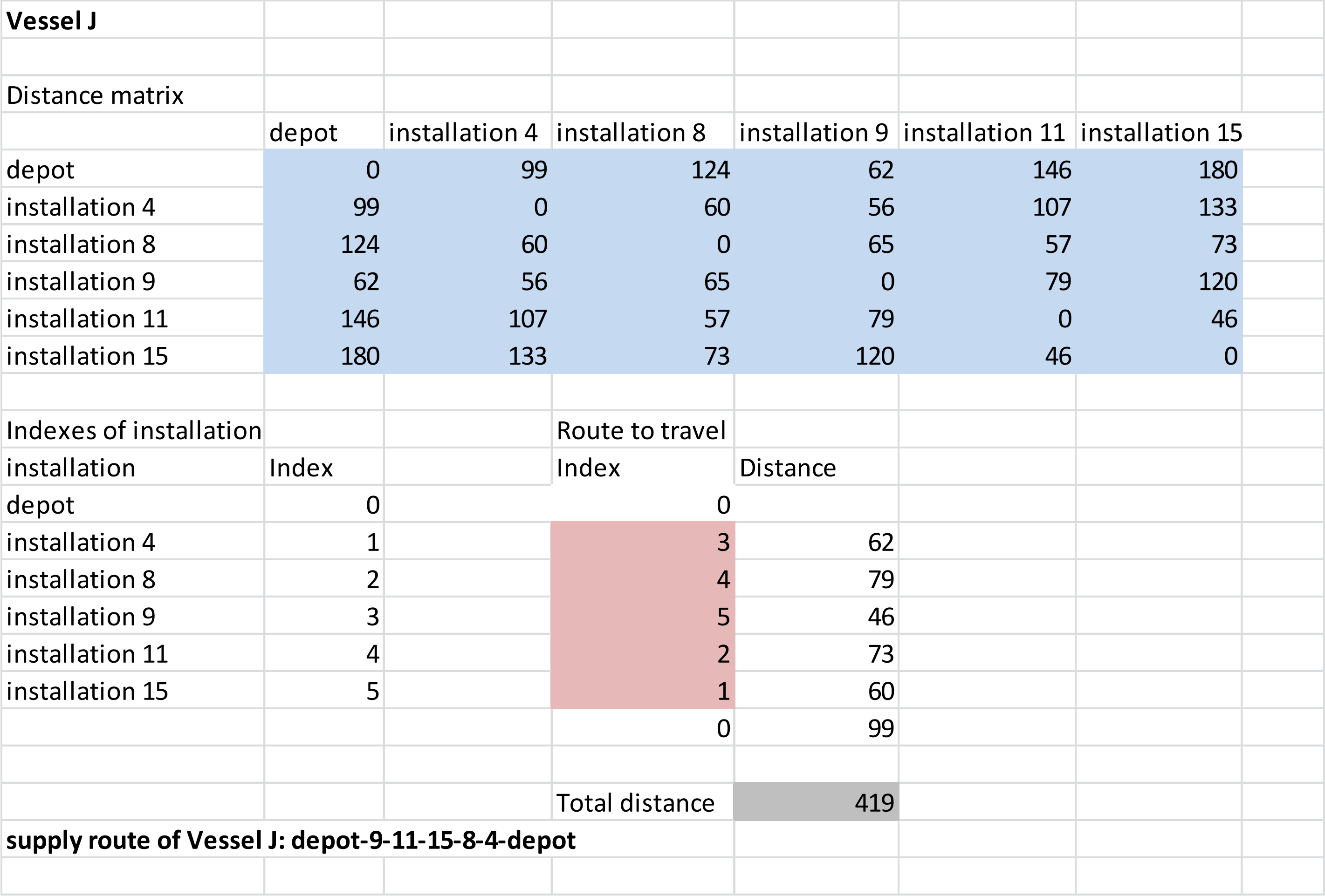
The supply route of Vessel K is: depot-6-7-5-3-2-1-13-10-depot, total distance is 460 n miles, Figure 13.

In case random routes were selected, reference is made to Figures 14, 15 and 16. See also discussions in Chapter 5.3.2.



Vessel I				
Distance matrix				
	depot	installation 12	installation 14	installation 16
depot	0	151	177	214
installation 12	151	0	24	65
installation 14	177	24	0	45
installation 16	214	65	45	0
Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 12	1		3	214
installation 14	2		2	45
installation 16	3		1	24
			0	151
			Total distance	434
supply route of Vessel I: depot-16-14-12-depot				

Figure 11 Spreadsheet model in Excel 2010 for Vessel I' shortest supply route



Vessel J

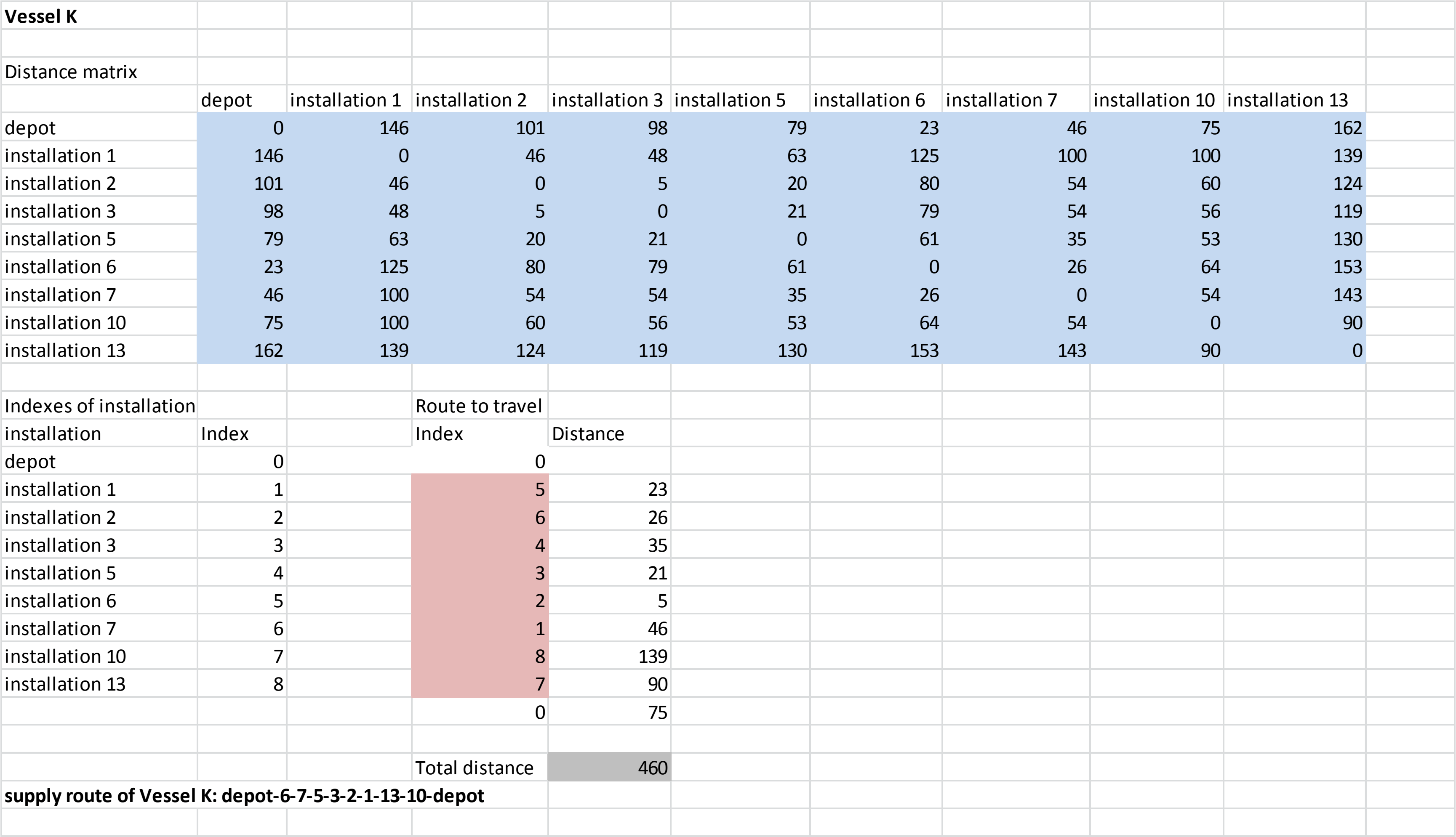
Distance matrix

	depot	installation 4	installation 8	installation 9	installation 11	installation 15
depot	0	99	124	62	146	180
installation 4	99	0	60	56	107	133
installation 8	124	60	0	65	57	73
installation 9	62	56	65	0	79	120
installation 11	146	107	57	79	0	46
installation 15	180	133	73	120	46	0

Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 4	1		3	62
installation 8	2		4	79
installation 9	3		5	46
installation 11	4		2	73
installation 15	5		1	60
			0	99
			Total distance	419

supply route of Vessel J: depot-9-11-15-8-4-depot

Figure 12 Spreadsheet model in Excel 2010 for Vessel J' shortest supply route



Vessel K

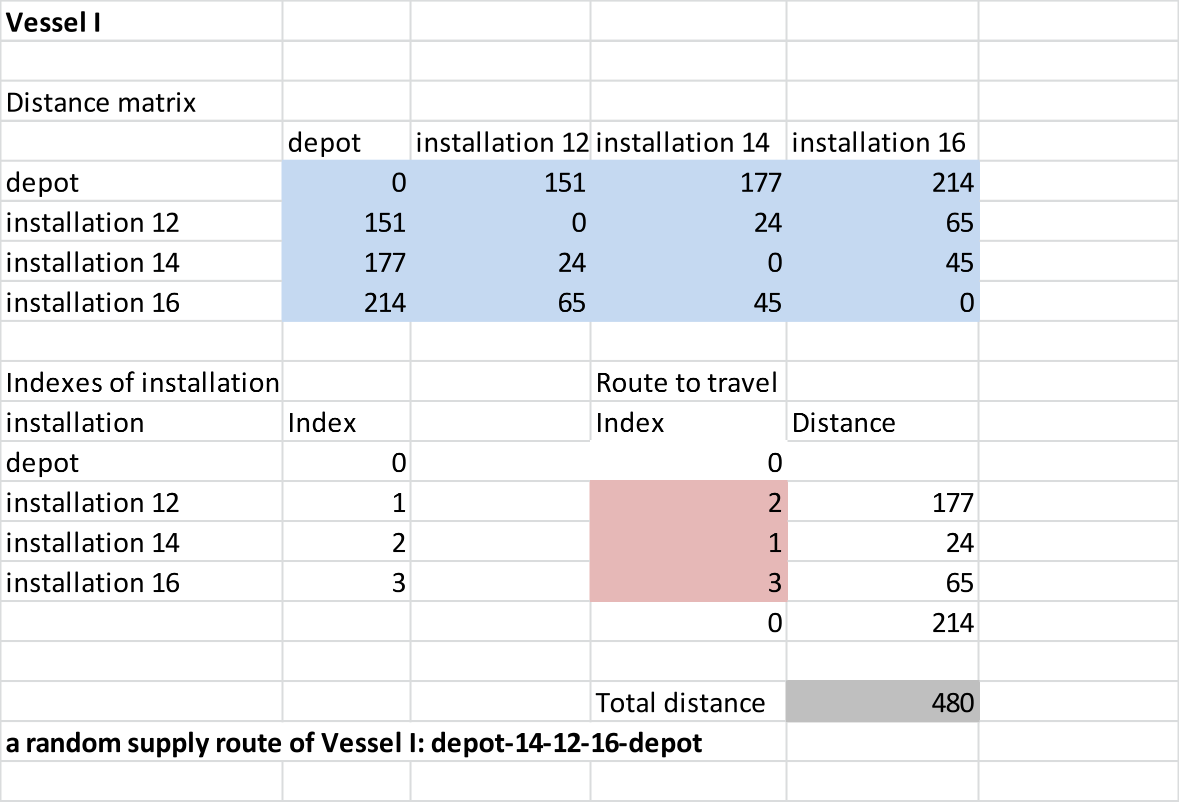
Distance matrix

	depot	installation 1	installation 2	installation 3	installation 5	installation 6	installation 7	installation 10	installation 13
depot	0	146	101	98	79	23	46	75	162
installation 1	146	0	46	48	63	125	100	100	139
installation 2	101	46	0	5	20	80	54	60	124
installation 3	98	48	5	0	21	79	54	56	119
installation 5	79	63	20	21	0	61	35	53	130
installation 6	23	125	80	79	61	0	26	64	153
installation 7	46	100	54	54	35	26	0	54	143
installation 10	75	100	60	56	53	64	54	0	90
installation 13	162	139	124	119	130	153	143	90	0

Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 1	1		5	23
installation 2	2		6	26
installation 3	3		4	35
installation 5	4		3	21
installation 6	5		2	5
installation 7	6		1	46
installation 10	7		8	139
installation 13	8		7	90
			0	75
			Total distance	460

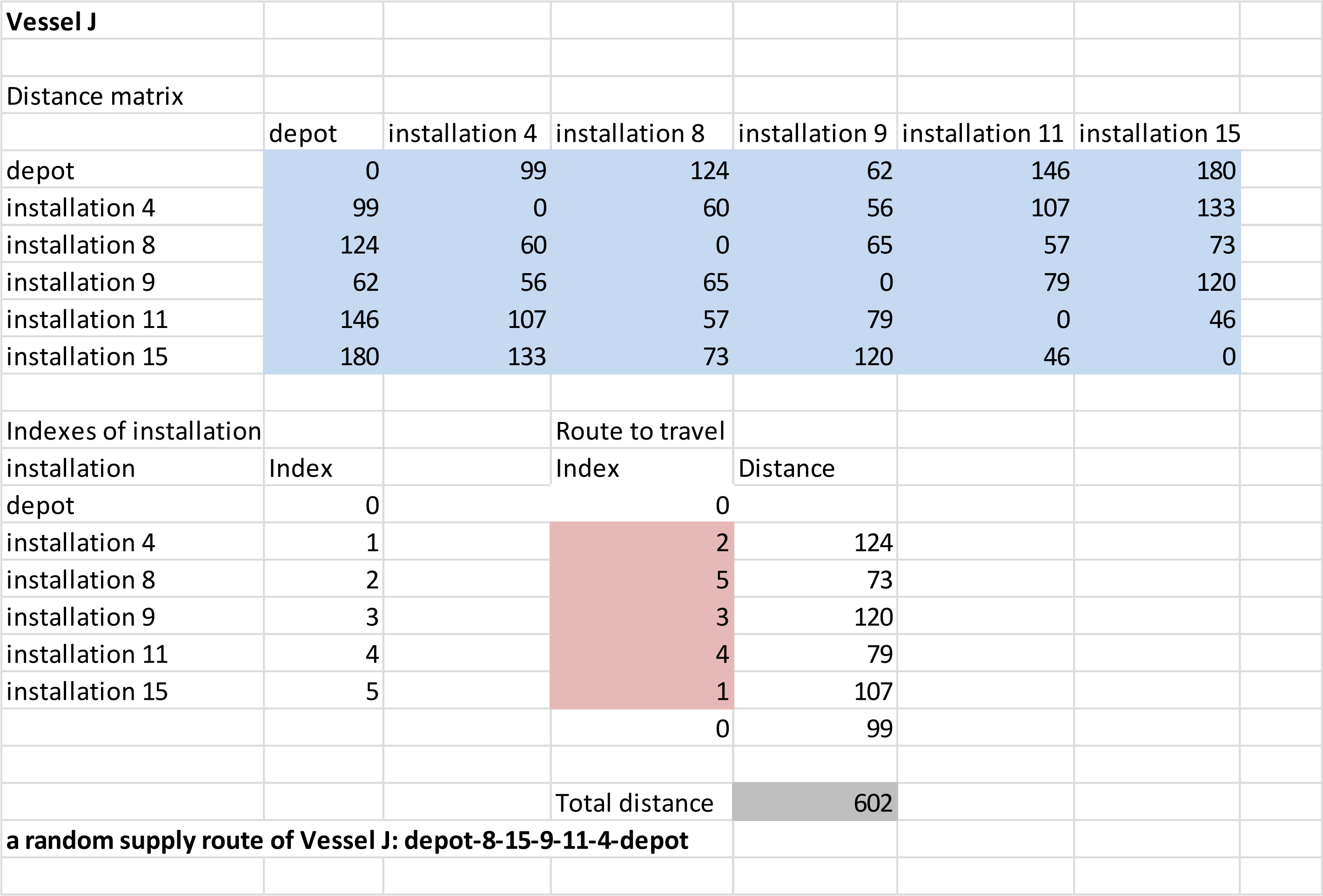
supply route of Vessel K: depot-6-7-5-3-2-1-13-10-depot

Figure 13 Spreadsheet model in Excel 2010 for Vessel K' shortest supply route
]



Vessel I				
Distance matrix				
	depot	installation 12	installation 14	installation 16
depot	0	151	177	214
installation 12	151	0	24	65
installation 14	177	24	0	45
installation 16	214	65	45	0
Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 12	1		2	177
installation 14	2		1	24
installation 16	3		3	65
			0	214
			Total distance	480
a random supply route of Vessel I: depot-14-12-16-depot				

Figure 14 Spreadsheet model in Excel 2010 for Vessel I' random supply route



Vessel J

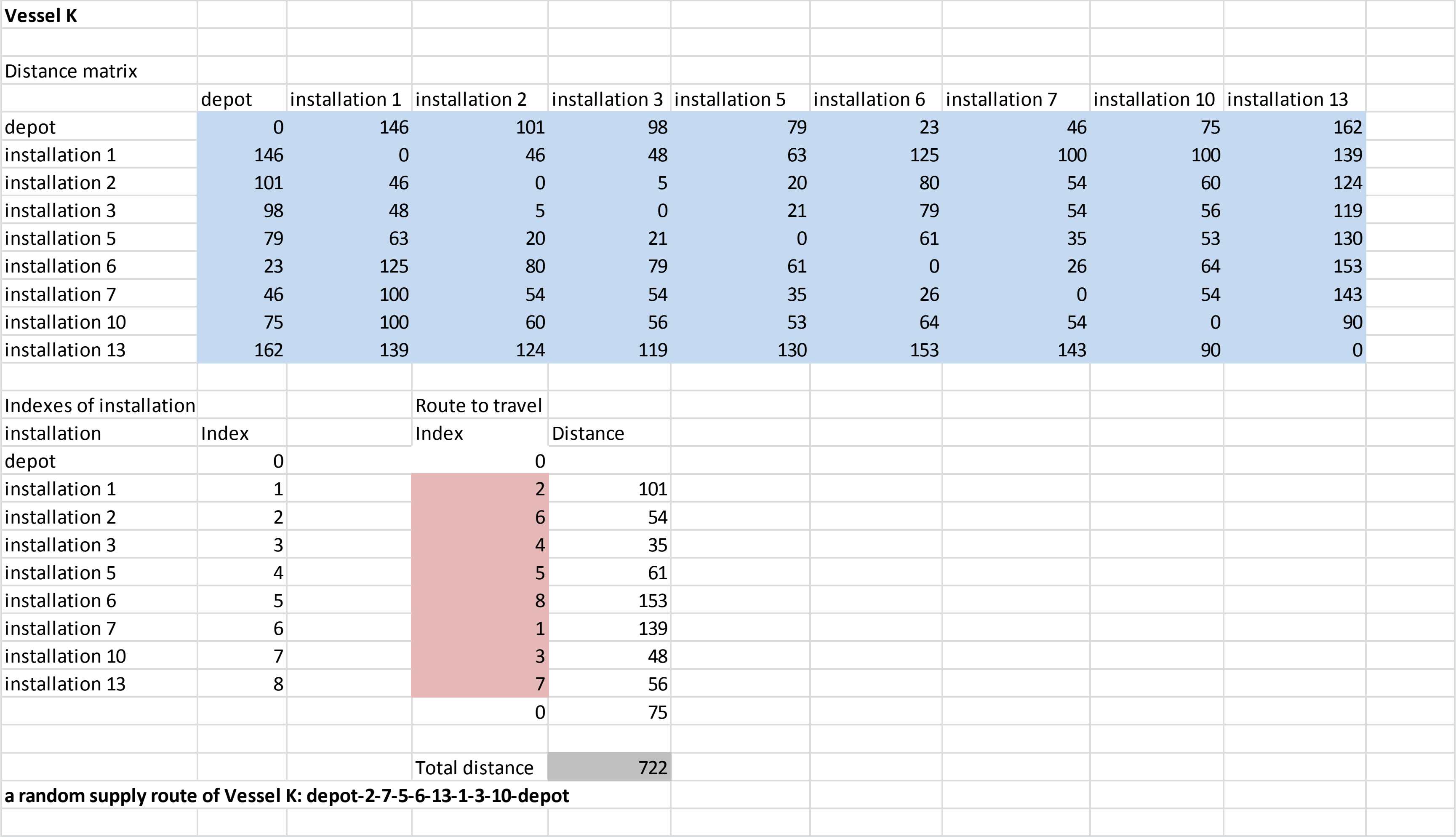
Distance matrix

	depot	installation 4	installation 8	installation 9	installation 11	installation 15
depot	0	99	124	62	146	180
installation 4	99	0	60	56	107	133
installation 8	124	60	0	65	57	73
installation 9	62	56	65	0	79	120
installation 11	146	107	57	79	0	46
installation 15	180	133	73	120	46	0

Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 4	1		2	124
installation 8	2		5	73
installation 9	3		3	120
installation 11	4		4	79
installation 15	5		1	107
			0	99
			Total distance	602

a random supply route of Vessel J: depot-8-15-9-11-4-depot

Figure 15 Spreadsheet model in Excel 2010 for Vessel J' random supply route



Vessel K

Distance matrix

	depot	installation 1	installation 2	installation 3	installation 5	installation 6	installation 7	installation 10	installation 13
depot	0	146	101	98	79	23	46	75	162
installation 1	146	0	46	48	63	125	100	100	139
installation 2	101	46	0	5	20	80	54	60	124
installation 3	98	48	5	0	21	79	54	56	119
installation 5	79	63	20	21	0	61	35	53	130
installation 6	23	125	80	79	61	0	26	64	153
installation 7	46	100	54	54	35	26	0	54	143
installation 10	75	100	60	56	53	64	54	0	90
installation 13	162	139	124	119	130	153	143	90	0

Indexes of installation			Route to travel	
installation	Index		Index	Distance
depot	0		0	
installation 1	1		2	101
installation 2	2		6	54
installation 3	3		4	35
installation 5	4		5	61
installation 6	5		8	153
installation 7	6		1	139
installation 10	7		3	48
installation 13	8		7	56
			0	75
			Total distance	722

a random supply route of Vessel K: depot-2-7-5-6-13-1-3-10-depot

Figure 16 Spreadsheet model in Excel 2010 for Vessel K' random supply route

5.3 Discussion

5.3.1 The result of optimization supply vessel fleet composition

As the results shows that the optimal supply vessel fleet is a compromise of using three vessels of two types, vessels I, J, and K, whose deck loading area are $500m^2$, $600m^2$, $600m^2$, with charter rates 110,000 RMB/day, 130,000 RMB/day, 130,000 RMB/day, and a total rate cost 370,000 RMB/day. After several computation experiments, this result have been proved to be the optimal composition with minimum rate cost. However, with the same optimal result, the “bin-packing” could be different, e.g. if vessel I services installations 4, 12, 14, instead of 12, 14, 16, the minimum charter rate can also be achieved by chartering the same vessels without violating the constraints. The results also indicate that the PSV with larger cargo loading capacity are preferred.

This optimization method can assist the planners to optimize the size and composition of the supply fleet and play an important role in the process of reducing the charter cost of supply vessels, while maintaining an efficient and reliable supply service at the onshore supply depot.

5.3.2 The result of optimization supply routes

The computational results of the shortest supply routes of vessels I, J, and K in the spreadsheet model in Excel 2010 are achieved by applying the Evolutionary Solver to find the minimum total supply distance. In order to contrast the optimization effect, a random supply route is generated for each supply vessel, as what is indicated in Figs. 14, 15, and 16. Table 11 shows the difference between the optimal supply route and a random supply route. From the differences, it is believed that the sequence of installations to be visited affects the total distance and the larger number of visited installations, the more optimization effects are realized by applying this model.

Table 11 The optimization effect of the optimal supply route

Vessel	Supply Route	Visit Sequence	Total distance (n mile)	Difference (n mile)
Vessel I	**Optimal**	depot-16-14-12-depot	**434**	**46**
	Random	depot-14-12-16-depot	**480**	
Vessel J	**Optimal**	depot-9-11-15-8-4-depot	**419**	**183**
	Random	depot-8-15-9-11-4-depot	**602**	
Vessel K	**Optimal**	depot-6-7-5-3-2-1-13-10-depot	**460**	**262**
	Random	depot-2-7-5-6-13-1-3-10-depot	**722**	

Under the same weather and sea current condition, the shortest sailing distance means the lowest fuel and time consumption for the vessels. So cost saving can also be realized by this optimization. The supply fleet can operate more efficiently and economically.

5.3.3 Recommendations for further research

In this thesis, the mathematical models and spreadsheet models in Excel 2010 are developed to optimal the offshore supply planning problem, including finding the best size and composition of the supply vessel fleet and the optimal sequence of installations to be visited by each supply vessel in this fleet, in such a way that the cost is minimum. However, a periodic schedule for the supply vessels in this fleet to go forth and back between depots and offshore installations has not been built. There are three main reasons: one is that, in real life, it is hard to establish a fixed schedule for offshore supply vessels, due to many uncontrollable events, such as bad weather which may cause delays to planned voyages, and schedules. Another is that the demands of the installations are varying. Finally, the information of the offshore supply planning in this specific offshore oil and gas production area available is not sufficient, due to many other offshore supply vessel companies sharing the supply services in this area. So, in further steps, the periodic schedule of the supply vessels will be the main topic to study, and there are still lots of work to do to develop a successful optimization model of the offshore supply vessel planning.

Chapter 6. Conclusion

In this thesis, we have presented a real life optimization problem of offshore supply vessel planning. In this optimization problem, the objective is to answer these two questions: what is the best size and composition of a supply vessel fleet and what sequence of installations to be visited by each supply vessel in this fleet, in such a way that the cost is lowest.

To solve this problem, first, the offshore supply vessel planning optimization problem is regarded as a special kind of vehicle routing problem, and is abstracted to be a combination of the bin-packing problem, which is to optimize the composition of the supply fleet and the travelling salesman problem with simultaneous pick-up and delivery, which is to optimize the supply routing planning. Then the mathematical models of these two questions are developed. In order to solve these mathematical models, the Genetic Algorithm and Genetic Algorithm based software are introduced. Thereafter, a pilot study is conducted to illustrate the use of the Excel 2010 Evolutionary Solver in solving the developed mathematical models. And it is successful applied to obtain the optimal solutions (it may be the near optimal solutions due to the limitation of the Genetic Algorithm and Evolutionary Solver). So far, a solution method of this optimization problem has been built. Finally, this method is introduced to solve a real offshore vessel planning problem for a specific offshore oil and gas production area.

In this developed optimization method, the offshore supply vessel planning problem is considered to be the combination of the bin-packing problem and the travelling salesman problem, which is based on the author's experience in this area. The results are still needed to be proven in further research or in real life planning. The Genetic Algorithm based software, Excel 2010 Evolutionary Solver, is applied to solve the offshore supply vessel planning problem. This software is very popular in office, not difficult to operate, as well as good in finding optimal results. However, it is not perfect and unable to solve more complex problems. Besides, this method has not been conducted in other software, like Matlab, in this thesis. So, these solutions cannot be proven so far. The solution may be optimal or just near optimal. This is also needed to be studied in the future.

In the industry, cost-saving and efficiency-enhancing are the common objective for every company. It is wished that the optimization method of the offshore supply vessel planning can be improved continuously and applied in real life, to be a decision support tool for the planner to make more efficient and economic offshore supply vessel planning.

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