Master's degree thesis

LOG953 Sustainable Energy Logistics

Short-term scheduling of support vessels in wind farm maintenance

Manru Xue

Number of pages including this page: 75

Molde, Monday May 2023

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Preface

This thesis aims to find a solution for determining the optimal short-term dispatch of support ships in the maintenance of offshore wind farms, thereby reducing costs and improving economic efficiency. It is necessary to find the best route to maintain the turbines for the Service Operating Vessel (SOV) and Crew Transfer Vessel (CTV) to solve this problem by researching and discussing different methods.

When completing my graduation thesis, I need to thank many people.

First, I would like to thank my supervisor, Paulo Cesar Ribas. Without his dedicated help, I would not be able to successfully complete the thesis. In the discussion meeting every week, he patiently guided me and gave a lot of valuable comments and carefully corrected every draft I updated. Thanks a lot for all of that.

Next, I would like to thank my wonderful parents for their unwavering spiritual support; they were solid backing me throughout my studies. I would also like to thank my friends for their company and for helping me ease my homesickness. I could not have done it without their encouragement and support. I am grateful for the opportunity to meet them and want to give my warmest wishes to everyone.

Molde May 22, 2023
Manru Xue

Abstract

With the continuous negative impact of traditional energy sources, the emergence of new sustainable energy sources with many advantages is welcomed by the society. Offshore wind energy is one of the most widely used sustainable energy sources. It has the advantages of cleanness, greenness, sustainability, low operating cost, and space-saving., but the expense of operating and maintaining logistics also puts enormous pressure on wind farm operators to cut costs for generating profitable energy. Improperly planned maintenance operations on large vessels such as Service Operation Vessels (SOV) and Crew Transfer Vessels (CTV) can lead to a low-reliability maintenance plan and high fuel consumption, increasing overall maintenance costs. Therefore, planning offshore wind farms' day-to-day operation and maintenance is a crucial issue. This thesis contains a study of different algorithms combined with the specific conditions of actual cases. By analyzing data from several groups, a set of models for supporting the short-term dispatch of ships in wind farm maintenance is established and implemented using AMPL coding. These models could be used to generate a reliable maintenance plan.

Keywords: Wind Energy, Offshore Wind Farm, Operation and maintenance, Short-term scheduling, Mathematical Modelling.

List of abbreviations:

CTVs	Crew transfer vessels
OWF	Offshore Wind Farm
O&M	Operation and maintenance
SOVs	Service Operation Vessels
SPIV	Self-propelled Installation vessels
GA	Genetic Algorithm
TSP	Traveling salesman problem
MTZ	Miller-Tucker-Zemlin
VRPPD	Vehicle routing problem with pickups and deliveries
VRPTW	Vehicle routing problem time windows
SMRP	Stochastic maintenance routing problem
DSS	Decision Support System

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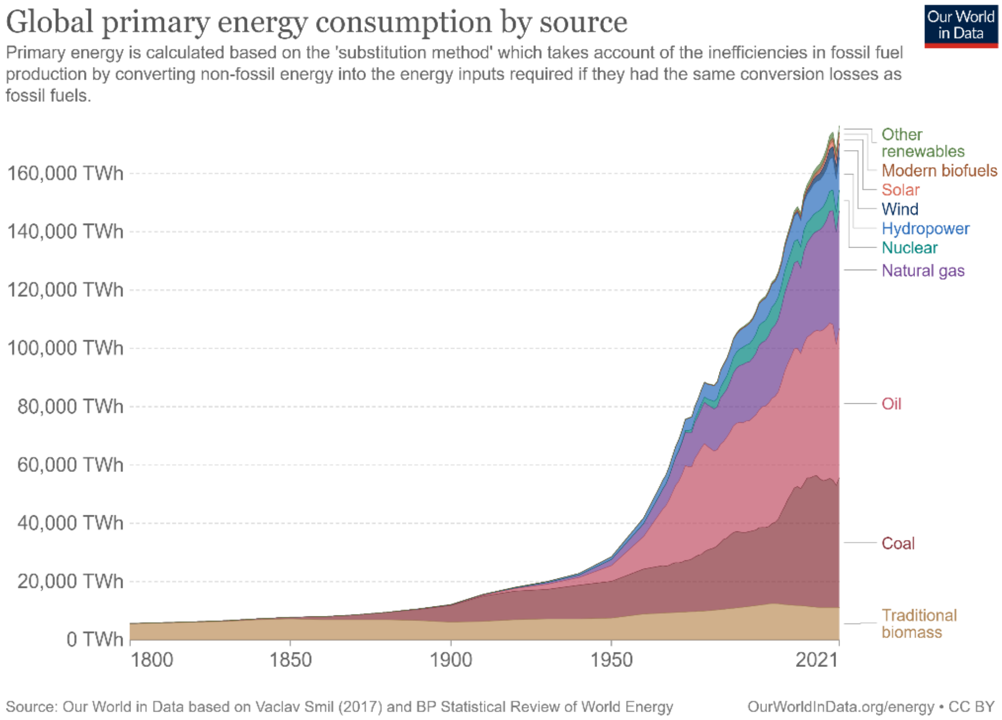
1.0 Introduction

With the ongoing development of the global economy, energy consumption is increasing. At the same time, due to the impact of the epidemic that lasted for more than two years, the energy supply has become tighter, and the most direct impact is reflected in the rise in oil and gas energy prices. The resulting increase in production and transportation costs, and even the rise in prices, has led to an increase in people's living costs and a series of adverse effects.

1.1 Description

When we discuss energy mixes today, we consider a wide range of sources, including coal, oil, gas, nuclear, hydropower, solar, wind, and biofuels. Currently, oil provides most of the world's energy consumption, followed by coal, gas, and hydroelectric power. The energy mix is broken down by country in the charts below. First, a higher-level breakdown of fossil fuels, nuclear, and renewable energy is provided. Then there is the breakdown by source, which includes coal, gas, oil, nuclear, hydro, solar, wind, and other renewable energy (including bioenergy, wave, and tidal) (Figure 1).



Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

Figure 1 - Energy consumption in the world by source (Source: https://ourworldindata.org/energy-production-consumption)

However, three-quarters of global greenhouse gases come from burning coal, oil, and natural gas. This has caused the warming of the Earth and endangered the living environment of human beings. To avoid global warming of 1.5°C, we must stop at least 80% of all energy and non-energy fossil fuel and biofuel emissions as soon as possible. (Figure 2) (Jacobson, M.,2019)

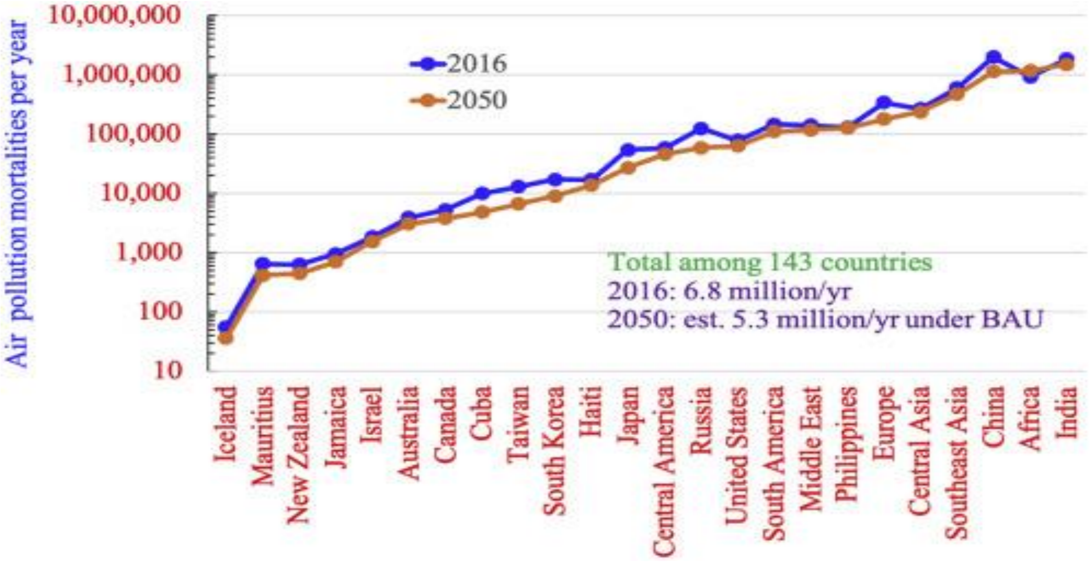


Figure 2 - Estimated BAU Air-Pollution Mortalities in 2016 and 2050 by World Region.

To prevent further deterioration of environmental problems, it is urgent to find a dry-friendly and sustainable energy source to replace fossil fuels. With the continuous exploration by people, several clean and relatively high-value sustainable energy sources have been discovered, including wind energy. Wind energy is a type of energy produced by air currents. In recent years, it has become common to separate between onshore wind power and offshore wind power. However, the effort to explore the offshore wind power industry has intensified due to certain geographical and environmental restrictions on onshore wind power. Although offshore wind power has become very popular, its industrial cost is also high. This includes not only the high manufacturing and installation costs of the turbines but also the associated high maintenance and operating costs (Lazakis and Khan, 2021). Among them, the route planning and scheduling of the daily maintenance fleet is one of the critical factors affecting the overall operation and maintenance cost. Determining an optimal maintenance plan has become a significant challenge for operators.

To solve this problem, we defined mathematical models for creating a maintenance plan for offshore windmills. For example, when there is an offshore wind farm, we need to formulate a plan to optimize daily operation and maintenance to minimize the total maintenance cost.

So assuming that a large service operating vessel (SOV) can carry two smaller crew transfer vessels (CTV) to complete a two-week maintenance mission. The SOV stops at different places every day, and the CTVs need to complete the maintenance tasks of the day and return to the SOV according to the plan. The distribution of maintenance points is random, and different personnel will complete the corresponding work duties. It seems easy to divide the schedule into two parts, one for the SOV and another for the CTVs.

1.2 Research Objective

- Can research on modeling improve the short-term scheduling of SOVs used as the base for CTVs?
- How can the use of SOVs in wind farm maintenance be improved if it is feasible?

1.2.1 Research questions

- How to ensure the execution of maintenance tasks at a minimum cost?
- Is it possible to create a suitable model for solving the short-scheduling problems?
- How should the model be used to optimize the route of vessels in wind farm maintenance?
- Does the model work in a realistic case inspired on Dogger Bank wind farms?

1.2.2 Research tasks

- Find the maximum number of tasks that can be completed.
- Find the minimal travel time (delivery time and pickup time).
- Verify the feasibility of the model.

1.3 Structure of the thesis

This work proposes a model for enabling short-term scheduling of wind farm overhaul ships by studying and debating several existing approaches to discover the optimum way to maintain service operation vessel (SOV) and crew transfer vessel (CTV) turbines. The goal is to reduce operational and maintenance costs, which relieves pressure on wind farm operators and increases economic benefits.

The remaining part of the thesis is organized as follows: Section 2 consists of a literature review, and Section 3 states the general problem description. Section 4 shows the methods, the case description is demonstrated in Section 5, and the results are provided in Section 6 before the conclusions are presented in Section 7.

2.0 Literature review

When planning the maintenance of offshore wind farms, it is necessary to find an effective solution to solve the deterministic maintenance problem of offshore wind farms by researching and discussing different methods from many case studies. There are currently several typical optimization methods and simulation tools.

2.1 O&M tool: an arc-flow model & a path-flow heuristic method. (Stålhane et al. 2015)

2.1.1 Arc-flow model

The goal is to find a network path for each ship, minimizing the overall cost of performing maintenance tasks. To address this problem, the paper shows an arc flow model with three sets of variables. Finally, constraints require that the delivery node be visited before the corresponding pickup node, and each x variable must be binary.

2.1.2 Path-flow model

The objective function aims to reduce the sum of the navigation cost and the penalty cost for failing to perform maintenance. Constraints require all maintenance tasks to be completed, or a penalty cost will be incurred. The constraints ensure that each ship sails on precisely one course. Finally, constraints specify that all the y and x variables must be binary. If costs are reduced, the arc flow model allows for a delay in the start of precautionary allocations. To apply the same flexibility to the labeling algorithm, a linear program for each complete path may need to be solved. This means the path flow model must be classified as a heuristic if preventive assignments are included.

2.2 Solve the Routing and Scheduling Problem of a Maintenance Fleet for Offshore Wind Farms (RSPMFOWF) model (Dawid et al., 2016)

This Short-term decision-making O&M tool may save time and resources while extending the effective remediation window.

The model is based on an actual case of offshore wind farms, and it enables efficient resource planning by automating the logistical decision-making process for offshore wind farm maintenance actions. Besides that, models that optimize decision-making may save time and resources while extending the effective repair window. The process produces user-friendly outputs that help visualize the policy, making it appealing to practitioners. This model's application is not limited to CTVs. Helicopters are increasingly common and can also be captured by the model.

2.3 Genetic Algorithm (GA) (Stock-Williams and Swamy 2019)

The goal of this model is to find the best possible transfer plan from a huge set of possible options.

Service orders are prioritized by sorting the reference list based on the decision vector value, and technicians are allocated using a cumulative curve, which must be converted to integer values for technicians. The Princess Amalia study uses only one crew transfer vessel for routine maintenance, based on data provided by Eneco for a case set up for the Princess Amalia wind farm in the Netherlands. This is accomplished by optimizing only small maintenance operations, and because wind farms are relatively small and managed by experienced dispatch teams, newer wind farms can produce higher returns.

2.4 Mixed Integer Linear Programming (MILP) Model (Irawan et al. 2021)

This model is designed to optimize the schedule and route of each vessel (maintenance within a planned period of several days), and the ability of the vessel to transport spare parts. An optimization model and solution method for the deterministic maintenance routing problem were evaluated using nine instances of each case study (based on the reference wind farm scenario developed in the EU FP7 LEANWIND project (http://www.leanwind.eu/) and the Sarnet wind farm in England layout). To deal with uncertain conditions, an SMRP simulation-based optimization algorithm was proposed to solve stochastic problems. This included Monte-Carlo simulations and a proposed combined metaheuristic. Extensive computational experiments were used to evaluate the performance of the proposed stochastic model for the maintenance routing problem under uncertainty (SMRP), making it more applicable to offshore wind farm operations. These models can be mixed with O&M strategic models to provide a more comprehensive decision support framework that takes strategic, tactical, and operational timescales into consideration.

2.5 OptiRoute (Lazakis and Khan 2021)

This tool is used for daily or short-term O&M based on route planning and scheduling while minimizing the cost under different operational constraints.

It is a new optimization heuristic framework for optimal route planning of offshore wind maintenance vessels, utilizing clustering techniques to complete offshore wind turbine maintenance with the lowest number of vessels, combined with climate data, vessel specifications, wind turbine failure/location, cost, pickup and drop-off of technicians, using both Service Operational Vessels (SOVs) and Crew Transfer Vessels (CTVs) to best demonstrate the combination of case studies.

2.6 A two-stage stochastic programming model (Stålhane et al. 2016)

This paper considers the problem of determining the optimal fleet size and mix of ships to support maintenance activities, proposing a two-stage stochastic programming model in which uncertainties in demand and weather conditions are considered. The model is designed to consider the entire lifecycle of an offshore wind farm while still being solvable for realistically sized problem instances, and to determine the cost-optimal mix of fleet size and offshore wind farm O&M activities for long-term planning. Emphasis is placed on developing models that can solve real-scale problem instances. Computational studies have shown that, in some cases, it is valuable to account for uncertainty in demand and weather conditions.

2.7 Three-stage stochastic programming model (Gundegjerde et al. 2015)

This research looks at the fleet size and mixing challenges that arise during offshore wind farm maintenance operations and presents a new three-stage stochastic programming model. In Phases 1 and 2, fleet size and mix decisions are established, and the fleet is deployed to execute maintenance operations in Phase 3. Uncertain parameters include ship spot rates, meteorological circumstances (wind speed and wave height), electricity prices, and failure uncertainty. The model was tested on real-world problem situations, and the results revealed that adopting a stochastic model exceeded the deterministic option. The proposed model can be used to deal with the problem on a large scale and serves as a significant decision-support tool for offshore wind farm operators. It can be used to establish not just the mix of vessel fleet size and O&M activities, but also to evaluate vessel willingness to pay and the potential cost savings of sharing a fleet with another offshore wind farm.

2.8 A new two-stage stochastic programming model (Stålhane et al. 2019)

This paper analyzes the topic of identifying the ideal fleet to support offshore wind farm maintenance operations, presenting a two-stage stochastic programming (SP) model of the problem to determine the optimal fleet to minimize an offshore wind farm's total O&M cost. The first step is to decide which bases to use and which ships to charter on long and short-term contracts. The daily deployment of a given fleet is modeled in the second stage using an ad hoc Dantzig-Wolfe decomposition to derive an estimate of ship operating costs and wind farm downtime costs. The model accounts for weather uncertainty as well as the rate of remedial O&M actions. The model presented in this work was created in partnership with the Norwegian offshore wind operators Equinor (previously Statoil) and Statkraft, and it has been used to give decision support during the development phase of multiple offshore wind farms.

2.9 A Decision Support System (DSS) (Li et al. 2016)

The paper describes a Decision Support System (DSS) for optimizing maintenance costs at an offshore wind farm (OWF). The DSS is intended for usage by numerous stakeholders in the OWF sector with the general purpose of guiding maintenance strategy and hence lowering total OWF lifecycle maintenance costs. The DSS is supported by two optimization models. The first is a deterministic model designed for stakeholders that have access to accurate failure rate data. The second is a stochastic model designed for stakeholders with less certainty regarding failure rates. As an example, solutions for both models are shown using a UK OWF that is currently under construction. By comparing the findings of the two models, conclusions about the value of failure rate data are reached. The turbine failure rate frequency and number of turbines at the site are subjected to sensitivity analysis, with near-linear trends identified for both. Finally, overall conclusions are presented in the context of OWF maintenance planning.

2.10 A dual level stochastic fleet size and mix problem for OWF Q&M (Stålhane et al. 2021)

The paper investigates the issue of two-tier fleet sizing and mixing to support offshore wind farm O&M activities. The goal is to investigate strategic fleet sizing and blending challenges for offshore wind farm maintenance. For reducing the expense of performing maintenance at one or more wind farms, a mathematical model for a two-level stochastic programming model was proposed, that the model includes both strategic and operational level uncertainties, taking into consideration both short-term operational uncertainty and long-term strategic uncertainty. Furthermore, the authors develop an ad-hoc integer-shaped method with a custom optimal cut for the main problem and symmetry-breaking constraints and effective inequalities for the subproblems. The model supports wind farm owners in making strategic decisions regarding the number, arrangement, lease term, and charter type to meet maintenance needs throughout the lifecycle of the wind farm.

2.11 OW turbine O&M: A state-of-the-art review (Ren et al. 2021)

This article analyzes the most recent OWT maintenance research, including strategy selection, schedule optimization, field operations, maintenance, evaluation criteria, recycling, and environmental challenges. In the paper, summarizing and comparing numerous ways, meanwhile, the limitations of OWT operation and maintenance research, as well as the lack of industrialization development, are discussed. Furthermore, the negative impact of offshore maintenance on marine animals, greenhouse gas emissions, and waste recovery are reviewed. Finally, attractive topics for future maintenance strategy development are indicated. It also serves as a foundation for developing maintenance strategies for future offshore wind-generating deployments. OWT maintenance research develops and accumulates in tandem with technical advancement and theoretical innovation in a variety of related fields. These technologies and their use are gradually lowering electricity costs while increasing market competition for offshore wind power.

2.12 Location-allocation problem (Manupati et al. 2021)

This research discusses the issue of convalescent plasma banking facility location allocation. It recommends a novel plasma supply chain model that takes into consideration stochastic parameters impacting plasma demand as well as the plasma supply chain's distinctive properties. It develops an effective mixed integer linear programming (MILP) model by balancing two conflicting objective functions: the minimization of total plasma transit time and the overall cost of the plasma supply chain network, which includes inventory costs to reduce waste. The MILP function is then solved using a CPLEX-based optimization approach. A comparative analysis using the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and the suggested modified NSGA-III confirms the practicality of the results. The suggested model's applicability is assessed by implementing it in a real-world case study in India. The optimized numerical results, as well as their sensitivity analyses, offer decision-makers significant decision support. Furthermore, plausibility and sensitivity analyses were carried out to explore the impact of random parameters on solution quality. The optimized numerical results, as well as their sensitivity analyses, provide decision-makers with significant decision support.

2.13 Miller–Tucker–Zemlin model (MTZ) (Campuzano et al. 2020)

In this paper, an easy-to-implement algorithmic approach is proposed for improving the computational performance of the Miller–Tucker–Zemlin (MTZ) model of the asymmetric traveling salesman problem (ATSP) by efficiently generating efficient inequalities from fractional solutions. It can help practitioners solve real-life problems to a near-optimal degree using standard optimization solvers and may help solve various routing problems using MTZ-type subtours to eliminate constraints, greatly improving the performance of MTZ-based formulations performance and obtain solutions that are competitive with those reported by recent state-of-the-art metaheuristics. This approach can also be extended to speed up other well-known ATSP models reported in the literature and can be used to enhance ranking-based models reported for multiple asymmetric traveling salesman problems.

2.14 Vehicle routing problem with pickups and deliveries (VRPPD) (Hoff et al. 2009)

This article is based on the case study of Oskar Sylte, a Norwegian beverage distributor. Taking into consideration the vehicle routing issue for pickup and delivery (VRPPD), where the same customer may require both delivery and pickup, a tabu search heuristic capable of generating lasso-solutions for the pickup and delivery vehicle routing problem is developed. The results of tests on a set of 35 examples demonstrate that, while generic solutions assaulted other solution types in terms of cost, their computation can be time-consuming. In general, an optimum lasso solution obtained within a certain time constraint exceeds an ideal general solution developed with the same computational effort. If each customer is replicated and the Hamiltonian route is built on the expanded graph, it can also produce a general solution where the same customers can be visited twice without the exact lasso structure of the solution. In practice, some organizations prefer to use lasso methods because they facilitate the handling of goods within the vehicle.

2.15 Vehicle Routing Problem with Time Windows (Kallehauge et al. 2005)

In this book chapter, the Vehicle Routing Problem with Time Windows is covered along with its mathematical model, organizational structure, and decomposition options. It includes the master problem and the subproblem, respectively, for the column generation method, shows a branch-and-bound framework and discusses acceleration techniques for branch-and-price approaches. Additionally, it discusses how the issue can be extended as well as gives computational outcomes for the traditional Solomon test sets. It has emphasized the important advancements for the VRPTW's best column generation techniques. The best-performing algorithms up to the publication date are those that apply to branch and cutting to solutions found using Dantzig-Wolfe decomposition. For this class of issues, valid inequalities have shown to be a crucial tool in supporting LP relaxation.

2.16 Vehicle routing problem with time windows (VRPTW) (El-Sherbeny 2010)

In this paper the vehicle routing problem with time windows (VRPTW) is reviewed together with certain limited exact methods, heuristics, and metaheuristics. Many areas of mathematics, computer science, and operations research use this problem as a model. The solution methods help managers in making decisions with their strong solutions that deliver high-quality answers to crucial applications in business, engineering, economics, and science in reasonable time frames. There are several constrained variations of the many approximate methods, including precise, heuristic, and metaheuristic approaches.

2.17 A multi-objective maintenance strategy optimization framework for OWF considering uncertainty (Li et al. 2022)

This research develops a general structure for combining maintenance techniques, decision-maker goals, and uncertainty modeling. The model takes into consideration uncertainties such as the stochastic nature of failure times, differences between actual and expected failure times of components, and unreliable maintenance effects. In the face of uncertainties, the suggested framework is applied to a basic 150 MW offshore wind farm in the North Sea, where the performance of the maintenance strategy deteriorates, and the solution exhibits wider dispersion. The proposed optimization framework is a useful decision-making tool for guiding long-term maintenance strategies for offshore wind farms in real-world conditions with considerable uncertainty. This method, in comparison to previous studies, is built for a more realistic maintenance decision-making environment, with the goal of measuring the influence of uncertainty on maintenance performance and presenting a set of maintenance methods.

2.18 Literature Review Summary

A large body of literature, including (Stålhane et al., 2015), (Stålhane et al., 2016), (Gundegjerde et al. 2015), (Stålhane et al., 2019), and (Stålhane et al., 2021). (Irawan et al., 2021) is based on expected turbine failure and optimally simulated operation planning for a wind farm's whole lifecycle.

Similar to the traveling salesman issue used for offshore wind farm route planning, (Stock-Williams and Swamy, 2019) provide a meta-heuristic optimization method to identify the strengths and weaknesses of any maintenance program and provide an estimate of the investment in implementation.

(Dawid et al., 2016) studied an O&M tool for short-term decision-making that saves time and costs while extending the effective remedy window. (Lazakis and Khan, 2021) create a novel optimization heuristic framework for daily or short-term operations based on route planning and scheduling, with the goal of reducing costs under various operational constraints. (Li et al., 2016) developed a decision support system (DSS) to reduce OWF maintenance costs. The DSS is designed to be used by a broad range of stakeholders in the OWF industry to guide maintenance strategies, eventually reducing the overall cost of OWF life cycle maintenance.

(Irawan et al., 2021) suggested an optimization approach for solving stochastic issues under unknown situations based on SMRP simulation. The model was created to optimize each ship's repair schedule and route over a period of many days, as well as the ship's ability to transfer spare parts. (Li et al., 2022) provided an optimization methodology to guide long-term maintenance strategies for offshore wind farms under actual settings with significant uncertainty. In comparison to earlier research, this technique is established for a more realistic maintenance decision-making environment, with the goal of quantifying the influence of uncertainty on maintenance performance and providing a set of maintenance methods.

(Ren and colleagues, 2021) The newest OWT maintenance research is examined in this study, including strategy selection, schedule optimization, field operations, maintenance, evaluation criteria, recycling, and environmental challenges. This paper analyzes the constraints of OWT operation and maintenance research as well as the lack of industrialization progress while describing and comparing different methodologies.

(Manupati et al., 2021) offer a novel plasma supply chain model that creates an efficient Mixed Integer Linear Programming (MILP) model by balancing two opposing objective functions. It also serves as the foundation for the model developed in Section 4.1 of this article.

(Campuzano et al., 2020) provide a simple algorithmic strategy for improving the computation of the Miller-Tucker-Zemlin (MTZ) model of the Asymmetric Traveling Salesman Problem (ATSP) by effectively generating efficient inequalities from fractional solution performance. This strategy is used to generate the model in Section 4.2 of this study.

Different phases of research on the vehicle routing problem with time windows (VRPTW) have been conducted (Kallehauge et al., 2005), (El-Sherbeny, 2010). The models provided in the literature provide useful inspiration for the development of the 4.3 model in this paper.

3.0 General problem description

Based on such the urgent situation, the Paris Agreement (UN 2015) was proposed and passed at the 21st United Nations Climate Change Conference (Paris Climate Conference) on December 12, 2015, and officially implemented on November 4, 2016. The agreement is a binding international treaty about climate change signed by 178 countries around the world, and it is a unified arrangement for global actions to deal with climate change after 2020. The Paris Agreement has 29 articles, including goals, mitigation, adaptation, loss and damage, funding, technology, capacity building, transparency, and global stocktaking. The agreement states that all parties will strengthen the global response to the threat of climate change, control the increase in the global average temperature above the pre-industrial level within 2 degrees Celsius, and strive to control the temperature rise within 1.5 degrees Celsius. Only when the world reaches the peak of greenhouse gas emissions as soon as possible and achieves net-zero emissions of greenhouse gases in the second half of this century can we reduce the ecological risks brought by climate change to the Earth and the survival crisis brought to human beings. (UN 2015)

Faced with so many situations, the world is beginning the transition to clean, renewable energy. The development of sustainable energy would be an effective way to change energy demand.

There are many types of renewable energy, the most common of which are the following (Figure 3):

- Hydropower
- Wind energy
- Solar
- Bio-power
- Geothermal
- Ocean power

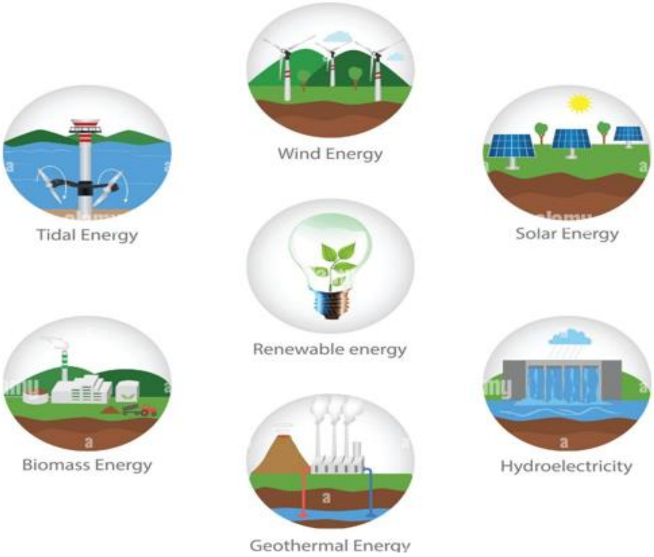


Figure 3 -The types of renewable energy. (https://c8.alamy.com/comp/H3MMDC/renewable-energy-types-power-plant-icons-vector-set-renewable-alternative-H3MMDC.jpg)

Figure 4 shows the distribution between different energy sources. About 30 percent of the world's electricity comes from renewable energy, including hydropower, solar and wind among others:

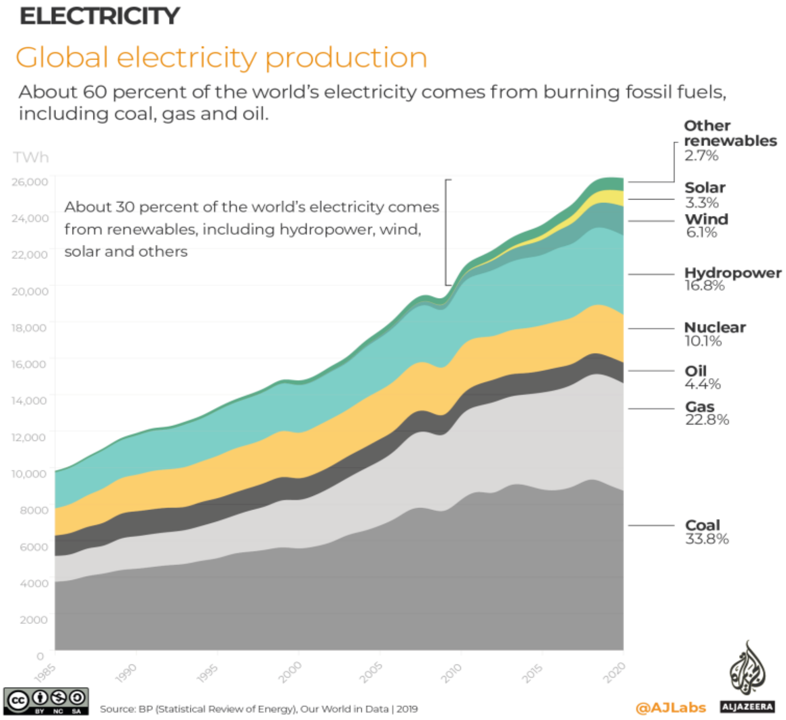


Figure 4 -How the world's electricity is consumed.

(Source: https://www.aljazeera.com/news/2022/1/20/interactive-how-much-of-your-countrys-electricity-is-renewable-infographic)

According to Figure 4, we can see that wind energy is an important source of renewable energy, which is in line with the values of sustainable development.

Also, Wind Energy has many pros:

- Clean, Green, and Renewable source of energy
- Low running costs
- Space efficient source of energy
- Jobs Opportunities
- Freely available
- Reduces dependency on conventional fuels

3.1 Wind Energy

There are two main ways of wind power generation, one is onshore wind power as shown in Figure 5 and the other is offshore wind power as shown in Figure 6.

Figure 5 -Onshore Wind (Source: https://www.istockphoto.com/photo/windmill-on-hill-gm501226210-81223513)

Figure 6 -Offshore Wind

(Source: https://www.istockphoto.com/photo/wind-turbines-in-an-offshore-wind-park-producing-electricity-during-sunset-gm1341414270-421170885)

However, onshore wind power has some negative issues such as geographical limitations and impact on the environment, and hence, offshore wind power has many advantages (Baidu 2022):

- The wind conditions at sea are good.
- The equipment is conveniently transported, and the power generation efficiency is high.
- The utilization rate of wind power is higher.
- No land occupation, no disturbance to the people.

3.1.1 Offshore Wind

Based on the benefits mentioned above, countries have gradually shifted from onshore wind power to offshore wind power in recent years, and, as technology develops, costs fall, and political support grows, global investment in offshore wind energy is expected to rise in the coming decades. (Figure 7)

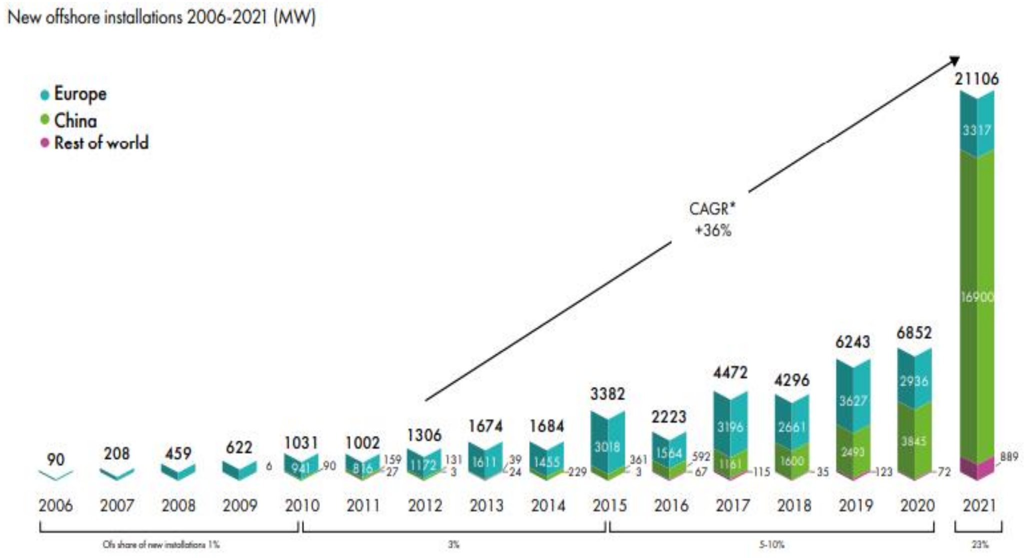


Figure 7 -Compound Annual Growth Rate. Source: GWEC Market Intelligence, June 2022

Figure 8 -Market Status 2021. Source: GWEC Market Intelligence, June 2022

From Figure 8 and Figure 9, we can know clearly about the market status of Global distribution of offshore wind farms.

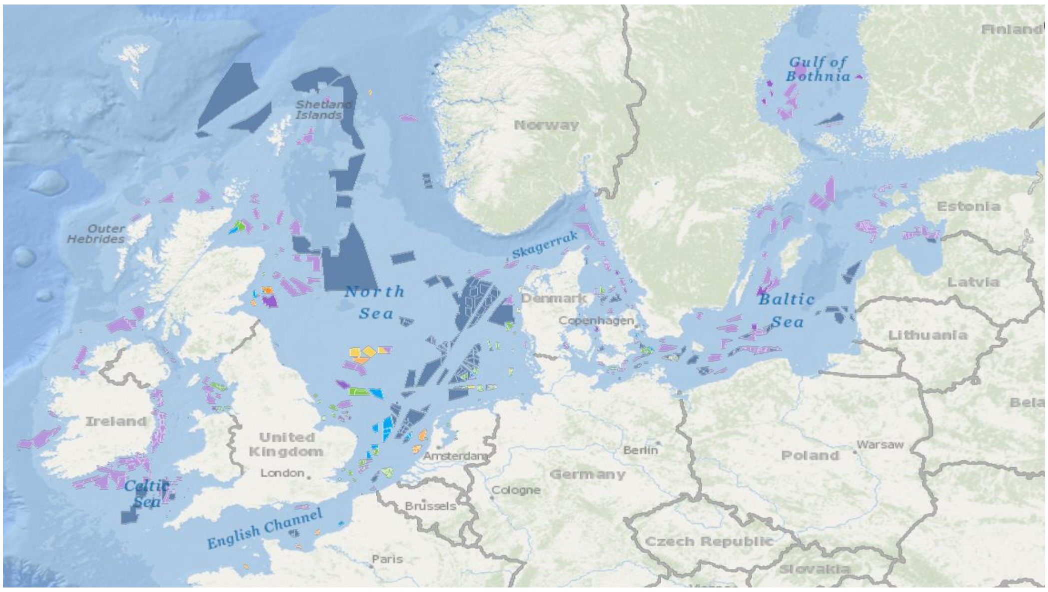


Figure 9 - Global offshore map. (Source: https://map.4coffshore.com/offshorewind)

At the UN climate change conference COP26 in 2021, global commitments to net zero gained any traction. Coupled with the renewed policy urgency for achieving energy independence from Russian oil and gas - and overall fossil fuel volatility - caused by Russia's invasion of Ukraine, the global offshore wind market outlook looks extremely promising in the medium and long term. As shown in Figure 10, with a compound annual growth rate of 6.3% until 2026 and 13.9% until the beginning of the next decade, new installations are expected to exceed 30 GW in 2027 and 50 GW by the end of this decade.

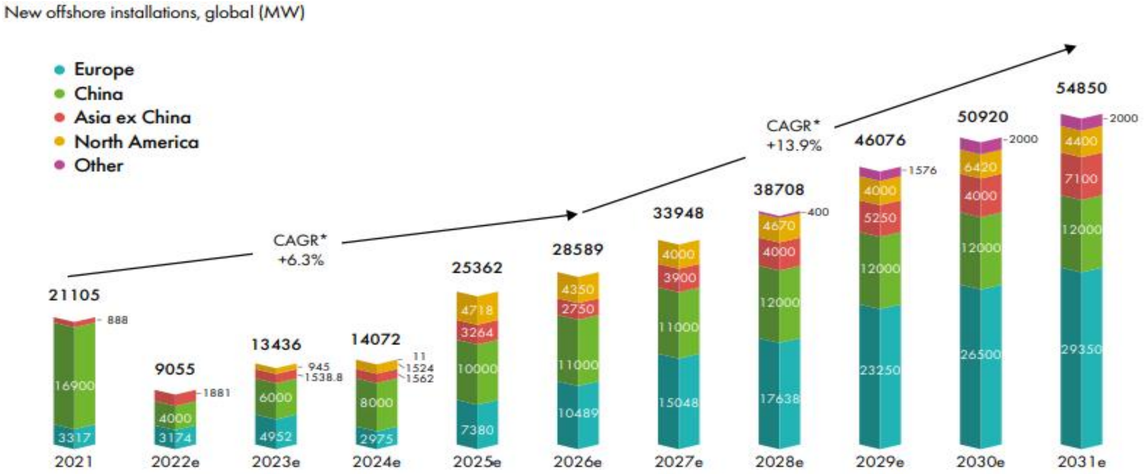


Figure 10 -Compound Annual Growth Rate. (Source: GWEC Market Intelligence, June 2022)

Nowadays, OW always faces many logistical challenges. For example, increasing sizes of wind turbine components, increasing distances from the coast, deeper water, larger sites for assembly and storage in ports, limited numbers of specialized vessels and fleet spread, long-term and multi-period planning, construction and operation in the same area, tasks performed in parallel, simultaneous planning of cargo and personnel, materials breakdown and failures, weather uncertainty factors, and emergency issues, etc.

3.2 The wind farm introduction

An electric power plant includes a few turbines that are linked to an internal grid for power transfer, one or more offshore substations, and an export cable that transmits power to the local grid. (Figure 11 and Figure 12)

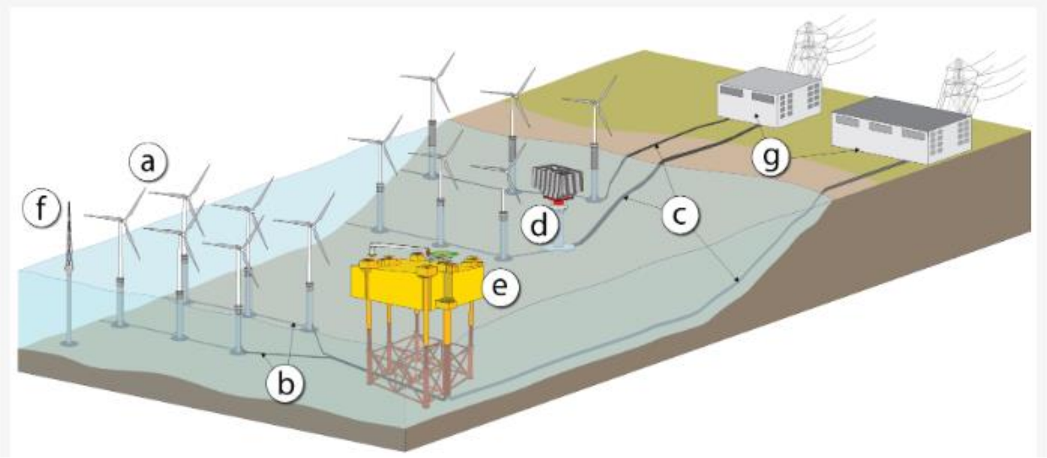
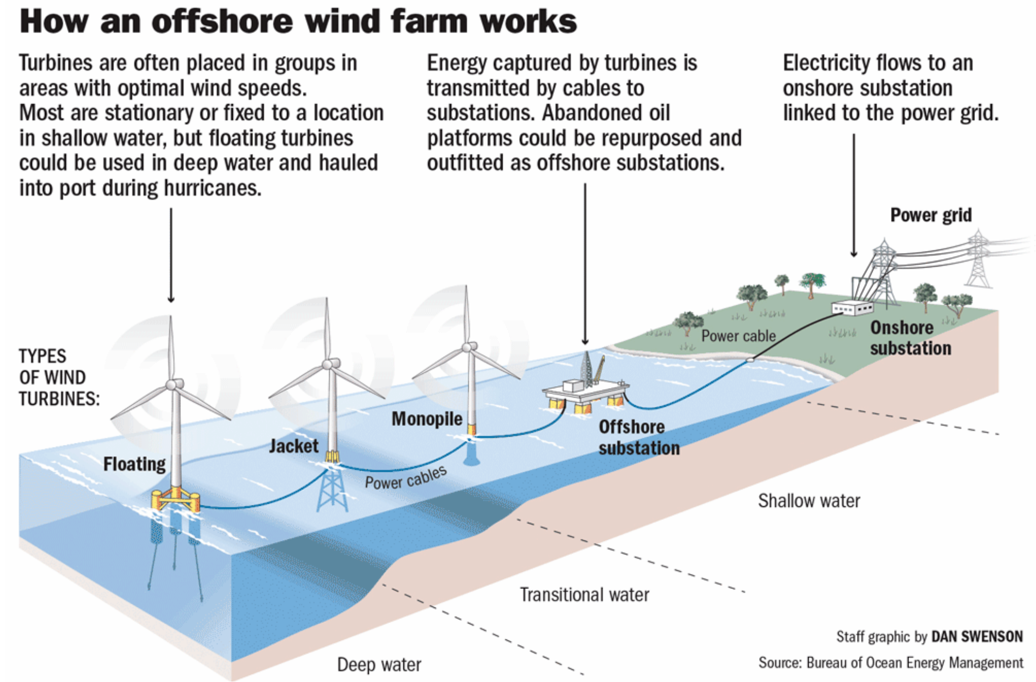


Figure 11 -the main components of an OWF: (a) Wind turbines; (b) Collection cables; (c) Export cables; (d) Transformer station; (e) Converter station; (f) Meteorological mast; (g) Onshore stations.

(Source: Rodrigues at al. (2016))



How an offshore wind farm works

Turbines are often placed in groups in areas with optimal wind speeds. Most are stationary or fixed to a location in shallow water, but floating turbines could be used in deep water and hauled into port during hurricanes.

Energy captured by turbines is transmitted by cables to substations. Abandoned oil platforms could be repurposed and outfitted as offshore substations.

Electricity flows to an onshore substation linked to the power grid.

Figure 12 - How an offshore wind farm works. (Source: https://bloximages.newyork1.vip.townnews.com/nola.com/content/tncms/assets/v3/editorial/e/02/e0213c3e-472b-11ec-866c-6b334608aaf8/6196abd5d5caf.image.gif)

An important part considered for an Offshore Wind Farm (OFW) is early design, it includes:

- Total farm capacity
- Site location (area) selection
- Shape selection
- Orientation selection
- Location of turbines within the shape
- Cable layout selection

For the Site location (area) selection, turbine parameters/model, distance from shore, and response to wind speed (Figure 13) and wind direction (Figure 14) should be considered.

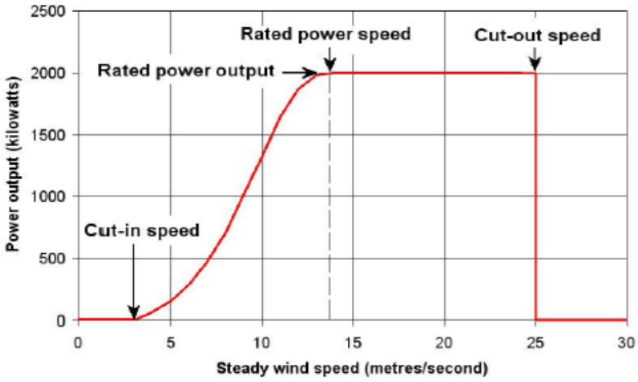


Figure 13 -Effect of wind speed factor on energy. (Source: Kim et al. 2018)

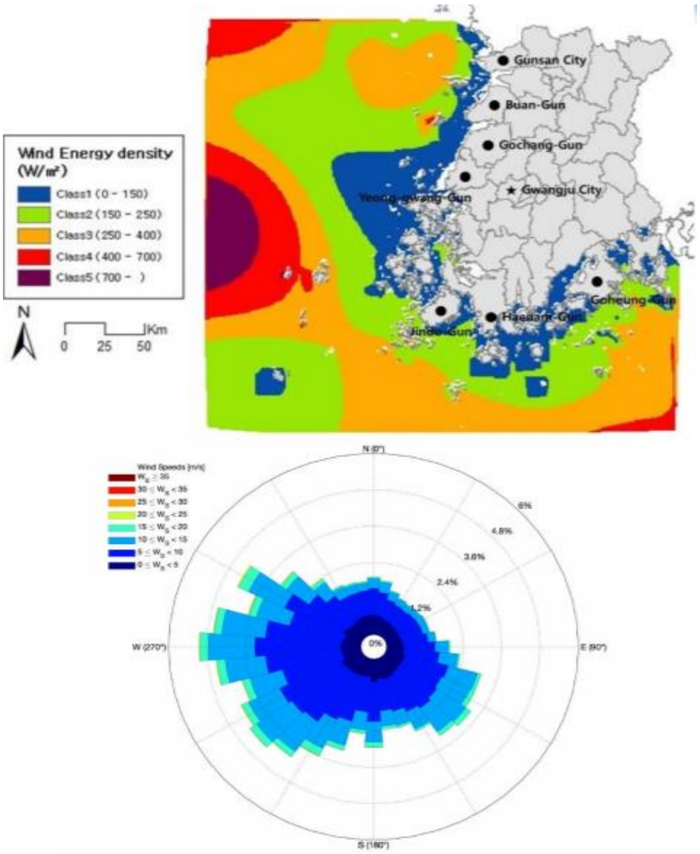


Figure 14 -Effect of wind density factor on energy. (Source: Mokhi and Addaim, 2020)

There are many shapes of OWF (Figure 15), it depends on different project.

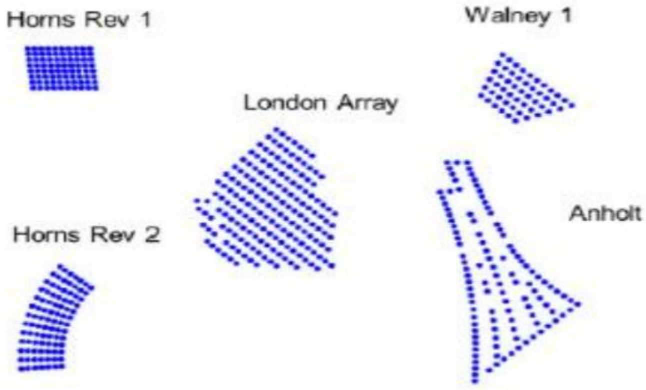


Figure 15 -Shapes of OWF. Source: Rodrigues et al. (2015)

Floating wind turbines may require joint optimization of location and wind direction response:

When a wind turbine is going to be connected other turbines in a wind farm, its efficiency is reduced. A wind turbine behind another turbine, particularly, is strongly influenced if the distance between the two turbines in the wind direction is insufficient. As a result, location selection is vital.

Location of turbines within the shape (Figure 16):

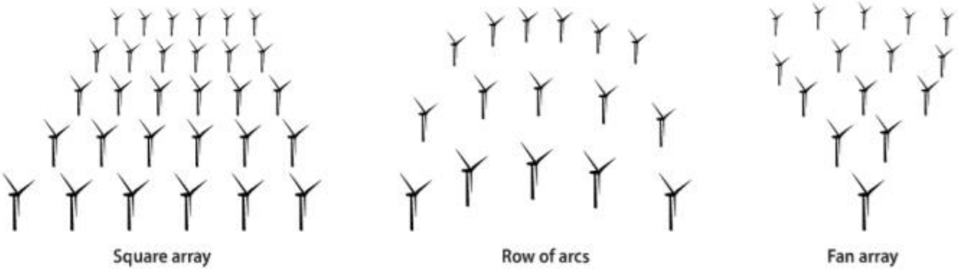


Figure 16 -Location of turbines within the shape. Source: knowablemagazine.org

OWF Substation Location: (Figure 17)

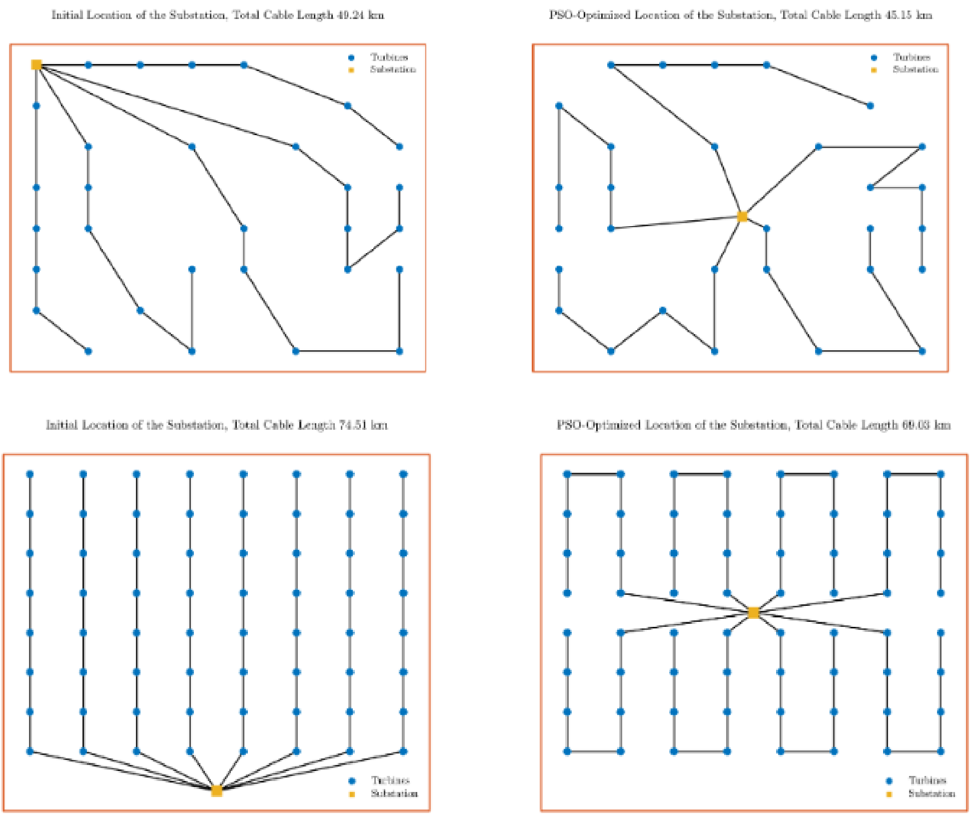


Figure 17 -OWF Substation Location. Source: El Mokhi and Addaim, 2020

For a wind farm with already optimized substation location, the optimizing of the collector topology (cable routing) is found as a solution to the single-depot Multiple Hamiltonian Path Problem. (Figure 18)

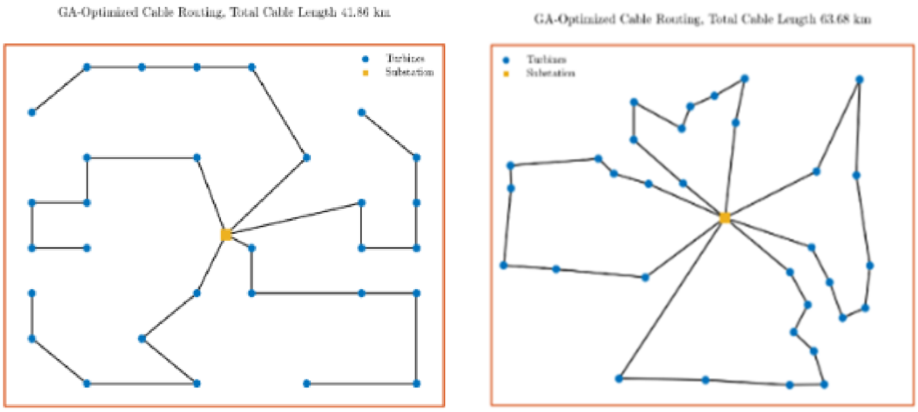


Figure 18 -Optimized cable routing. Source: El Mokhi and Addaim, 2020

Offshore wind farms are currently being installed away from the coast in search of locations that meet space and wind conditions to increase energy production. These locations may be suitable for the deployment of wind turbines and have optimal conditions for energy production, but the logistics of carrying out operations and maintenance are becoming increasingly complex. Wind farm operators are under considerable pressure to cut costs to make energy production profitable.

3.3 Offshore wind – operation and maintenance

Apart from continuous technological development, how to reduce costs more effectively has become an important topic for the development of offshore wind power. Offshore wind construction includes two main phases: Construction and Operation and Maintenance. And different phases have different logistics needs. The key elements of energy costs are Turbine, O&M, Installation, Foundation, Electrical, and Project. Figure 19 shows that O&M is the second largest element in among the energy costs.

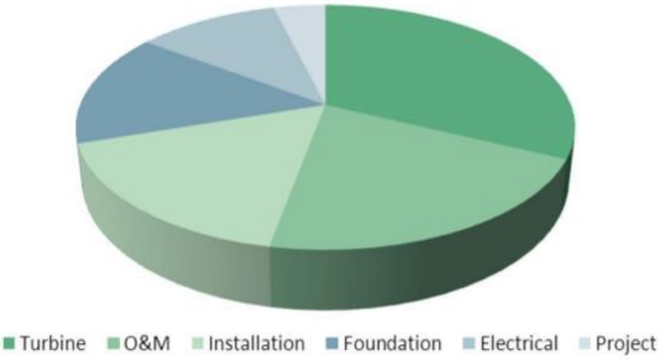


Figure 19 - Cost factors in offshore wind. Source: Renewable UK (2011)

Figure 20 shows an overview of activities within operations and maintenance for offshore wind parks.

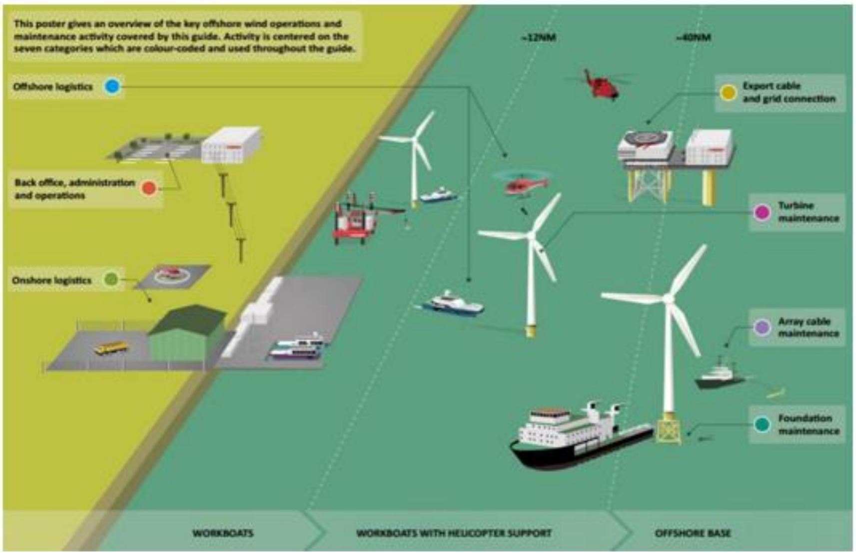

This poster gives an overview of the key offshore wind operations and maintenance activity covered by this guide. Activity is centered on the seven categories which are colour-coded and used throughout the guide.

Figure 20 - GL Garrad Hasson's A Guide to UK Offshore Wind Operations and Maintenance.

OWF typically requires two types of vessels: installation vessels and heavy-lift vessels. Installation vessels include lifeboats, jack-up barges, self-propelled installation vessels (SPIV), and heavy-lift vessels. The other category is cable laying vessels, which includes export cable laying vessels such as inner-array cable laying vessels (modified offshore supply vessel, and main installation vessel and export cable vessel can be used). Also, there are some common vessel types that can be used at the OWF: tugs, dive support, multicast, scour protection vessels, crew transfer vessels (CTV), and service operation vessels (SOV). Features of the vessel types of CTV and SOV used for O&M of wind farms are shown below:

- ➢ Crew transfer vessel (CTV) (Figure 21)
  - The "traditional" wind farms have been supporting:
    - Wind farm close to shore; usually between 0 and 60 km
    - CTVs are small:
      - 8-12 passengers
      - Little cargo (enough to support 1 day of work)
      - Relatively high sensitivity to waves (max approx. 1,0-1,2 m)
    - Straightforward logistics planning:
      - 1-day separate vessel logistics planning
      - Economic consequences of non-optimal planning are low

Figure 21 -Crew transfer vessels. https://i.ytimg.com/vi/ubwNTWfDOF8/maxresdefault.jpg

- ➢ Service Operation Vessels (SOV) (Figure 22)

- The “new” wind farms will be supporting in the future:
    - Wind farm far from shore; usually between 60 and 300 km
    - SOVs are large:
        - 60-80 passengers
        - Large quantity of cargo (enough to support 14 days of work)
        - Less sensitivity to waves (max approx. 3,0-3,5 m)
    - Complex logistics planning:
        - 2-weeks joint SOV – daughter craft - helicopter logistics planning
        - Economic consequences of non-optimal planning are high
        - Introduction of the “Service Train & Pit Stop” logistics philosophy

Figure 22 - Service operation vessels

(Source: https://i.guim.co.uk/img/media/b784d5303b245fdb4de93beb5720e375e7d39ef0/0_0_4762_2859/master/4762.jpg?width=1200&height=900&quality=85&auto=format&fit=crop&s=39e8faa29c087d0b0b30513e08862c80)

3.3.1 Improve economic efficiency by reducing costs

Offshore wind farms are currently being installed away from the coast in search of locations that meet space and wind conditions to increase energy production (World-Energy, 2022). These locations may be suitable for the deployment of wind turbines and have optimal conditions for energy production, but the logistics of carrying out operations and maintenance are becoming increasingly complex. Wind farm operators are under considerable pressure to cut costs to make energy production profitable. Maintenance operations are one of the most expensive components of an offshore wind farm, accounting for up to 25% of the total costs (Stålhane, 2015).

Offshore wind power has a longer industrial chain than onshore wind power. As a result, there is more room for cost-cutting and efficiency improvement. The offshore wind power industrial chain includes pre-coordination work, main engine equipment during project construction, electrical (offshore boost), power transmission (cable), installation and construction, and so on, as well as project operation and maintenance. Every day, wind farm operators make logistical decisions that necessitate the efficient use of resources to maximize wind turbine availability. Due to multiple constraints such as weather, type of failure, and available vessels and technicians, deciding which turbines to maintain, the order in which to access them, and the route of the vessel is difficult. Poor maintenance operations planning on large vessels such as Service Operation Vessels (SOVs) and Crew Transfer Vessels (CTVs) can result in high fuel consumption, increasing overall maintenance costs and, more importantly, contributing to the carbon footprint of offshore wind farms. As a result, planning the day-to-day operation and maintenance of offshore wind farms is a key but complex and difficult problem. To solve this problem, it is necessary to find the best route to maintain the turbines for the Service Operating Vessel (SOV) and Crew Transfer Vessel (CTV) to minimize the total cost. It apart from continuous technological development, how to reduce costs more effectively has become an important topic for the development of offshore wind power.

3.4 An optimal plan for O&M

The main goal for the case is to use them to find an optimal plan for O&M. It can be divided into Tactical Maintenance Planning and Strategic Maintenance Planning.

For Tactical Maintenance Planning should achieve the following goals:

- Transportation of technicians and spare parts from onshore port(s) or offshore station to individual wind turbines by vessels or helicopters to perform a set of maintenance tasks.
- For each route with a schedule should be designed to access a set of turbines including several types of technicians (electrical, mechanical, etc.) required by the vessel.
- The objective is to minimize maintenance costs including turbine downtime costs. Each maintenance task consists of delivery of personnel and a subsequent pickup.
- Each task may require several visits to complete.
- Tasks may be performed in parallel.

It can be considered into two types, One-period planning, and multi-period planning. (Figure 23)

For the One-period planning:

- Daily Routing planning.
- Vessels return to base at the end of the day.

And for Multi-period planning:

- Multi-day planning
- Vessels can return or stay offshore for several days.

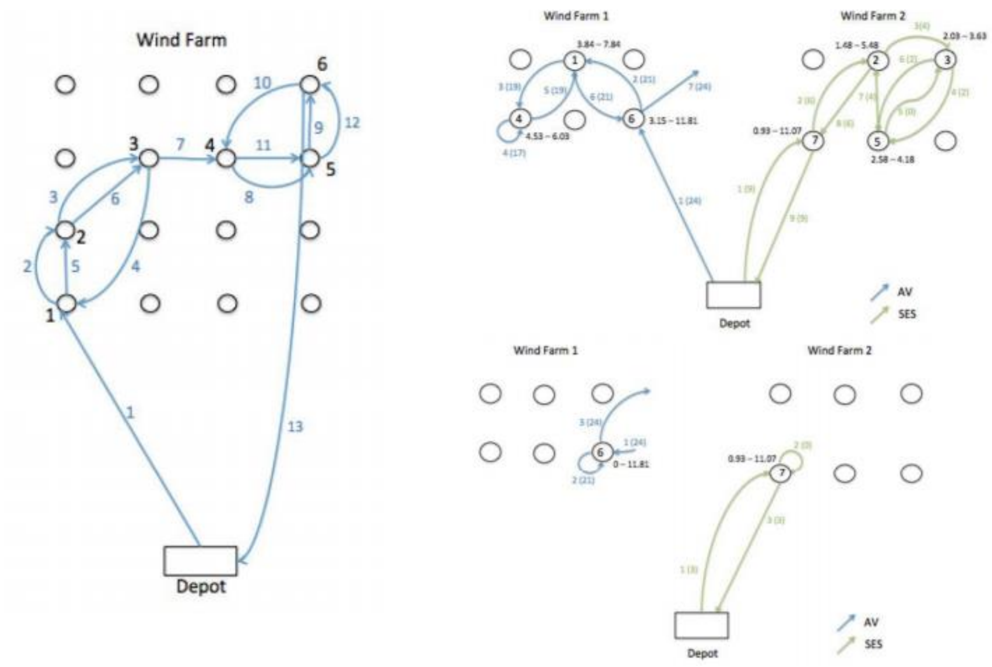


Figure 23 - One-period planning vs multi-period planning

For Strategical planning one should consider

- ➢ Annual or longer time horizon.
- ➢ Fleet size and mix.
- ➢ Other strategic decisions to be considered.
- ➢ Analyses to conduct, for example:
  - How does the distance from shore influence the fleet choices?
  - How does vessel capabilities (wave height compatibility) influence the downtime costs.
  - How to plan preventive maintenance. (Figure 24)

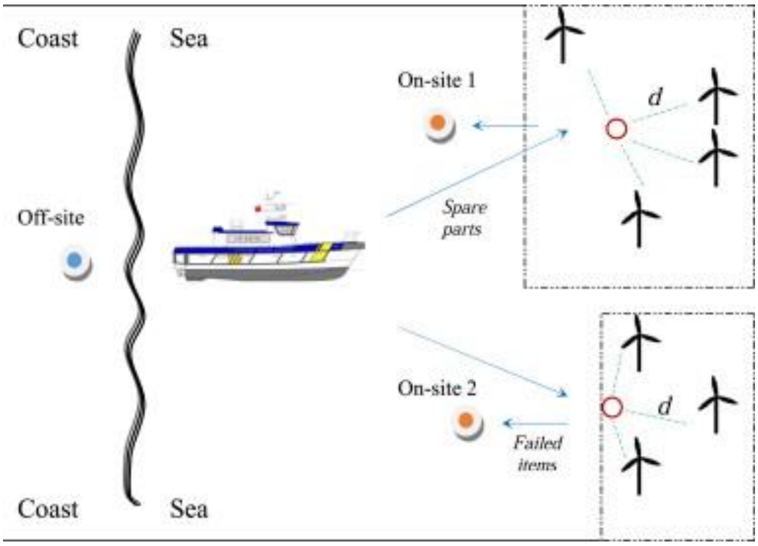


Figure 24 - An organization of maintenance accommodations for OWF.

(Source: https://ars.els-cdn.com/content/image/1-s2.0-S0960148114007605-gr4.jpg)

4.0 Methods

First, we set up a research project on improving the short-term scheduling of wind farm maintenance ships. We analyze a maintenance cycle of 12 days, using one SOV and two CTVs as maintenance ships, and define a mathematical model to solve with AMPL for finding the best sailing route for daily maintenance ships.

The overall case is divided into three tasks:

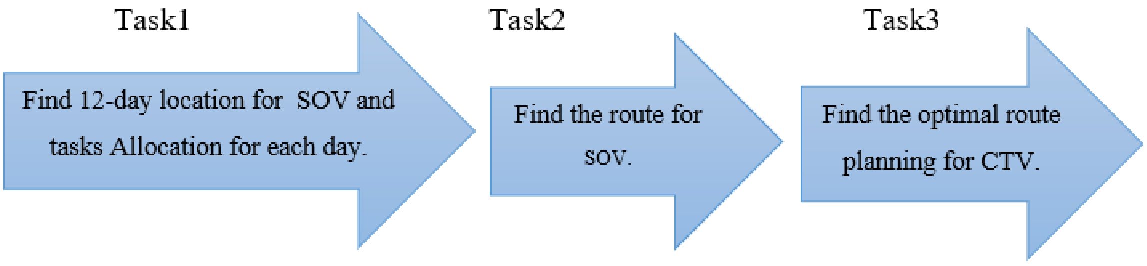


Figure 25 - Solution Approach

In task 1, we will use the wind farm location data, assuming the working cycle and working time and obtaining a 12-day location of the SOV through the model. This includes a grouping of the turbines that must be repaired each day (Allocation). Next, in task 2, based on the position data of the wind turbines, the model will find the optimal route for the 12-day stops for the SOV is obtained. Task 3 consists of finding the optimal routing for the CTVs by considering the tasks location, the number of people, and the working time of the operations defined for the single days obtained in the previous steps.

The following sections contain a further explanation of the three created models.

4.1 Location & Allocation

For Task 1, we aim to find a 12-day schedule for the SOV. The mathematical model is created based on the Location & Allocation Problem. (Manupatiet et al., 2021).

Sets and parameters:

P: *Set of turbines where there are tasks to be done and where it is possible for the ship to stay a day.*

w_j: *Time spent to performer task j*

a_{ij}: *The distance between two turbines*

max_a: *Maximum distance allowed between task and site*

n: *The number of chosen sites*

s: *Net available working time for each day in the ship*

Variables:

$$X_{ji} = \begin{cases} 1 \ \ if\ task\ j\ is\ served\ by\ site\ i, (i,j) \in P \\ 0\ otherwise \end{cases}$$

$$Y_i = \begin{cases} 1 \ \ if\ i\ is\ used\ as\ a\ site\ for\ the\ mother\ ship, i,j \in P \\ 0 \ \ otherwise \end{cases}$$

The objective function aims to minimize the total maintenance cost time, which includes the distance between two turbines spent to perform task j. The objective function is expressed as follows:

$$min \sum_{i \in P} \sum_{j \in P} a_{ij} w_j X_{ji} \qquad (1.1)$$

Constraints

$$Y_i \geq X_{ji} \qquad \forall (\ i,j) \in P \qquad (1.2)$$

$$\sum_{i \in P} Y_i = n \qquad \forall\ i \in P \qquad (1.3)$$

$$\sum_{i \in P} X_{ji} = 1 \qquad \forall\ (i,j) \in P \qquad (1.4)$$

$$\sum_{j \in P} w_j X_{ji} \leq s \qquad \forall\ (i,j) \in P \qquad (1.5)$$

$$a_{ij} X_{ji} \ \leq \max\_a \qquad \forall\ (i,j) \in P \qquad (1.6)$$

Constraint (1.2) makes sure that a task cannot be served by a site unless the site is established.

Constraint (1.3) ensures that the number of turbines to be located is fixed.

Constraint (1.4) ensures that a turbine can be assigned to only one location site.

Constraint (1.5) ensures that time spent on performer task j should be less or equal to the net available working time for each day on the ship.

Constraint (1.6) ensures that the distance between two turbines should be less than or equal to the maximum distance allowed between the task and the site.

4.2 TSP (MTZ: Miller-Tucker- Zemlin) with sub-cycle elimination

Task 2 is used to find the location for the SOV based on the solution of Task 1 by including the Miller-Tucker-Zemlin (MTZ) Campuzano et al. 2020) sub-cycle prohibiting constraints.

Sets and parameters:

A: *The set of arcs*

$cost_A$: $time\ spent\ to\ performer\ task\ j$

N: *The number of nodes*

Variables

$$X_{ji} = \begin{cases} 1 & if\ arc\ (i,j)\ is\ used, (i,j) \in N \\ 0 & otherwise \end{cases}$$

y_i: *where* y_i *are continuous variables interpreted as the number of units of load after visiting node i*

The objective function

$$min \sum_{(i,j)\in A} c_{ij}X_{ij} \qquad (2.1)$$

Constraints

$$\sum_{(i,j)\in A} x_{ij} = 1, \ \ \forall\, i \in N \qquad (2.2)$$

$$\sum_{(i,j)\in A} x_{ij} = 1\,, \ \forall\, j \in N \qquad (2.3)$$

$$x_{ij} \in \{0,1\}, \quad \forall\, (i,j) \in A \qquad (2.4)$$

$$y_j \geq \ y_i + 1 + (n-1)\big(x_{ij} - 1\big) \ \forall\, (i,j) \in N \qquad (2.5)$$

The objective function (2.1) expresses that we need minimize the total costs for all used edges.

Constraints (2.2) represent that in the solution out from every node i there must go exactly one arc.

Constraints (2.3) represent that there must go exactly one arc into each node.

Constraints (2.4) x_{ij} decision variables should be binary (1 if arc (i, j) is used, 0 otherwise).

Constraints (2.5) represent the connectivity requirements.

4.3 VRPPD (Vehicle Routing Problem with Pickups and Deliveries) and Time Windows

According to the last two tasks, we created the Task 3 by researching the route planning. The mathematical model to find the route to CTVs for each day.

Sets

K: The *set of vehicles k*

Parameters

n: number of customers i

m: number of vehicles k

$cost_A$: travel costs along the arc (i, j), $A \in ARCS$

d_i: demand to delivery passengers at i

p_i: demand to pick up passengers at i

Q_k: capacity of vehicles k

t_{ij}: time to travel form i to j + time to delivery (or pickup) the passengers at point j

et_i: time to performe (execute) the task i

M: big number.

Variables:

$x_{i,j,k}$: route variable i, j locations and k vehicle

$$y_{ik} = \begin{cases} 1 & \text{if the vehicle } k \text{ performs delivery at } i, \; i \in 1..2n, k \in K \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ik} = \begin{cases} 1 & \text{if the vehicle } k \text{ performs pick up at } i, \; i \in 1..2n, k \in K \\ 0 & \text{otherwise} \end{cases}$$

$$w_{ik} = \begin{cases} 1 & \text{if the vehicle } k \text{ performs pick up or delivery at } i, \; i \in 1..2n, k \in K \\ 0 & \text{otherwise} \end{cases}$$

r_{ik}: integer, sequence of visit of vehicle k at i

v_{ik}: delivery load of vehicle k, in poin i

u_{ik}: pickup load of vehicle k, in point i

s_{ik}: the time when vehicle k starts to service turbine i.

sd_i: the time when the delivery service in turbine i starts.

sp_i: the time when the pick-up service in turbine i starts.

The objective function

$$min \sum_{k \in K} \sum_{i=0}^{2n} \sum_{j=0}^{2n} cost_{ij} \, x_{ijk} \qquad (3.1)$$

Constraints

$$\sum_{j=1}^{2n} x_{0jk} = 1, \forall\, k \in K \tag{3.2}$$

$$\sum_{j=0}^{2n} x_{ijk} = \sum_{j=0}^{2n} x_{jik}\,, \forall\, i \in 0..2n; k \in K \tag{3.3}$$

$$\sum_{k\in K} \sum_{j=0}^{2n\,[j<>i]} x_{ijk} = 1, \forall\, i \in 1..2n \tag{3.4}$$

$$\sum_{j=0}^{2n\,[j<>i]} x_{ijk} \geq y_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \tag{3.5}$$

$$\sum_{j=0}^{2n\,[j<>i]} x_{ijk} \geq z_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \tag{3.6}$$

$$u_{0k} = 0, \forall\, k \in K \tag{3.7}$$

$$u_{jk} \geq u_{ik} + p_j z_{jk} - \left(1 - x_{ijk}\right) * Q_k \;\; , \forall\, i \in 0..2n;\;\; j \in 1..2n;\; k \in K \tag{3.8}$$

$$u_{jk} \leq u_{ik} + p_j z_{jk} + \left(1 - x_{ijk}\right) * Q_k \;\; , \forall\, i \in 0..2n;\;\; j \in 1..2n;\; k \in K \tag{3.9}$$

$$v_{0k} = \sum_{i=1}^{n} d_i y_{ik} \quad , \forall\, k \in K \tag{3.10}$$

$$v_{jk} \geq v_{ik} - d_j y_{jk} - \left(1 - x_{ijk}\right) * Q_k \;\; , \forall\, i \in 0..2n;\; j \in 1..2n;\; k \in K \tag{3.11}$$

$$v_{jk} \leq v_{ik} - d_j y_{ik} + \left(1 - x_{ijk}\right) * Q_k \;\; , \forall\, i \in 0..2n;\; j \in 1..2n;\; k \in K \tag{3.12}$$

$$0 \leq u_{ik} + v_{ik} \leq Q_k \;\; , \forall\, i \in 0..2n; k \in K \tag{3.13}$$

$$x_{ijk} \leq y_{ik} + z_{ik} \;\; , \forall\, i \in 1..2n;\;\; j \in 0..2n;\; k \in K \tag{3.14}$$

$$s_{ik} + t_{ij} - M\left(1 - x_{ijk}\right) \leq s_{jk} \;\; , \forall\, i \in 1..2n;\;\; \forall j \in 0..2n;\; k \in K \tag{3.15}$$

$$t_{0j} - M\left(1 - x_{0jk}\right) \leq s_{jk} \;\; , \;\forall j \in 1..2n;\; k \in K \tag{3.16}$$

$$sd_i \geq s_{ik} - M(1 - y_{ik}), \forall\, i \in 1..2n;\; k \in K \tag{3.17}$$

$$sd_i \leq s_{ik} + M(1 - y_{ik}), \forall\, i \in 1..2n;\; k \in K \tag{3.18}$$

$$sd_i + et_i \leq sp_{i+n}, \forall\, i \in 1..n \tag{3.19}$$

$$sp_i \geq s_{ik} - M(1 - z_{ik}), \forall\, i \in 1..2n;\; k \in K \tag{3.20}$$

$$sp_i \leq s_{ik} + M(1 - z_{ik}), \forall\, i \in 1..2n;\; k \in K \tag{3.21}$$

$$w_{ik} \geq z_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \tag{3.22}$$

$$w_{ik} \geq y_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \tag{3.23}$$

$$w_{ik} \leq y_{ik} + z_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \tag{3.24}$$

$$r_{jk} \geq r_{ik} + 1 + 2 * n * (x_{ijk} - 1) \;, \forall\, i \in 1..2n;\; j \in 1..2n; i \neq j;\; k \in K \qquad (3.25)$$

$$r_{ik} \leq M * w_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \qquad (3.26)$$

$$r_{ik} \geq w_{ik}, \forall\, i \in 1..2n, \forall\, k \in K \qquad (3.27)$$

$$sp_i \leq M/2, \forall\, i \in 1..2n;\; k \in K \qquad (3.28)$$

$$sd_i \leq M/2, \forall\, i \in 1..2n;\; k \in K \qquad (3.29)$$

$$\sum_{k\in K} y_{ik} * M \geq d_i, \forall\, i \in 1..2n \qquad (3.30)$$

$$\sum_{k\in K} y_{ik} \leq d_i, \forall\, i \in 1..2n \qquad (3.31)$$

$$\sum_{k\in K} z_{ik} * M \geq p_i, \forall\, i \in 1..2n \qquad (3.32)$$

$$\sum_{k\in K} z_{ik} \leq p_i, \forall\, i \in 1..2n \qquad (3.33)$$

The objective function (1) expresses that we should minimize the total costs for distance of pickups and deliveries.

Constraints (3.2) represent that each vehicle should leave the depot.

Constraint (3.3) ensures that the number of vehicles leaving and returning to the depot is equal.

Constraints (3.4) represent the connection of outgoing and incoming arcs in a location.

Constraints (3.5 & 3.6) states that the number of passengers on the CTV should be more or equal to the number of deliver or pick up.

Constraints (3.7) represent the initial cargo pick up.

Constraints (3.8 & 3.9) represent that the control the cargo between pick up load of vehicle and pick up of point.

Constraint (3.10) represents Initial cargo to delivery.

Constraint (3.11 & 3.12) represent that the control the cargo to delivery between delivery load of vehicle and delivery of point.

Constraint (3.13) represents that cargo to delivery and pick up should not more than vehicles capacity.

Constraint (3.14) if the CTV travel by x_{ijk} (x_{ij} =1), so pick up or deliver in i.

Constraint (3.15) represents that the visit time when vehicle k starts to service turbine i and the time which to travel form i to j and to deliver the passengers at point j should be less or equal to the time when vehicle k starts to service turbine j.

Constraint (3.16) represents that the visit time when vehicle k travel form starts point should be less or equal to the time when vehicle k starts to service turbine j.

Constraint (3.17) represents that the delivery time when vehicle k delivers the passengers to point i should be more or equal to the time when vehicle k starts to service turbine j if the vehicle k performs delivery at i.

Constraint (3.18) represents that the delivery time when vehicle k delivers the passengers to point i should be less or equal to the time when vehicle k starts to service turbine j if the vehicle k performs delivery at i.

Constraint (3.19) represents that time pick up time after finish service should be more or equal to the time when the delivery service in turbine i starts.

Constraint (3.20) represents that the pickup time when vehicle k picks up the passengers to point i should be more or equal to the time when vehicle k starts to service turbine j if the vehicle k performs pick up at i.

Constraint (3.21) represents that the pickup time when vehicle k picks up the passengers to point i should be less or equal to the time when vehicle k starts to service turbine j if the vehicle k performs pickup at i.

Constraint (3.22) represents that if the vehicle k has pick up, then w_{ik} will be 1.

Constraint (3.23) represents that if the vehicle k has delivered, then w_{ik} will be 1.

Constraint (3.24) represents that if the vehicle k does not have delivered or pick up, then w_{ik} will be 0.

Constraint (3.25) represents that if x_{ij} is equal to 1, $r_i$is smaller than r_j.

Constraint (3.26) represents that if w_i is 0, r_i is 0.

Constraint (3.27) represents that if w_i is 1, r_i is not 0.

Constraint (3.28 & 3.29) represents that the limit time when the delivery or pickup service in turbine i starts.

Constraints (3.30) represent that if a demand for delivery exists at turbine i, then at least one vehicle needs to visit the turbine.

Constraints (3.31) represent that no vehicle should visit a turbine for delivery unless it is a demand for delivering passengers at the turbine.

Constraints (3.32) represent that if a demand for pickup exists at turbine i, then at least one vehicle needs to visit the turbine.

Constraints (3.33) represent that no vehicle should visit a turbine for pickup unless it is a demand for picking up passengers at the turbine.

5.0 Case description

Based on the mathematical models shown above, we have tested their feasibility to find a short-term scheduling of support vessels in wind farm maintenance for the Doggerbank A's case.

5.1 Doggerbank

Dogger Bank is a sandbar in the middle of the southern North Sea that straddles the waters of the United Kingdom, Germany, Denmark, and the Netherlands. Studies and evidence of human activity, vegetation, and mammal remain indicate that the region was once the land bridge connecting the United Kingdom and continental Europe. This area is known as Doggerland. The Dogger Bank offshore development is located between 125 and 290 kilometers off the east coast of Yorkshire and encompasses an area of roughly 8,660 square kilometers with ocean depths ranging from 18 to 63 meters. (Figure 26) SSE Renewables, Equinor, and Vårgrønn collaborated on the first three phases of the Dogger Bank wind farm (known as Dogger Bank A, B, and C). The project, which will be located more than 130 kilometers off the coast of Yorkshire, will provide enough renewable energy to power 6 million UK households. Onshore work began in 2020 and is still ongoing, while offshore building at Dogger Bank A began in April 2022. Dogger Bank A and B are expected to be operational for the first time in the summers of 2023 and 2024, respectively.

Figure 26 - The Dogger Bank Location map. Source: Dogger Bank 2023

- Dogger Bank A

  The Dogger Bank wind farm's first phase is about 131 kilometers from the nearest point of the coast, with a development area of around 515 square kilometers. Its installed capacity will be 1.2 GW when completed. The distance between the two extremes is 38 kilometers, which comprises 100 turbines. (Figure 27)

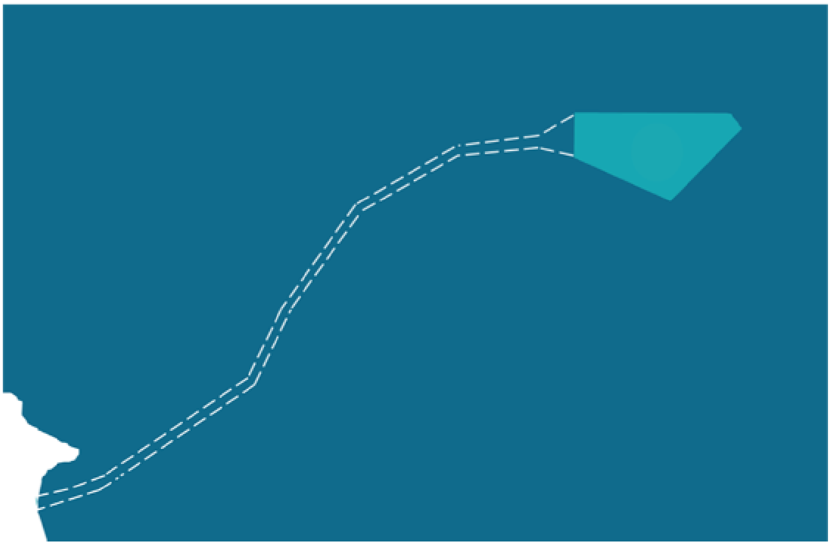


Figure 27 - The Dogger Bank A Location map. Source: Dogger Bank 2023

- Dogger Bank B

  The greatest of these projects, with a total development area of around 599 square kilometers, is located approximately 131 kilometers from the nearest coast. Dogger Bank B will also have 1.2 GW of installed capacity. (Figure 28)

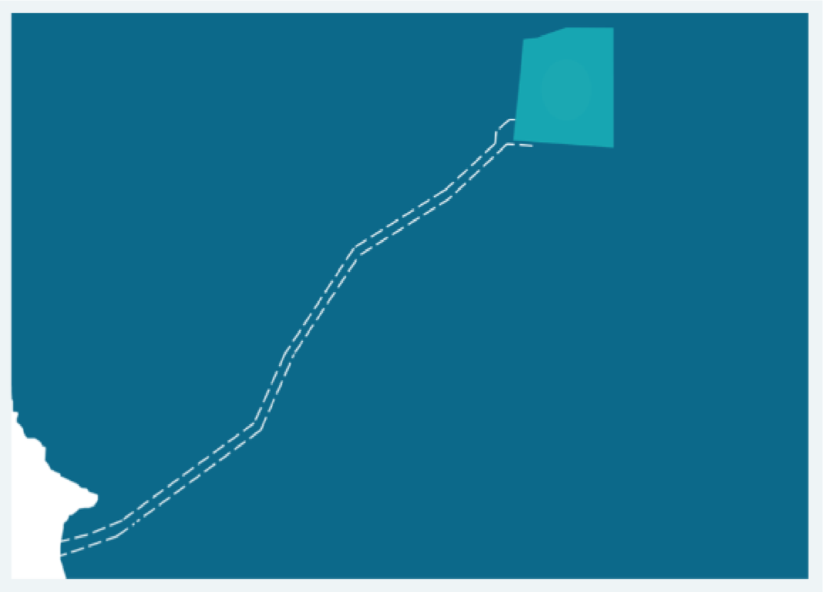


Figure 28 - The Dogger Bank B Location map. Source: Dogger Bank 2023

- Dogger Bank C

  It will also contain 1.2GW of installed capacity and will cover 560 square kilometers, 196 kilometers from the coast. The link will be built to Teesside's existing Rakenby substation. (Figure 29)

Figure 29 - The Dogger Bank C Location map. Source: Dogger Bank 2023

5.2 Data

To evaluate our model, several data were used to build the models. Some data is real, some are realistic data based on different real operations.

5.2.1 Common data for 3 models

We are using the real field location, and the real number of turbine. The Average distance between two turbines is 1300 m, and we used this distance to generate a realistic turbine position (uniform distribution) at Dogger Bank A (Table 1) as the common data, Task 1 used to find the location (12 days) for the SOV, Task 2 used it to calculate the minimal route for the SOV.

Turbine	Latitude	Longitude	Turbine	Latitude	Longitude
1	54.8075	1.7691667	51	54.749167	2.0958333
2	54.784167	2.09	52	54.690833	1.9966667
3	54.813333	2.1541667	53	54.7725	1.8041667
4	54.679167	1.9791667	54	54.731667	1.8216667
5	54.731667	1.8508333	55	54.819167	1.9791667
6	54.7025	1.8975	56	54.784167	2.0375

7	54.708333	2.0141667	57	54.8075	1.7983333
8	54.749167	1.95	58	54.825	2.1716667
9	54.714167	1.9908333	59	54.749167	1.9616667
10	54.661667	1.9675	60	54.778333	2.0083333
11	54.778333	1.9091667	61	54.7025	1.9791667
12	54.795833	1.74	62	54.79	2.0433333
13	54.778333	1.9966667	63	54.760833	1.9383333
14	54.813333	2.0958333	64	54.830833	2.0083333
15	54.7025	2.0025	65	54.714167	1.8333333
16	54.725833	2.055	66	54.825	2.1075
17	54.795833	2.0083333	67	54.79	1.8683333
18	54.766667	1.95	68	54.755	1.6816667
19	54.755	1.775	69	54.72	1.915
20	54.72	1.9208333	70	54.7725	1.7691667
21	54.801667	1.7575	71	54.731667	1.9966667
22	54.825	2.1833333	72	54.836667	2.1016667
23	54.778333	1.8216667	73	54.714167	2.0258333
24	54.708333	1.8216667	74	54.685	1.9675
25	54.8075	1.8275	75	54.755	1.6641667
26	54.760833	1.8158333	76	54.778333	2.0725
27	54.766667	2.0491667	77	54.825	2.0958333
28	54.7725	1.8975	78	54.778333	1.95
29	54.731667	1.8333333	79	54.760833	1.8975
30	54.749167	1.9266667	80	54.819167	1.74
31	54.708333	1.8916667	81	54.813333	2.0783333
32	54.784167	2.0375	82	54.795833	1.9383333
33	54.725833	1.7866667	83	54.801667	1.9733333
34	54.825	2.1658333	84	54.836667	2.125
35	54.708333	1.9266667	85	54.749167	2.055
36	54.766667	1.8275	86	54.7725	1.9383333
37	54.743333	1.7225	87	54.760833	1.9616667
38	54.819167	2.0725	88	54.801667	1.635
39	54.8075	1.7458333	89	54.725833	1.8975
40	54.743333	1.7166667	90	54.760833	2.0841667
41	54.795833	1.95	91	54.778333	2.0025
42	54.7375	1.9966667	92	54.813333	1.9325
43	54.708333	1.81	93	54.778333	1.9733333
44	54.685	1.9966667	94	54.760833	2.1366667
45	54.749167	1.8566667	95	54.7725	2.1191667
46	54.813333	1.6525	96	54.731667	2.0783333
47	54.743333	2.0316667	97	54.79	1.8566667
48	54.7375	1.74	98	54.7725	1.8683333
49	54.7725	1.775	99	54.795833	2.0375
50	54.7375	1.9733333	100	54.825	1.6466667

Table 1 - The location of turbines.

The locations for the turbines are shown in Figure 30:

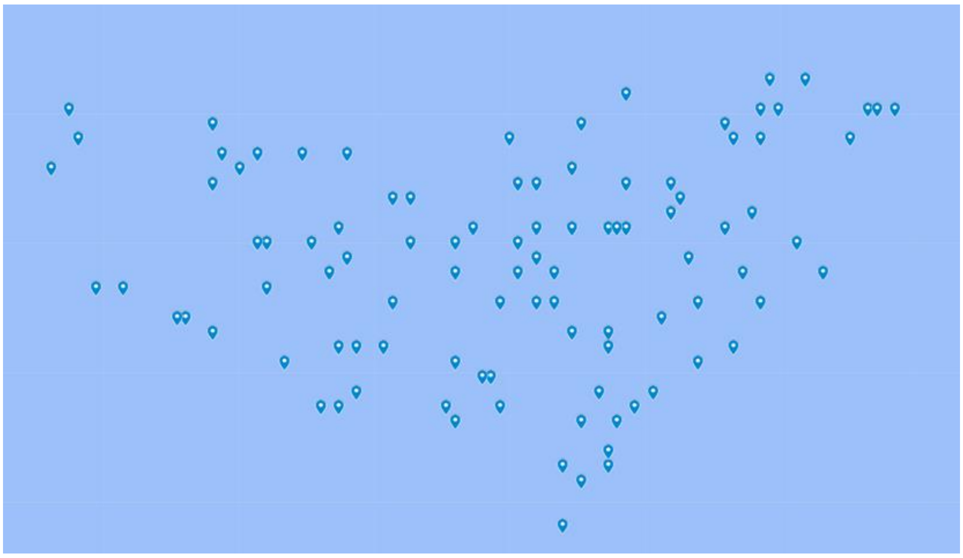


Figure 30 - The location of the turbines.

We also classify the maintenance work (Stålhane et al. 2021) into 5 situations and set relevant data according to different situations of operation. (Table 2)

Task	Type	Num Tech	Hours
a	Preventive	18	10
b	Reset	2	3
c	Minor	2	7.5
d	Major	12	8.666667
e	Medium	8	8.25

Table 2 -The maintenance work data.

In Table 2, the Num Tech means the number of technicians, and hours is the time to fix the problem. These data will be used in the tasks.

5.2.2 Data for model Task 1

We used the location data to calculate the distance between the individual turbines (Table 3) and used this as data to run the model, the data is to one scenario. (The '1' is the turbine which SOV need to stay; it is also the one need to be fixed)

Turbines	1	Turbines	1
Turbines	**Distance**	**Turbines**	**Distance**
1	0	26	7.53923073
2	0	27	16.4052583
3	9.16037663	28	6.9737006
4	8.65852181	29	3.15
5	10.3944697	30	17.5559107
6	10.8556437	31	5.47836655
7	8.46537064	32	7.98122798

8	18.9808456	33	8.26029661
9	10.8556437	34	2.82179021
10	6.11248722	35	15.962456
11	16.1038039	36	2.66552059
12	16.7305858	37	19.2627231
13	2.66552059	38	3.22684056
14	11.5711927	39	1.10679718
15	15.7188581	40	8.40728851
16	10.0224747	41	21.1047388
17	12.7401923	42	9.12688337
18	3.15	43	9.12688337
19	18.5334832	44	7.07831195
20	22.1856936	45	9.12688337
21	6.26099034	46	27.3201849
22	6.26099034	47	12.0686578
23	4.27229447	48	1.44308697
24	21.1858443	49	3.22684056
25	18.9129585	50	3.22684056

Table 3 - The distance between the individual turbines.

The time for each works also be used. (Table 4)

Turbines	Fix time	Turbines	Fix time
1	10	26	7.5
2	3	27	3
3	3	28	3
4	3	29	7.5
5	3	30	3
6	7.5	31	3
7	3	32	3
8	7.5	33	3
9	3	34	10
10	10	35	3
11	3	36	3
12	3	37	3
13	3	38	7.5
14	3	39	7.5
15	3	40	3
16	3	41	3
17	3	42	10
18	7.5	43	8.66666667
19	3	44	3
20	3	45	3
21	10	46	3
22	3	47	3
23	3	48	3
24	3	49	3
25	3	50	7.5

Table 4 - The time to be used for each works.

5.2.3 Data for model Task 2

In this task, we calculated the distance (Table 5) between the turbine and depot based on SOV schedule of Task 1 to run Task 2. (The table is the data of one scenario, the base is the depot.)

Turbines	Base
Base	0
2	212.818626
22	218.286876
32	209.673859
42	207.411324
50	206.015
62	210.003278
65	197.749127
72	213.361107
76	211.790757
82	203.693565
82	203.693565
19	194.070246

Table 5 -calculated the distance between the turbine and depot.

5.2.4 Data for model Task 3

In Task 3, we used the distance data from the Table 3, calculated the time data of SOV sailing from each turbine (Table 6), and found the corresponding data for each turbine in Table2 (Table 7):

Turbines	time
65	0
24	0.85652476
29	0.91
31	1.40349129
54	0.95238859
89	1.48262379
24	0.85652476
29	0.91
31	1.40349129
54	0.95238859
89	1.48262379

Table 6 -The time of SOV sailing from each turbine.

Task	Turbine	Point	Deliver	Pickup	Hours(et)
Depot	T65	0			
	T24	1	2		3
	T29	2	2		3
	T31	3	2		3
	T54	4	2		3
	T89	5	2		3
	T24	6		2	
	T29	7		2	
	T31	8		2	
	T54	9		2	
	T89	10		2	

Table 7 - The work time and number of passengers of for each turbine.

The Depot in Table 7 is the turbine which SOV need to stay, CTV will start from SOV to the turbines.

6.0 Results

For showing that the model is general, it was run with data from ten different scenarios. For each task, we will use the solution from one scenario to show the result for the next, i.e. the solution from Task 1 is used to run Task 2, which again gives the solution used for running Task 3.

6.1 Task 1

In this task, we will find the minimum of the total maintenance cost time including the distance between the turbines allocated to each place. The results when solving for the ten scenarios are shown in Table 8:

Task	Total cost	Total solving time (s)
S1	902.363	0.875
S2	79.6805	1.15625
S3	859.466	1.125
S4	574.261	1.46875
S5	646.601	0.484375
S6	949.303	1.3125
S7	796.926	0.6875
S8	847.928	0.921875
S9	1110.21	1.89062
S10	938.73	1.07812
Average	770.54685	1.099999

Table 8 -The total maintenance cost time includes the distance between the turbines allocated to each place.

The total cost is shown as the distance/hours traveled for maintenance between the turbines allocated to each place.

The total solving time is the time, in seconds, used for solving the AMPL model. The average is around 1.1 seconds, so it is speedy.

For one representative scenario, the solution found is shown in Table 9. The table shows the schedule for the SOV staying point for 12 days. For example, on day 1, the SOV will post at Turbine 2 point and fix the same turbine. On day 3, the SOV will post at Turbine 32 to fix turbines 27, 32, 47, 56, and 99. The green cells show which turbine the SOV should stay for operating a full day, while the blue cells show the position of the SOV when also serving other turbines the same day.

Task	Post	The turbines need to be fixed				
Day 1	T2	T2				
Day 2	T22	T22				
Day 3	T32	T27	T32	T47	T56	T99

Day 4	T42	T42									
Day 5	T50	T30	T42	T50	T4	T59	T61	T8	T10	T20	
Day 6	T62	T62									
Day 7	T65	T24	T29	T31	T54	T65	T89				
Day 8	T72	T58	T66	T72							
Day 9	T76	T2	T76	T90	T96						
Day 10	T82	T28	T55	T78	T82	T83	T86	T11	T18		
Day 11	T82	T82									
Day 12	T19	T23	T33	T37	T48	T49	T57	T70	T80	T88	T19

Table 9 - The schedule of the SOV staying point for 12 days and the turbines to be fixed.

The two maps in Figures 31 and 32 show the results more intuitively. Figure 31 shows the post of the turbines for each day, while Fig 32 shows the group of turbines to be fixed for the different days. While the SOV in Day 1 and Day 2 only will fix the same turbine as it is posted at, on Day 3, it is posted and fixing the issues at Turbine 32, and it also delivers a CTV to fix the Turbines 27, 47, 56 and 99.

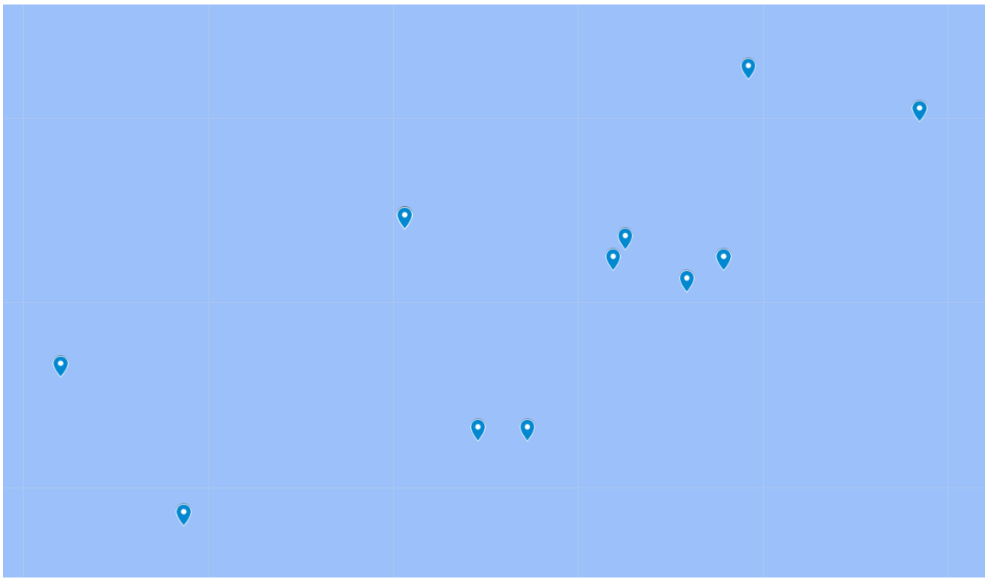


Figure 31 - The schedule of the SOV staying point for the 12 days.

Figure 32 -The turbines which need to be fixed for each day.

6.2 Task 2

Using the result shown in Table 9 to find the turbine's location where the SOV should stay and run with data from 10 scenarios in Task 2, we got the minimum total cost of all used edges for all the scenarios. The result is shown in Table 10 (including the model running time):

Task	Total cost (n mile)	Total solving time (s)
S1	429.619	16.1562
S2	441.8	13.9844
S3	439.268	4.78125
S4	438.259	2.42188
S5	436.8	3.70312
S6	435.64	10.7188
S7	433.752	67.0781
S8	432.417	2.375
S9	429.308	3.78125
S10	434.404	16.9062
Average	435.1267	14.19062

Table 10 - The minimum total cost of all used edges (including the model running time).

Table 10 shows the total time cost of all used edges for all the tasks, and the average time is 435.1267 n miles, and the time for solving the AMPL model is on average 14.19 seconds, which is acceptable.

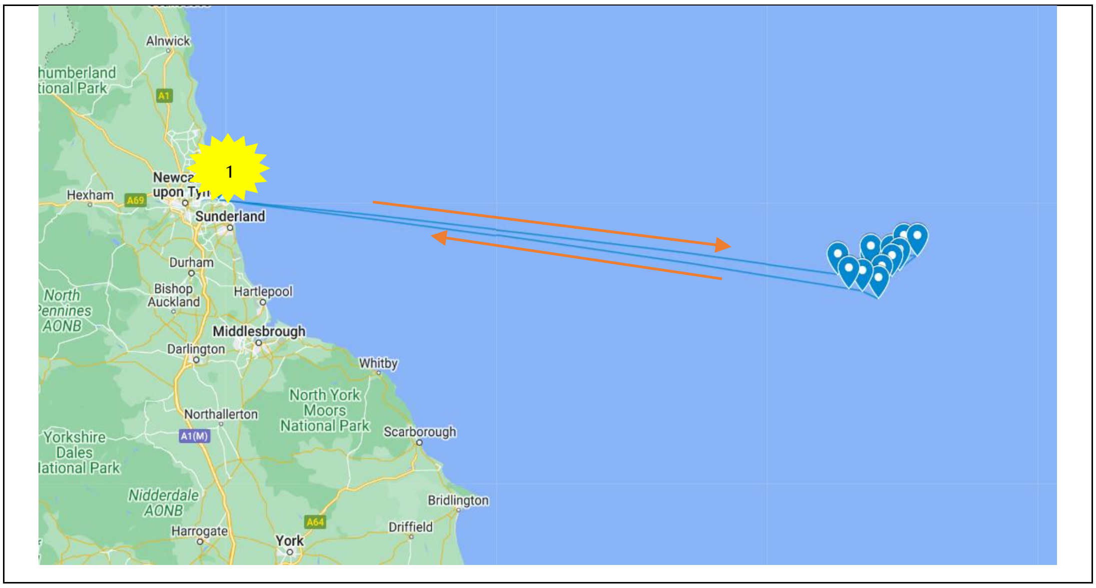
The solution from one of the scenarios is shown in Table 11. It shows the SOV loading points and route for the period of 12 days.

Day	Loading point
0	1
1	13
2	11
3	12
4	4
5	7
6	9
7	3
8	2
9	10
10	5
11	6
12	8
13	1

Table 11 - The SOV loading points and route for the period of 12 days.

Table 11 shows the routing of the SOV over a 12-day planning period. It starts at the depot in loading point 1 and visits point 13 on the first day. Then it continues to point 11 on the second day before visiting point 12 on the third day, and so on. The last visit at point 8 is performed on day 12, and after finishing all the maintenance work, the SOV returns to the depot at point 1.

This solution can be visualized in Figure 33, which shows the position related to the base in Teesside, UK, and the route details between the loading points.



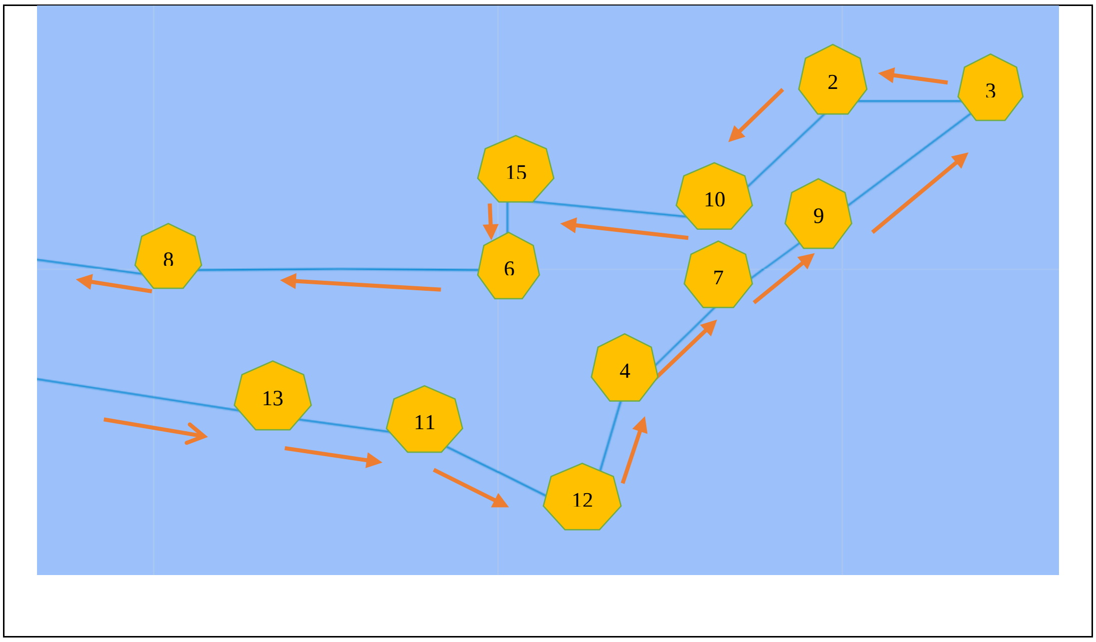


Figure 33 - The route of the SOV sailing during the 12 days.

6.3 Task 3

By using the location and route of SOV found in Task 2, we run Task 3 to determine the route of the CTVs for each day:

CTV	Route
K1	0-1-6-2-4-9-7-0
K2	0-3-8-5-10-0

Table 12 -The route of each CTV.

Table 12 shows the routing of the two CTVs. The five actual locations are each split into one delivery and one pickup location. To distinguish easily, we define turbines 1, 2, 3, 4, and 5 as the sending location, while 6, 7, 8, 9, and 10 are the corresponding pickup locations. The solution shows that the route for K1 is 0-1-6-2-4-9-7-0. This means that the vessel starts at node 0 and then visits Turbine 1 to deliver passengers before picking up passengers from Turbine 6, which is the same location. This means that the vessel has to wait at the node until the operations performed by the workers are completed. Next, it performs delivery at Turbine 2 before continuing to Node 4 for delivery and pickup at the same location (Turbine 9). On the way back, the vessel stops for pickup at Turbine 7, which previously was visited for delivery as Turbine 2. Hence, the actual route is 0-1-1-2-4-4-2-0. Looking at the K2 vessel, it performs delivery and pickup at the same visit, since Turbine 3 corresponds to 8 and Turbine 5 corresponds to 10, so the real route is 0-3-3-5-5-0.

We also got the number of passengers that deliver and pickup for each CTV (Table 13):

Point	Deliver	Pickup	Hours (et)
0			
1	2		3
2	2		3
3	2		3
4	2		3
5	2		3
1		2	
2		2	
3		2	
4		2	
5		2	

Table 13 - The number of Deliver, Pickup, and hours (et) of each CTV.

Table 13 shows we should deliver 2 passengers at Turbine 1, 2, 3, 4 and 5, and pick up the same number of passengers from the same turbines. This estimated time for the operations to perform is 3 hours for each of the locations.

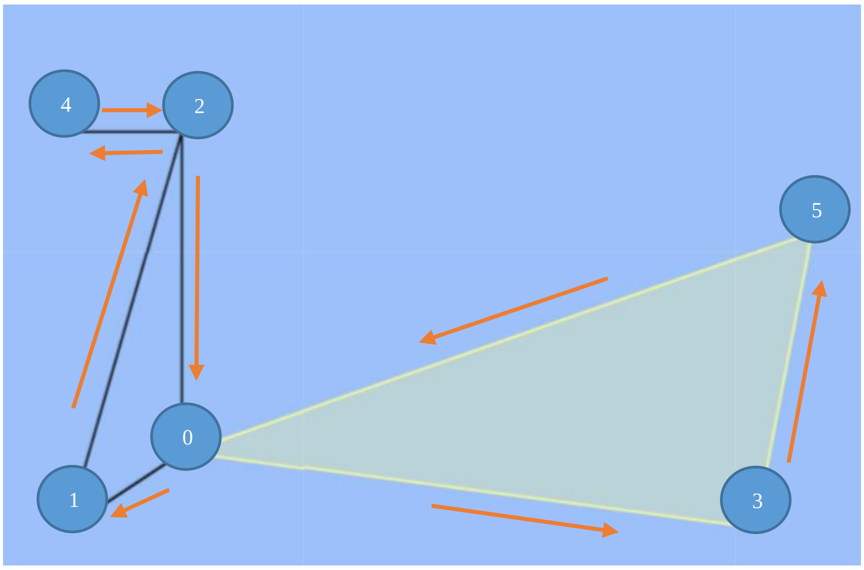


Figure 34 - The location and route of the CTV based on the position of the SOV.

Fig.34 shows the route presented in Table 12 graphically. Vessel K1 is starting from the SOV and delivering passengers (2) to Turbine 1 and then waiting for their work to be finished before picking them up from the same location. Then it continues to Turbine 2 for delivering passengers (2), continues to Turbine 4, waiting for the passengers (2) to finish their job and picking them up, going back to Turbine 2 for picking up passengers (2) left there on the previous visit, and return back to the SOV. For the vessel K2, it is also starting from the SOV, and then delivering passengers (2) to Turbine 3, waiting for them to finish the job and then picking them up, travelling to Turbine 5 for delivery, waiting and then picking them up, and returning to the SOV.

Task	Total cost (n miles)	Total solving time (s)	Number of Stops
S3	6.88682	0.28125	8 (4 turbines)
S5	24.9788	870.812	16 (8 turbines)
S7	13.3352	2.89062	10 (5 turbines)
S8	10.0811	0.0625	4 (2 turbines)
S9	8.08198	0.15625	6 (3 turbines)
S10	19.684	396.594	14 (7 turbines)
S12	With Out Result	Time Limit	18 (9 turbines)
Average	13.84	211.80	

Table 14 - The total costs for distance of pickups and deliveries of CTV.

Table 14 shows the distance for six scenarios with pickups and deliveries of CTVs, where the average cost in these scenarios is 13.84 n miles. And S1, S2, S4, S6, S11 are huge jobs, SOV will stay the whole day, so no CTV to be used.

The table also shows the solving time for the model, and here we can see a very high variation between the scenarios, where some are solved within less than a second (for the small instances), and it used up to 15 minutes for the instances with 16 stops. This is still within an acceptable solving time for such a model.

The S12 instance has 18 stops; it took more than 3 hours to run the model and did not find a result. To solve instances of this size or bigger future work will be done focusing on improving the model’s performance.

7.0 Conclusions

This thesis has presented a mathematical model for solving the problem of planning the maintenance of offshore windmill parts. It also analyzed related research problems through relevant literature research, and many data calculations were performed to test the model. After several tests, a satisfactory result was obtained on the test cases based on real-world data.

At the beginning of the thesis work, we introduced the background of the problem and explained the tasks needing to be done to formulate the research question. Next, we determined the direction for the research by studying many works of literature and existing models.

Then, based on the actual case, mathematical models were defined for solving the three stages of the actual problem, and several calculations were performed to test the models. After completing the analysis and research, the conclusion is that the model can be used for improving the short-term scheduling of service operation vessels as the base for the crew transfer vessels for performing maintenance operations on offshore wind farms.

Through Model 1, we find the minimum value of the total maintenance cost time, including the distance between the turbines assigned to each place. And found the 12-day stay of SOV and the schedule of turbines to be repaired. Then by Model II, we find the minimum total cost of all used edges for all scenarios and SOV loading points and routes for a period of 12 days. Finally, by running Model 3, the distances of the six cases in the CTV pickup and delivery scenarios, as well as the location of the CTV and the location of the SOV based on the route, are found.

7.1 Future works.

The content of this thesis is mainly based on a real case study inspired by the Dogger Bank wind farm. While this shows relevant information about the problem, there are still many tasks to be done in the future:

- The next step is to improve the model to solve task 3 to solve all size problems that exist in the real case.
- So modelling the application with real locations and real forecasted demand.
- After that, an integrated model could be developed by combining, for its solution, mathematical modeling and heuristics.

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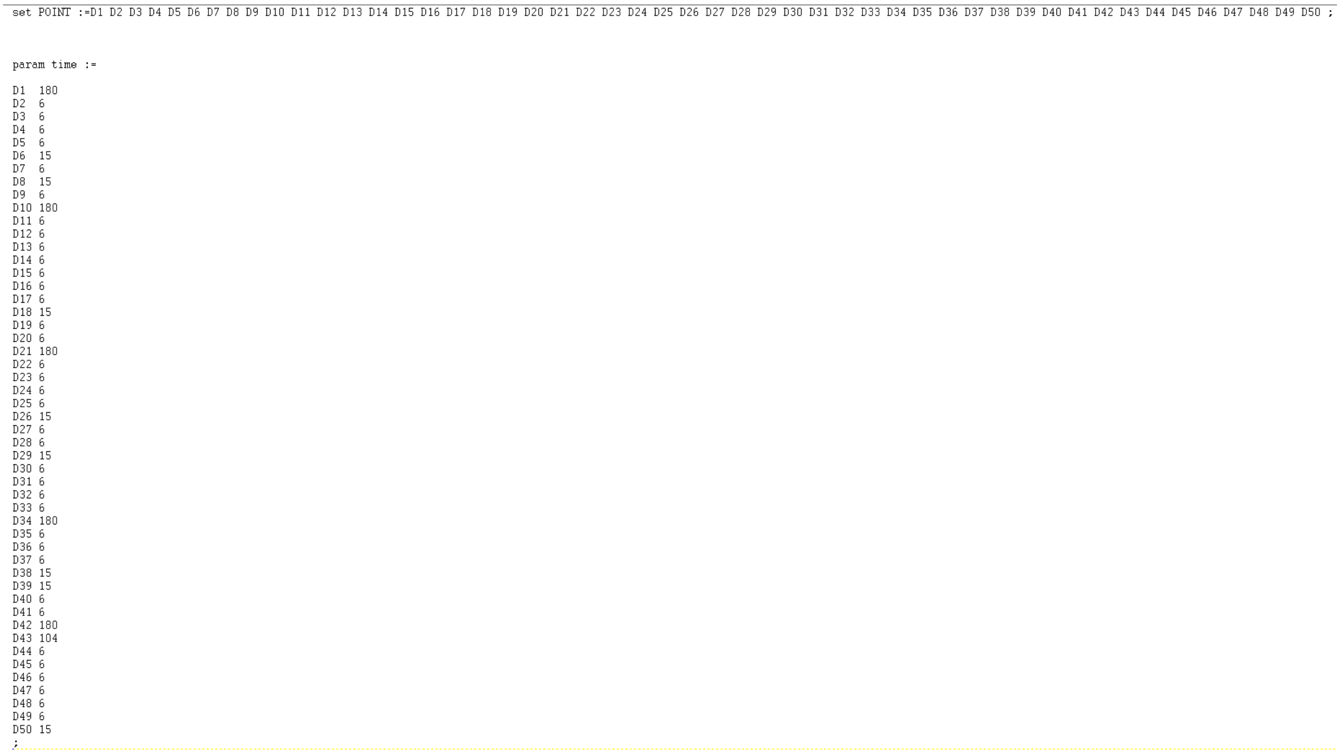
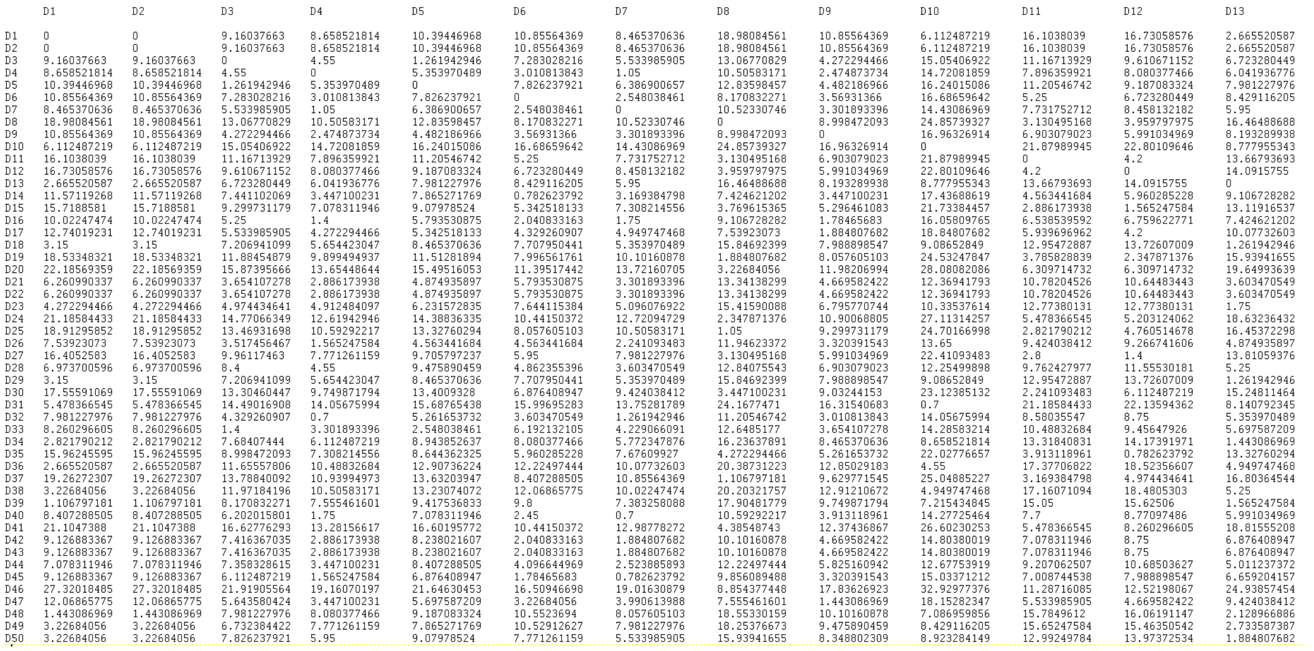
Appendix 1- Relevant data

1. data



```
set POINT :=D1 D2 D3 D4 D5 D6 D7 D8 D9 D10 D11 D12 D13 D14 D15 D16 D17 D18 D19 D20 D21 D22 D23 D24 D25 D26 D27 D28 D29 D30 D31 D32 D33 D34 D35 D36 D37 D38 D39 D40 D41 D42 D43 D44 D45 D46 D47 D48 D49 D50 ;


param time :=

D1  180
D2  6
D3  6
D4  6
D5  6
D6  15
D7  6
D8  15
D9  6
D10 180
D11 6
D12 6
D13 6
D14 6
D15 6
D16 6
D17 6
D18 15
D19 6
D20 6
D21 180
D22 6
D23 6
D24 6
D25 6
D26 15
D27 6
D28 6
D29 15
D30 6
D31 6
D32 6
D33 6
D34 180
D35 6
D36 6
D37 6
D38 15
D39 15
D40 6
D41 6
D42 180
D43 104
D44 6
D45 6
D46 6
D47 6
D48 6
D49 6
D50 15
;
```

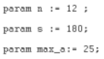


```
      D1           D2           D3           D4           D5           D6           D7           D8           D9           D10          D11          D12          D13

D1    0            0            9.16037663   8.658521814  10.39446968  10.85564369  8.465370636  18.98084561  10.85564369  6.112487219  16.1038039   16.73058576  2.665520587
D2    0            0            9.16037663   8.658521814  10.39446968  10.85564369  8.465370636  18.98084561  10.85564369  6.112487219  16.1038039   16.73058576  2.665520587
D3    9.16037663   9.16037663   0            4.55         1.261942946  7.283028216  5.533985905  13.06770829  4.272294466  15.05406922  11.16713929  9.610671152  6.723280449
D4    8.658521814  8.658521814  4.55         0            5.353970489  3.010813843  1.05         10.50583171  2.474873734  14.72081859  7.896359921  8.080377466  6.041936776
D5    10.39446968  10.39446968  1.261942946  5.353970489  0            7.826237921  6.386900657  12.83598457  4.482186966  16.24015086  11.20546742  9.187083324  7.981227976
D6    10.85564369  10.85564369  7.283028216  3.010813843  7.826237921  0            2.548038461  8.170832271  3.56931366   16.68659642  5.25         6.723280449  8.429116205
D7    8.465370636  8.465370636  5.533985905  1.05         6.386900657  2.548038461  0            10.52330746  3.301893396  14.43086969  7.731752712  8.458132182  5.95
D8    18.98084561  18.98084561  13.06770829  10.50583171  12.83598457  8.170832271  10.52330746  0            8.998472093  24.85739327  3.130495168  3.959797975  16.46488688
D9    10.85564369  10.85564369  4.272294466  2.474873734  4.482186966  3.56931366   3.301893396  8.998472093  0            16.96326914  6.903079023  5.991034969  8.193289938
D10   6.112487219  6.112487219  15.05406922  14.72081859  16.24015086  16.68659642  14.43086969  24.85739327  16.96326914  0            21.87989945  22.80109646  8.777955343
D11   16.1038039   16.1038039   11.16713929  7.896359921  11.20546742  5.25         7.731752712  3.130495168  6.903079023  21.87989945  0            4.2          13.66793693
D12   16.73058576  16.73058576  9.610671152  8.080377466  9.187083324  6.723280449  8.458132182  3.959797975  5.991034969  22.80109646  4.2          0            14.0915755
D13   2.665520587  2.665520587  6.723280449  6.041936776  7.981227976  8.429116205  5.95         16.46488688  8.193289938  8.777955343  13.66793693  14.0915755   0
D14   11.57119268  11.57119268  7.441102069  3.447100231  7.865271769  0.782623792  3.169384798  7.424621202  3.447100231  17.43688619  4.563441684  5.960285228  9.106728282
D15   15.7188581   15.7188581   9.299731179  7.078311946  9.07978524   5.342518133  7.308214556  3.769615365  5.296461083  21.73384457  2.886173938  1.565247584  13.11916537
D16   10.02247474  10.02247474  5.25         1.4          5.793530875  2.040833163  1.75         9.106728282  1.78465683   16.05809765  6.538539592  6.759622771  7.424621202
D17   12.74019231  12.74019231  5.533985905  4.272294466  5.342518133  4.329260907  4.949747468  7.53923073   1.884807682  18.84807682  5.939696962  4.2          10.07732603
D18   3.15         3.15         7.206941099  5.654423047  8.465370636  7.707950441  5.353970489  15.84692399  7.988898547  9.08652849   12.95472887  13.72607009  1.261942946
D19   18.53348321  18.53348321  11.88454879  9.899494937  11.51281894  7.996561761  10.10160878  1.884807682  8.057605103  24.53247847  3.785828839  2.347871376  15.93941655
D20   22.18569359  22.18569359  15.87395666  13.65448644  15.49516053  11.39517442  13.72160705  3.22684056   11.98206994  28.08082086  6.309714732  6.309714732  19.64993639
D21   6.260990337  6.260990337  3.654107278  2.886173938  4.874935897  5.793530875  3.301893396  13.34138299  4.669582422  12.36941793  10.78204526  10.64483443  3.603470549
D22   6.260990337  6.260990337  3.654107278  2.886173938  4.874935897  5.793530875  3.301893396  13.34138299  4.669582422  12.36941793  10.78204526  10.64483443  3.603470549
D23   4.272294466  4.272294466  4.974434641  4.912484097  6.231572835  7.644115384  5.096076922  15.41590088  6.795770744  10.33537614  12.77380131  12.77380131  1.75
D24   21.18584433  21.18584433  14.77066349  12.61942946  14.38836335  10.44150372  12.72094729  2.347871376  10.90068805  27.11314257  5.478366545  5.203124062  18.63236432
D25   18.91295852  18.91295852  13.46931698  10.59292217  13.32760294  8.057605103  10.50583171  1.05         9.299731179  24.70166998  2.821790212  4.760514678  16.45372298
D26   7.53923073   7.53923073   3.517456467  1.565247584  4.563441684  4.563441684  2.241093483  11.94623372  3.320391543  13.65        9.424038412  9.266741606  4.874935897
D27   16.4052583   16.4052583   9.96117463   7.771261159  9.705797237  5.95         7.981227976  3.130495168  5.991034969  22.41093483  2.8          1.4          13.81059376
D28   6.973700596  6.973700596  8.4          4.55         9.475890459  4.862355396  3.603470549  12.84075543  6.903079023  12.25499898  9.762427977  11.55530181  5.25
D29   3.15         3.15         7.206941099  5.654423047  8.465370636  7.707950441  5.353970489  15.84692399  7.988898547  9.08652849   12.95472887  13.72607009  1.261942946
D30   17.55591069  17.55591069  13.30460447  9.749871794  13.4009328   6.876408947  9.424038412  3.447100231  9.03244153   23.12385132  2.241093483  6.112487219  15.24811464
D31   5.478366545  5.478366545  14.49016908  14.05675994  15.68765438  15.99695283  13.75281789  24.1677471   16.31540683  0.7          21.18584433  22.13594362  8.140792345
D32   7.981227976  7.981227976  4.329260907  0.7          5.261653732  3.603470549  1.261942946  11.20546742  3.010813843  14.05675994  8.58035547   8.75         5.353970489
D33   8.260296605  8.260296605  1.4          3.301893396  2.548038461  6.192132105  4.229066091  12.6485177   3.654107278  14.28583214  10.48832684  9.45647926   5.697587209
D34   2.821790212  2.821790212  7.68407444   6.112487219  8.943852637  8.080377466  5.772347876  16.23637891  8.465370636  8.658521814  13.31840831  14.17391971  1.443086969
D35   15.96245595  15.96245595  8.998472093  7.308214556  8.644362325  5.960285228  7.67609927   4.272294466  5.261653732  22.02776657  3.913118961  0.782623792  13.32760294
D36   2.665520587  2.665520587  11.65557806  10.48832684  12.90736224  12.22497444  10.07732603  20.38731223  12.85029183  4.55         17.37706822  18.52356607  4.949747468
D37   19.26272307  19.26272307  13.78840092  10.93994973  13.63203947  8.407288505  10.85564369  1.106797181  9.629771545  25.04885227  3.169384798  4.974434641  16.80364544
D38   3.22684056   3.22684056   11.97184196  10.50583171  13.23074072  12.06865775  10.02247474  20.20321757  12.91210672  4.949747468  17.16071094  18.4805303   5.25
D39   1.106797181  1.106797181  8.170832271  7.555461601  9.417536833  9.8          7.383258088  17.90481779  9.749871794  7.215434845  15.05        15.62506     1.565247584
D40   8.407288505  8.407288505  6.202015801  1.75         7.078311946  2.45         0.7          10.59292217  3.913118961  14.27725464  7.7          8.77097486   5.991034969
D41   21.1047388   21.1047388   16.62776293  13.28156617  16.60195772  10.44150372  12.98778272  4.38548743   12.37436867  26.60230253  5.478366545  8.260296605  18.81555208
D42   9.126883367  9.126883367  7.416367035  2.886173938  8.238021607  2.040833163  1.884807682  10.10160878  4.669582422  14.80380019  7.078311946  8.75         6.876408947
D43   9.126883367  9.126883367  7.416367035  2.886173938  8.238021607  2.040833163  1.884807682  10.10160878  4.669582422  14.80380019  7.078311946  8.75         6.876408947
D44   7.078311946  7.078311946  7.358328615  3.447100231  8.407288505  4.096644969  2.523885893  12.22497444  5.825160942  12.67753919  9.207062507  10.68503627  5.011237372
D45   9.126883367  9.126883367  6.112487219  1.565247584  6.876408947  1.78465683   0.782623792  9.856089488  3.320391543  15.03371212  7.008744538  7.988898547  6.659204157
D46   27.32018485  27.32018485  21.91905564  19.16070197  21.64630453  16.50946698  19.01630879  8.854377448  17.83626923  32.92977376  11.28716085  12.52198067  24.93857454
D47   12.06865775  12.06865775  5.643580424  3.447100231  5.697587209  3.22684056   3.990613988  7.555461601  1.443086969  18.15282347  5.533985905  4.669582422  9.424038412
D48   1.443086969  1.443086969  7.981227976  8.080377466  9.187083324  10.5523694   8.057605103  18.55330159  10.10160878  7.086959856  15.7849612   16.06191147  2.128966886
D49   3.22684056   3.22684056   6.732384422  7.771261159  7.865271769  10.52912627  7.981227976  18.25376673  9.475890459  8.429116205  15.65247584  15.46350542  2.733587387
D50   3.22684056   3.22684056   7.826237921  5.95         9.07978524   7.771261159  5.533985905  15.93941655  8.348802309  8.923284149  12.99249784  13.97372534  1.884807682
```

D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	D26
11.57119268	15.7188581	10.02247474	12.74019231	3.15	18.53348321	22.18569359	6.260990337	6.260990337	4.272294466	21.18584433	18.91295852	7.53923073
11.57119268	15.7188581	10.02247474	12.74019231	3.15	18.53348321	22.18569359	6.260990337	6.260990337	4.272294466	21.18584433	18.91295852	7.53923073
7.441102069	9.299731179	5.25	5.533985905	7.206941099	11.88454879	15.87395666	3.654107278	3.654107278	4.974434641	14.77066349	13.46931698	3.517456467
3.447100231	7.078311946	1.4	4.272294466	5.654423047	9.899494937	13.65448644	2.886173938	2.886173938	4.912484097	12.61942946	10.59292217	1.565247584
7.865271769	9.07978524	5.793530875	5.342518133	8.465370636	11.51281894	15.49516053	4.874935897	4.874935897	6.231572835	14.38836335	13.32760294	4.563441684
0.782623792	5.342518133	2.040833163	4.329260907	7.707950441	7.996561761	11.39517442	5.793530875	5.793530875	7.644115384	10.44150372	8.057605103	4.563441684
3.169384798	7.308214556	1.75	4.949747468	5.353970489	10.10160878	13.72160705	3.301893396	3.301893396	5.096076922	12.72094729	10.50583171	2.241093483
7.424621202	3.769615365	9.106728282	7.53923073	15.84692399	1.884807682	3.22684056	13.34138299	13.34138299	15.41590088	2.347871376	1.05	11.94623372
3.447100231	5.296461083	1.78465683	1.884807682	7.988898547	8.057605103	11.98206994	4.669582422	4.669582422	6.795770744	10.90068805	9.299731179	3.320391543
17.43688619	21.73384457	16.05809765	18.84807682	9.08652849	24.53247847	28.08082086	12.36941793	12.36941793	10.33537614	27.11314257	24.70166998	13.65
4.563441684	2.886173938	6.538539592	5.939696962	12.95472887	3.785828839	6.309714732	10.78204526	10.78204526	12.77380131	5.478366545	2.821790212	9.424038412
5.960285228	1.565247584	6.759622771	4.2	13.72607009	2.347871376	6.309714732	10.64483443	10.64483443	12.77380131	5.203124062	4.760514678	9.266741606
9.106728282	13.11916537	7.424621202	10.07732603	1.261942946	15.93941655	19.64993639	3.603470549	3.603470549	1.75	18.63236432	16.45372298	4.874935897
0	4.563441684	2.241093483	3.865876356	8.429116205	7.215434845	10.64483443	6.309714732	6.309714732	8.238021607	9.68052168	7.35	5.011237372
4.563441684	0	5.697587209	3.769615365	12.6485177	2.821790212	6.686740611	9.806248008	9.806248008	11.92057046	5.61092684	4.272294466	8.407288505
2.241093483	5.697587209	0	3.22684056	6.973700596	8.515867542	12.25499898	4.257933771	4.257933771	6.309714732	11.22185368	9.207062507	2.886173938
3.865876356	3.769615365	3.22684056	0	9.862301963	6.386900657	10.36496503	6.538539592	6.538539592	8.658521814	9.266741606	7.988898547	5.203124062
8.429116205	12.6485177	6.973700596	9.862301963	0	15.45161804	19.05813475	3.720551034	3.720551034	2.474873734	18.0682733	15.76554788	4.760514678
7.215434845	2.821790212	8.515867542	6.386900657	15.45161804	0	3.990613988	12.61942946	12.61942946	14.73745229	2.886173938	2.886173938	11.22185368
10.64483443	6.686740611	12.25499898	10.36496503	19.05813475	3.990613988	0	16.45372298	16.45372298	18.55	1.106797181	3.603470549	15.05406922
6.309714732	9.806248008	4.257933771	6.538539592	3.720551034	12.61942946	16.45372298	0	0	2.128966886	15.4	13.46476884	1.4
6.309714732	9.806248008	4.257933771	6.538539592	3.720551034	12.61942946	16.45372298	0	0	2.128966886	15.4	13.46476884	1.4
8.238021607	11.92057046	6.309714732	8.658521814	2.474873734	14.73745229	18.55	2.128966886	2.128966886	0	17.50349965	15.49911288	3.517456467
9.68052168	5.61092684	11.22185368	9.266741606	18.0682733	2.886173938	1.106797181	15.4	15.4	17.50349965	0	2.969848481	14
7.35	4.272294466	9.207062507	7.988898547	15.76554788	2.886173938	3.603470549	13.46476884	13.46476884	15.49911288	2.969848481	0	12.08387355
5.011237372	8.407288505	2.886173938	5.203124062	4.760514678	11.22185368	15.05406922	1.4	1.4	3.517456467	14	12.08387355	0
5.167688071	0.7	6.386900657	4.427188724	13.32760294	2.128966886	5.991034969	10.50583171	10.50583171	12.61942946	4.912484097	3.720551034	9.106728282
5.643580424	10.20416582	5.25	8.472602906	4.081666326	12.83598457	16.05809765	5.011237372	5.011237372	5.533985905	15.16352532	12.56592615	4.912484097
8.429116205	12.6485177	6.973700596	9.862301963	0	15.45161804	19.05813475	3.720551034	3.720551034	2.474873734	18.0682733	15.76554788	4.760514678
6.309714732	5.011237372	8.458132182	8.170832271	14.41813095	4.949747468	5.960285228	12.61942946	12.61942946	14.51972796	5.467174773	2.523885893	11.30884609
16.74888056	21.05825254	15.38806356	18.2	8.414570696	23.8539829	27.39183272	11.73935688	11.73935688	9.724710793	26.42673835	24.0075509	13.00663292
4.096644969	7.771261159	2.1	4.862355396	5.011237372	10.59292217	14.35426766	2.213594362	2.213594362	4.214558103	13.31840831	11.28716085	0.989949494
6.45368112	8.923284149	4.214558103	5.261653732	6.021627687	11.6345391	15.59366859	2.347871376	2.347871376	3.990613988	14.50284455	12.95	2.128966886
8.812774818	13.07707918	7.416367035	10.33537614	0.494974747	15.87395666	19.45257052	4.214558103	4.214558103	2.886173938	18.47058472	16.1342028	5.25
5.203124062	1.05	5.980802622	3.517456467	12.95	2.886173938	6.876408947	9.899494937	9.899494937	12.02798819	5.772347876	4.949747468	8.515867542
12.98778272	17.37706822	11.76541542	14.72081859	4.862355396	20.14857315	23.61397891	8.472602906	8.472602906	6.686740611	22.6663848	20.19715326	9.610671152
7.7	4.563441684	9.553140845	8.297288714	16.11521021	2.990401311	3.301893396	13.81059376	13.81059376	15.84692399	2.733587387	0.35	12.42869663
12.84075543	17.28872465	11.73935688	14.76651618	4.974434641	20.03578049	23.42909516	8.665592882	8.665592882	7	22.50094442	19.9745463	9.731007142
10.50583171	14.620619	8.923284149	11.6345391	2.128966886	17.43688619	21.1047388	5.167688071	5.167688071	3.22684056	20.09987562	17.85343104	6.434671709
3.169384798	7.53923073	2.241093483	5.467174773	5.261653732	10.29380882	13.81059376	3.720551034	3.720551034	5.331041174	12.83598457	10.50583171	2.821790212
9.856089488	7.67609927	11.96160524	11.27086953	17.97310491	6.260990337	4.669582422	16.16075493	16.16075493	18.08182789	4.9	3.5	14.83273407
2.821790212	7.383258088	2.886173938	5.95	5.991034969	10.02247474	13.32760294	4.949747468	4.949747468	6.425145913	12.4040316	9.899494937	4.081666326
2.821790212	7.383258088	2.886173938	5.95	5.991034969	10.02247474	13.32760294	4.949747468	4.949747468	6.425145913	12.4040316	9.899494937	4.081666326
4.874935897	9.391485505	4.214558103	7.441102069	3.990613988	12.08894123	15.45161804	4.096644969	4.096644969	4.949747468	14.51972796	12.02798819	3.85
2.45	6.759622771	1.565247584	4.760514678	5.991034969	9.521029356	13.06770829	4.081666326	4.081666326	5.867069115	12.08387355	9.8	2.969848481
15.84692399	12.61942946	17.78124011	16.38657988	24.17281531	10.1741093	6.309714732	22.03888609	22.03888609	24.05597639	7.383258088	8.58035547	20.661861
2.8	3.865876356	2.241093483	1.106797181	9.1	6.65	10.5523694	5.991034969	5.991034969	8.118189453	9.475890459	7.865271769	4.603531253
11.22185368	15.15140258	9.475890459	11.97184196	3.130495168	17.97310491	21.72538837	5.433461144	5.433461144	3.320391543	20.69740322	18.56320285	6.795770744
11.12317401	14.7	9.16037663	11.28716085	3.990613988	17.50349965	21.36147233	4.912484097	4.912484097	2.886173938	20.30301702	18.36416347	6.309714732
8.515867542	12.84075543	7.215434845	10.20416582	0.7	15.62506	19.16070197	4.272294466	4.272294466	3.169384798	18.18990104	15.8120998	5.203124062

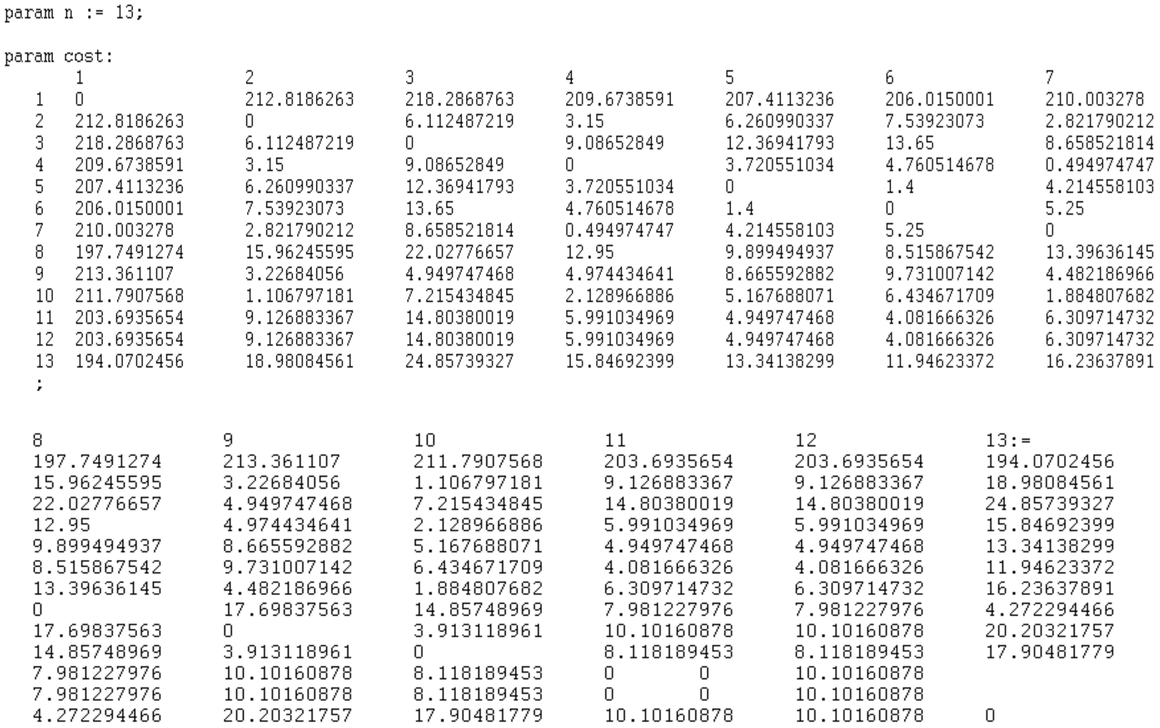
D27	D28	D29	D30	D31	D32	D33	D34	D35	D36	D37	D38	D39
16.4052583	6.973700596	3.15	17.55591069	5.478366545	7.981227976	8.260296605	2.821790212	15.96245595	2.665520587	19.26272307	3.22684056	1.106797181
16.4052583	6.973700596	3.15	17.55591069	5.478366545	7.981227976	8.260296605	2.821790212	15.96245595	2.665520587	19.26272307	3.22684056	1.106797181
9.96117463	8.4	7.206941099	13.30460447	14.49016908	4.329260907	1.4	7.68407444	8.998472093	11.65557806	13.78840092	11.97184196	8.170832271
7.771261159	4.55	5.654423047	9.749871794	14.05675994	0.7	3.301893396	6.112487219	7.308214556	10.48832684	10.93994973	10.50583171	7.555461601
9.705797237	9.475890459	8.465370636	13.4009328	15.68765438	5.261653732	2.548038461	8.943852637	8.644362325	12.90736224	13.63203947	13.23074072	9.417536833
5.95	4.862355396	7.707950441	6.876408947	15.99695283	3.603470549	6.192132105	8.080377466	5.960285228	12.22497444	8.407288505	12.06865775	9.8
7.981227976	3.603470549	5.353970489	9.424038412	13.75281789	1.261942946	4.229066091	5.772347876	7.67609927	10.07732603	10.85564369	10.02247474	7.383258088
3.130495168	12.84075543	15.84692399	3.447100231	24.1677471	11.20546742	12.6485177	16.23637891	4.272294466	20.38731223	1.106797181	20.20321757	17.90481779
5.991034969	6.903079023	7.988898547	9.03244153	16.31540683	3.010813843	3.654107278	8.465370636	5.261653732	12.85029183	9.629771545	12.91210672	9.749871794
22.41093483	12.25499898	9.08652849	23.12385132	0.7	14.05675994	14.28583214	8.658521814	22.02776657	4.55	25.04885227	4.949747468	7.215434845
2.8	9.762427977	12.95472887	2.241093483	21.18584433	8.58035547	10.48832684	13.31840831	3.913118961	17.37706822	3.169384798	17.16071094	15.05
1.4	11.55530181	13.72607009	6.112487219	22.13594362	8.75	9.45647926	14.17391971	0.782623792	18.52356607	4.974434641	18.4805303	15.62506
13.81059376	5.25	1.261942946	15.24811464	8.140792345	5.353970489	5.697587209	1.443086969	13.32760294	4.949747468	16.80364544	5.25	1.565247584
5.167688071	5.643580424	8.429116205	6.309714732	16.74888056	4.096644969	6.45368112	8.812774818	5.203124062	12.98778272	7.7	12.84075543	10.50583171
0.7	10.20416582	12.6485177	5.011237372	21.05825254	7.771261159	8.923284149	13.07707918	1.05	17.37706822	4.563441684	17.28872465	14.620619
6.386900657	5.25	6.973700596	8.458132182	15.38806356	2.1	4.214558103	7.416367035	5.980802622	11.76541542	9.553140845	11.73935688	8.923284149
4.427188724	8.472602906	9.862301963	8.170832271	18.2	4.862355396	5.261653732	10.33537614	3.517456467	14.72081859	8.297288714	14.76651618	11.6345391
13.32760294	4.081666326	0	14.41813095	8.414570696	5.011237372	6.021627687	0.494974747	12.95	4.862355396	16.11521021	4.974434641	2.128966886
2.128966886	12.83598457	15.45161804	4.949747468	23.8539829	10.59292217	11.6345391	15.87395666	2.886173938	20.14857315	2.990401311	20.03578049	17.43688619
5.991034969	16.05809765	19.05813475	5.960285228	27.39183272	14.35426766	15.59366859	19.45257052	6.876408947	23.61397891	3.301893396	23.42909516	21.1047388
10.50583171	5.011237372	3.720551034	12.61942946	11.73935688	2.213594362	2.347871376	4.214558103	9.899494937	8.472602906	13.81059376	8.665592882	5.167688071
10.50583171	5.011237372	3.720551034	12.61942946	11.73935688	2.213594362	2.347871376	4.214558103	9.899494937	8.472602906	13.81059376	8.665592882	5.167688071
12.61942946	5.533985905	2.474873734	14.51972796	9.724710793	4.214558103	3.990613988	2.886173938	12.02798819	6.686740611	15.84692399	7	3.22684056
4.912484097	15.16352532	18.0682733	5.467174773	26.42673835	13.31840831	14.50284455	18.47058472	5.772347876	22.6663848	2.733587387	22.50094442	20.09987562
3.720551034	12.56592615	15.76554788	2.523885893	24.0075509	11.28716085	12.95	16.1342028	4.949747468	20.19715326	0.35	19.9745463	17.85343104
9.106728282	4.912484097	4.760514678	11.30884609	13.00663292	0.989949494	2.128966886	5.25	8.515867542	9.610671152	12.42869663	9.731007142	6.434671709
0	10.81041165	13.32760294	4.760514678	21.73384457	8.465370636	9.610671152	13.75281789	1.261942946	18.04113356	3.990613988	17.94240787	15.30824941
10.81041165	0	4.081666326	10.8725572	11.55530181	4.329260907	7	4.229066091	10.78204526	7.707950441	12.90736224	7.424621202	6.112487219
13.32760294	4.081666326	0	14.41813095	8.414570696	5.011237372	6.021627687	0.494974747	12.95	4.862355396	16.11521021	4.974434641	2.128966886
4.760514678	10.8725572	14.41813095	0	22.42459587	10.40624812	12.54641383	14.73745229	5.980802622	18.57969322	2.733587387	18.28394104	16.54282322
21.73384457	11.55530181	8.414570696	22.42459587	0	13.39636145	13.69032505	7.981227976	21.36147233	3.85	24.35456836	4.257933771	6.57590298
8.465370636	4.329260907	5.011237372	10.40624812	13.39636145	0	2.990401311	5.478366545	7.981227976	9.862301963	11.6345391	9.905680189	6.876408947
9.610671152	7	6.021627687	12.54641383	13.69032505	2.990401311	0	6.510376333	8.777955343	10.64483443	13.28156617	10.90068805	7.215434845
13.75281789	4.229066091	0.494974747	14.73745229	7.981227976	5.478366545	6.510376333	0	13.39636145	4.38548743	16.48347658	4.482186966	1.884807682
1.261942946	10.78204526	12.95	5.980802622	21.36147233	7.981227976	8.777955343	13.39636145	0	17.7433086	5.203124062	17.69837563	14.85748969
18.04113356	7.707950441	4.862355396	18.57969322	3.85	9.862301963	10.64483443	4.38548743	17.7433086	0	20.54294283	0.782623792	3.5
3.990613988	12.90736224	16.11521021	2.733587387	24.35456836	11.6345391	13.28156617	16.48347658	5.203124062	20.54294283	0	20.31809538	18.20336507
17.94240787	7.424621202	4.974434641	18.28394104	4.257933771	9.905680189	10.90068805	4.482186966	17.69837563	0.782623792	20.31809538	0	3.913118961
15.30824941	6.112487219	2.128966886	16.54282322	6.57590298	6.876408947	7.215434845	1.884807682	14.85748969	3.5	18.20336507	3.913118961	0
8.193289938	3.010813843	5.261653732	9.266741606	13.59154149	1.884807682	4.874935897	5.643580424	7.988898547	9.856089488	10.85564369	9.749871794	7.35
7.181399585	14.35	17.97310491	3.56931366	25.90236476	13.94740119	15.96629262	18.28394104	8.429116205	22.0527776	3.301893396	21.72538837	20.09987562
7.988898547	2.821790212	5.991034969	8.429116205	14.10895106	3.130495168	6.112487219	6.309714732	7.981227976	10.29975728	10.24609682	10.10160878	8.118189453
7.988898547	2.821790212	5.991034969	8.429116205	14.10895106	3.130495168	6.112487219	6.309714732	7.981227976	10.29975728	10.24609682	10.10160878	8.118189453
10.02247474	1.106797181	3.990613988	10.50583171	11.98206994	3.22684056	5.960285228	4.257933771	9.905680189	8.170832271	12.37436867	7.981227976	6.112487219
7.416367035	3.720551034	5.991034969	8.658521814	14.35	1.979898987	4.862355396	6.386900657	7.206941099	10.62755852	10.15	10.52912627	8.057605103
11.96160524	20.67667768	24.17281531	9.806248008	32.23042041	19.85151128	21.49011401	24.50999796	13.00663292	28.38454685	8.238021607	28.07863957	26.28730682
4.563441684	7.441102069	9.1	7.707950441	17.4929986	4.096644969	5.096076922	9.559550199	3.913118961	13.93422047	8.193289938	13.93861543	10.96232183
15.84692399	7.206941099	3.130495168	17.37706822	6.510376333	7.383258088	7.206941099	3.010813843	15.30824941	4.096644969	18.91295852	4.669582422	1.261942946
15.4	7.935048834	3.990613988	17.40524346	7.919595949	7.078311946	6.202015801	4.081666326	14.73745229	5.867069115	18.71109297	6.45368112	2.821790212
13.51018135	3.769615365	0.7	14.36706303	8.238021607	5.342518133	6.603786792	0.494974747	13.19365378	4.55	16.16075493	4.563441684	2.347871376

D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50:=
8.407288505	21.1047388	9.126883367	9.126883367	7.078311946	9.126883367	27.32018485	12.06865775	1.443086969	3.22684056	3.22684056
8.407288505	21.1047388	9.126883367	9.126883367	7.078311946	9.126883367	27.32018485	12.06865775	1.443086969	3.22684056	3.22684056
6.202015801	16.62776293	7.416367035	7.416367035	7.358328615	6.112487219	21.91905564	5.643580424	7.981227976	6.732384422	7.826237921
1.75	13.28156617	2.886173938	2.886173938	3.447100231	1.565247584	19.16070197	3.447100231	8.080377466	7.771261159	5.95
7.078311946	16.60195772	8.238021607	8.238021607	8.407288505	6.876408947	21.64630453	5.697587209	9.187083324	7.865271769	9.07978524
2.45	10.44150372	2.040833163	2.040833163	4.096644969	1.78465683	16.50946698	3.22684056	10.5523694	10.52912627	7.771261159
0.7	12.98778272	1.884807682	1.884807682	2.523885893	0.782623792	19.01630879	3.990613988	8.057605103	7.981227976	5.533985905
10.59292217	4.38548743	10.10160878	10.10160878	12.22497444	9.856089488	8.854377448	7.555461601	18.55330159	18.25376673	15.93941655
3.913118961	12.37436867	4.669582422	4.669582422	5.825160942	3.320391543	17.83626923	1.443086969	10.10160878	9.475890459	8.348802309
14.27725464	26.60230253	14.80380019	14.80380019	12.67753919	15.03371212	32.92977376	18.15282347	7.086959856	8.429116205	8.923284149
7.7	5.478366545	7.078311946	7.078311946	9.207062507	7.008744538	11.28716085	5.533985905	15.7849612	15.65247584	12.99249784
8.77097486	8.260296605	8.75	8.75	10.68503627	7.988898547	12.52198067	4.669582422	16.06191147	15.46350542	13.97372534
5.991034969	18.81555208	6.876408947	6.876408947	5.011237372	6.659204157	24.93857454	9.424038412	2.128966886	2.733587387	1.884807682
3.169384798	9.856089488	2.821790212	2.821790212	4.874935897	2.45	15.84692399	2.8	11.22185368	11.12317401	8.515867542
7.53923073	7.67609927	7.383258088	7.383258088	9.391485505	6.759622771	12.61942946	3.865876356	15.15140258	14.7	12.84075543
2.241093483	11.96160524	2.886173938	2.886173938	4.214558103	1.565247584	17.78124011	2.241093483	9.475890459	9.16037663	7.215434845
5.467174773	11.27086953	5.95	5.95	7.441102069	4.760514678	16.38657988	1.106797181	11.97184196	11.28716085	10.20416582
5.261653732	17.97310491	5.991034969	5.991034969	3.990613988	5.991034969	24.17281531	9.1	3.130495168	3.990613988	0.7
10.29380882	6.260990337	10.02247474	10.02247474	12.08894123	9.521029356	10.1741093	6.65	17.97310491	17.50349965	15.62506
13.81059376	4.669582422	13.32760294	13.32760294	15.45161804	13.06770829	6.309714732	10.5523694	21.72538837	21.36147233	19.16070197
3.720551034	16.16075493	4.949747468	4.949747468	4.096644969	4.081666326	22.03888609	5.991034969	5.433461144	4.912484097	4.272294466
3.720551034	16.16075493	4.949747468	4.949747468	4.096644969	4.081666326	22.03888609	5.991034969	5.433461144	4.912484097	4.272294466
5.331041174	18.08182789	6.425145913	6.425145913	4.949747468	5.867069115	24.05597639	8.118189453	3.320391543	2.886173938	3.169384798
12.83598457	4.9	12.4040316	12.4040316	14.51972796	12.08387355	7.383258088	9.475890459	20.69740322	20.30301702	18.18990104
10.50583171	3.5	9.899494937	9.899494937	12.02798819	9.8	8.58035547	7.865271769	18.56320285	18.36416347	15.8120998
2.821790212	14.83273407	4.081666326	4.081666326	3.85	2.969848481	20.661861	4.603531253	6.795770744	6.309714732	5.203124062
8.193289938	7.181399585	7.988898547	7.988898547	10.02247474	7.416367035	11.96160524	4.563441684	15.84692399	15.4	13.51018135
3.010813843	14.35	2.821790212	2.821790212	1.106797181	3.720551034	20.67667768	7.441102069	7.206941099	7.935048834	3.769615365
5.261653732	17.97310491	5.991034969	5.991034969	3.990613988	5.991034969	24.17281531	9.1	3.130495168	3.990613988	0.7
9.266741606	3.56931366	8.429116205	8.429116205	10.50583171	8.658521814	9.806248008	7.707950441	17.37706822	17.40524346	14.36706303
13.59154149	25.90236476	14.10895106	14.10895106	11.98206994	14.35	32.23042041	17.4929986	6.510376333	7.919595949	8.238021607
1.884807682	13.94740119	3.130495168	3.130495168	3.22684056	1.979898987	19.85151128	4.096644969	7.383258088	7.078311946	5.342518133
4.874935897	15.96629262	6.112487219	6.112487219	5.960285228	4.862355396	21.49011401	5.096076922	7.206941099	6.202015801	6.603786792
5.643580424	18.28394104	6.309714732	6.309714732	4.257933771	6.386900657	24.50999796	9.559550199	3.010813843	4.081666326	0.494974747
7.988898547	8.429116205	7.981227976	7.981227976	9.905680189	7.206941099	13.00663292	3.913118961	15.30824941	14.73745229	13.19365378
9.856089488	22.0527776	10.29975728	10.29975728	8.170832271	10.62755852	28.38454685	13.93422047	4.096644969	5.867069115	4.55
10.85564369	3.301893396	10.24609682	10.24609682	12.37436867	10.15	8.238021607	8.193289938	18.91295852	18.71109297	16.16075493
9.749871794	21.72538837	10.10160878	10.10160878	7.981227976	10.52912627	28.07863957	13.93861543	4.669582422	6.45368112	4.563441684
7.35	20.09987562	8.118189453	8.118189453	6.112487219	8.057605103	26.28730682	10.96232183	1.261942946	2.821790212	2.347871376
0	12.83598457	1.261942946	1.261942946	1.979898987	0.782623792	18.95178092	4.454772721	8.118189453	8.193289938	5.353970489
12.83598457	0	11.98206994	11.98206994	14.03931978	12.22497444	6.386900657	10.98464838	20.94451002	20.96789212	17.90481779
1.261942946	11.98206994	0	0	2.128966886	1.4	18.20336507	4.862355396	8.998472093	9.240265148	5.95
1.261942946	11.98206994	0	0	2.128966886	1.4	18.20336507	4.862355396	8.998472093	9.240265148	5.95
1.979898987	14.03931978	2.128966886	2.128966886	0	2.733587387	20.3	6.434671709	7.086959856	7.571657678	3.865876356
0.782623792	12.22497444	1.4	1.4	2.733587387	0	18.28394104	3.720551034	8.777955343	8.75	6.112487219
18.95178092	6.386900657	18.20336507	18.20336507	20.3	18.28394104	0	16.3940538	27.06113449	26.92953769	24.1525361
4.454772721	10.98464838	4.862355396	4.862355396	6.434671709	3.720551034	16.3940538	0	11.39517442	10.85564369	9.391485505
8.118189453	20.94451002	8.998472093	8.998472093	7.086959856	8.777955343	27.06113449	11.39517442	0	1.78465683	3.5
8.193289938	20.96789212	9.240265148	9.240265148	7.571657678	8.75	26.92953769	10.85564369	1.78465683	0	4.563441684
5.353970489	17.90481779	5.95	5.95	3.865876356	6.112487219	24.1525361	9.391485505	3.5	4.563441684	0



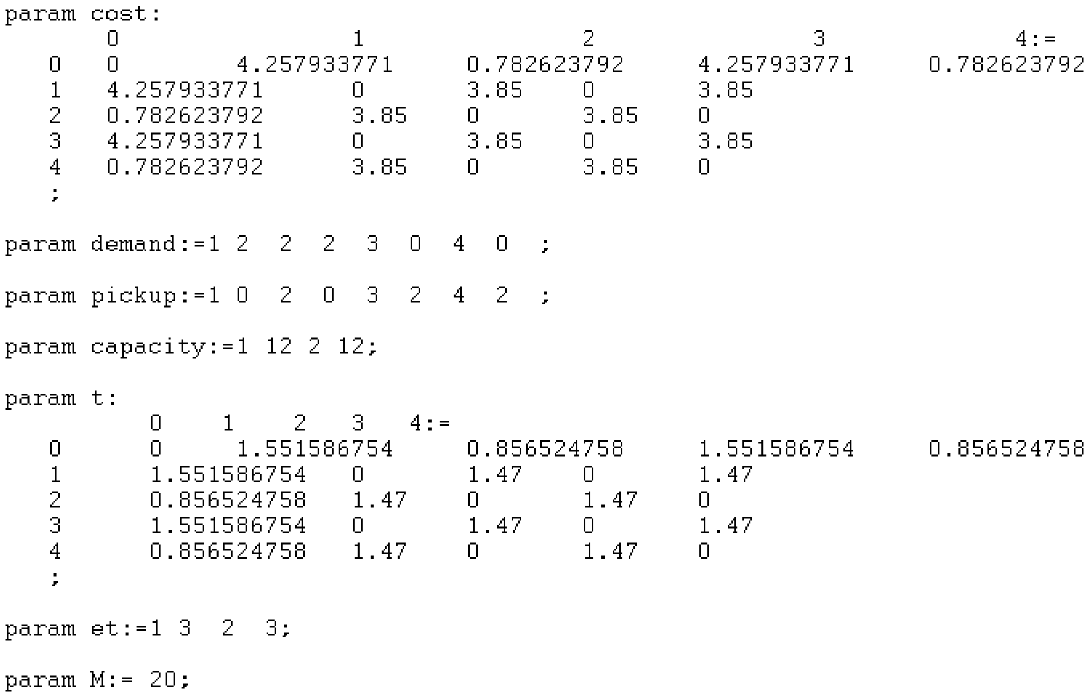
```
param n := 12 ;
param s := 180;
param max_a:= 25;
```

2. data



```
param n := 13;

param cost:
      1              2              3              4              5              6              7
  1   0              212.8186263    218.2868763    209.6738591    207.4113236    206.0150001    210.003278
  2   212.8186263    0              6.112487219    3.15           6.260990337    7.53923073     2.821790212
  3   218.2868763    6.112487219    0              9.08652849     12.36941793    13.65          8.658521814
  4   209.6738591    3.15           9.08652849     0              3.720551034    4.760514678    0.494974747
  5   207.4113236    6.260990337    12.36941793    3.720551034    0              1.4            4.214558103
  6   206.0150001    7.53923073     13.65          4.760514678    1.4            0              5.25
  7   210.003278     2.821790212    8.658521814    0.494974747    4.214558103    5.25           0
  8   197.7491274    15.96245595    22.02776657    12.95          9.899494937    8.515867542    13.39636145
  9   213.361107     3.22684056     4.949747468    4.974434641    8.665592882    9.731007142    4.482186966
  10  211.7907568    1.106797181    7.215434845    2.128966886    5.167688071    6.434671709    1.884807682
  11  203.6935654    9.126883367    14.80380019    5.991034969    4.949747468    4.081666326    6.309714732
  12  203.6935654    9.126883367    14.80380019    5.991034969    4.949747468    4.081666326    6.309714732
  13  194.0702456    18.98084561    24.85739327    15.84692399    13.34138299    11.94623372    16.23637891
  ;

  8              9              10             11             12             13:=
  197.7491274    213.361107     211.7907568    203.6935654    203.6935654    194.0702456
  15.96245595    3.22684056     1.106797181    9.126883367    9.126883367    18.98084561
  22.02776657    4.949747468    7.215434845    14.80380019    14.80380019    24.85739327
  12.95          4.974434641    2.128966886    5.991034969    5.991034969    15.84692399
  9.899494937    8.665592882    5.167688071    4.949747468    4.949747468    13.34138299
  8.515867542    9.731007142    6.434671709    4.081666326    4.081666326    11.94623372
  13.39636145    4.482186966    1.884807682    6.309714732    6.309714732    16.23637891
  0              17.69837563    14.85748969    7.981227976    7.981227976    4.272294466
  17.69837563    0              3.913118961    10.10160878    10.10160878    20.20321757
  14.85748969    3.913118961    0              8.118189453    8.118189453    17.90481779
  7.981227976    10.10160878    8.118189453    0       0      10.10160878
  7.981227976    10.10160878    8.118189453    0       0      10.10160878
  4.272294466    20.20321757    17.90481779    10.10160878    10.10160878    0
```

3. data

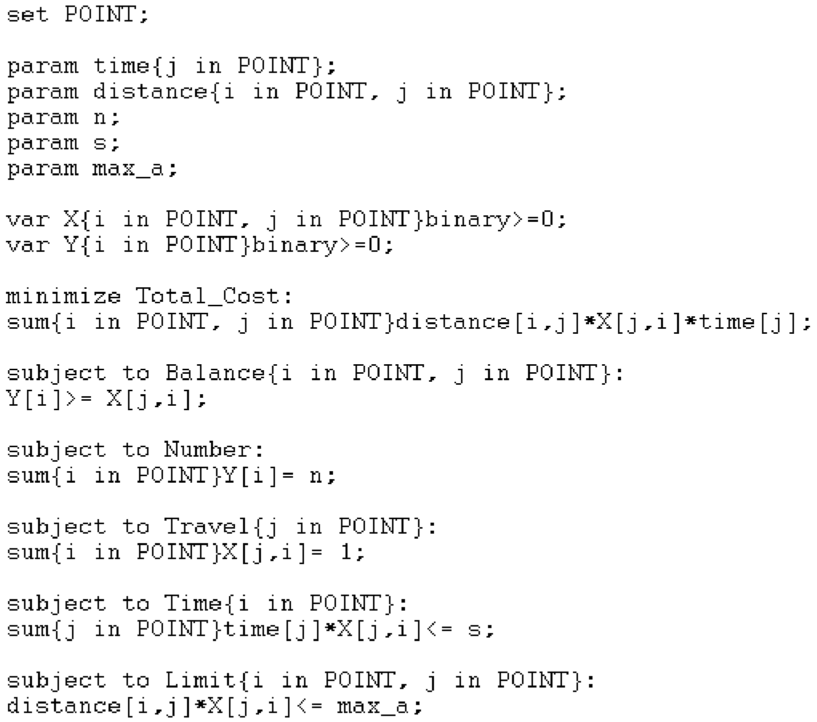


```
param cost:
        0           1               2               3               4:=
   0    0        4.257933771     0.782623792     4.257933771     0.782623792
   1    4.257933771      0       3.85       0        3.85
   2    0.782623792      3.85    0          3.85     0
   3    4.257933771      0       3.85       0        3.85
   4    0.782623792      3.85    0          3.85     0
   ;

param demand:=1 2  2  2  3  0  4  0  ;

param pickup:=1 0  2  0  3  2  4  2  ;

param capacity:=1 12 2 12;

param t:
           0    1    2   3   4:=
   0       0     1.551586754     0.856524758     1.551586754     0.856524758
   1       1.551586754   0       1.47     0        1.47
   2       0.856524758   1.47    0        1.47     0
   3       1.551586754   0       1.47     0        1.47
   4       0.856524758   1.47    0        1.47     0
   ;

param et:=1 3  2  3;

param M:= 20;
```

Appendix 2- html code for AMPL

The Task 1.

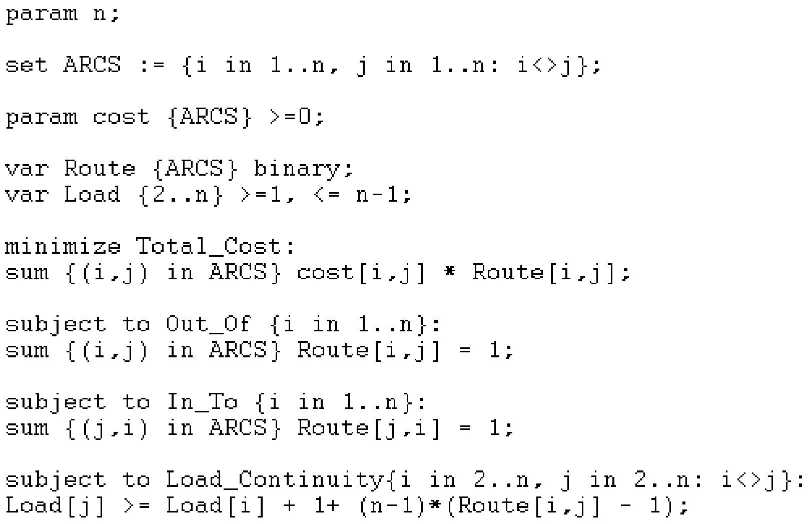
< model.File>



```
set POINT;

param time{j in POINT};
param distance{i in POINT, j in POINT};
param n;
param s;
param max_a;

var X{i in POINT, j in POINT}binary>=0;
var Y{i in POINT}binary>=0;

minimize Total_Cost:
sum{i in POINT, j in POINT}distance[i,j]*X[j,i]*time[j];

subject to Balance{i in POINT, j in POINT}:
Y[i]>= X[j,i];

subject to Number:
sum{i in POINT}Y[i]= n;

subject to Travel{j in POINT}:
sum{i in POINT}X[j,i]= 1;

subject to Time{i in POINT}:
sum{j in POINT}time[j]*X[j,i]<= s;

subject to Limit{i in POINT, j in POINT}:
distance[i,j]*X[j,i]<= max_a;
```

The Task 2.

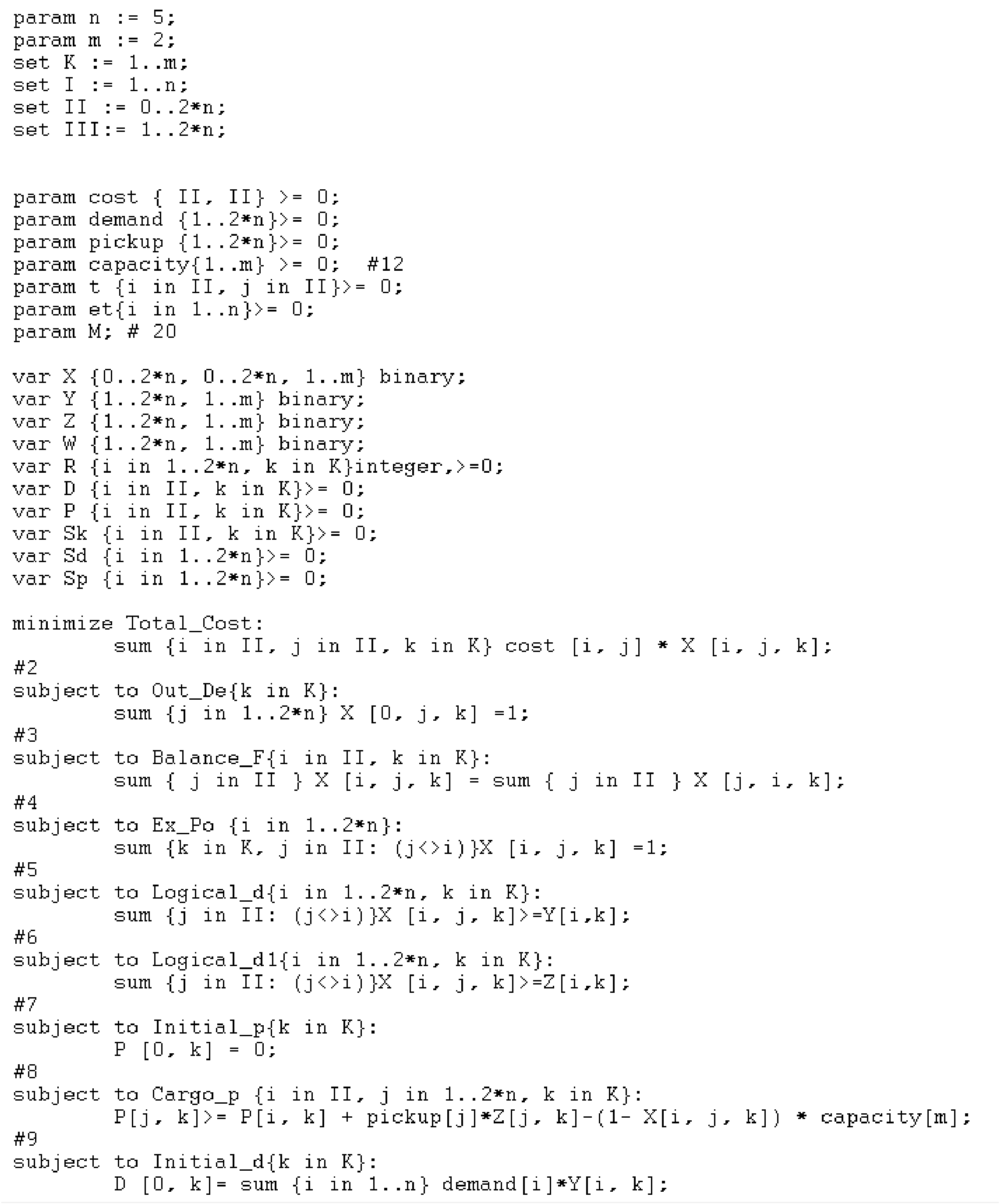
< model.File>



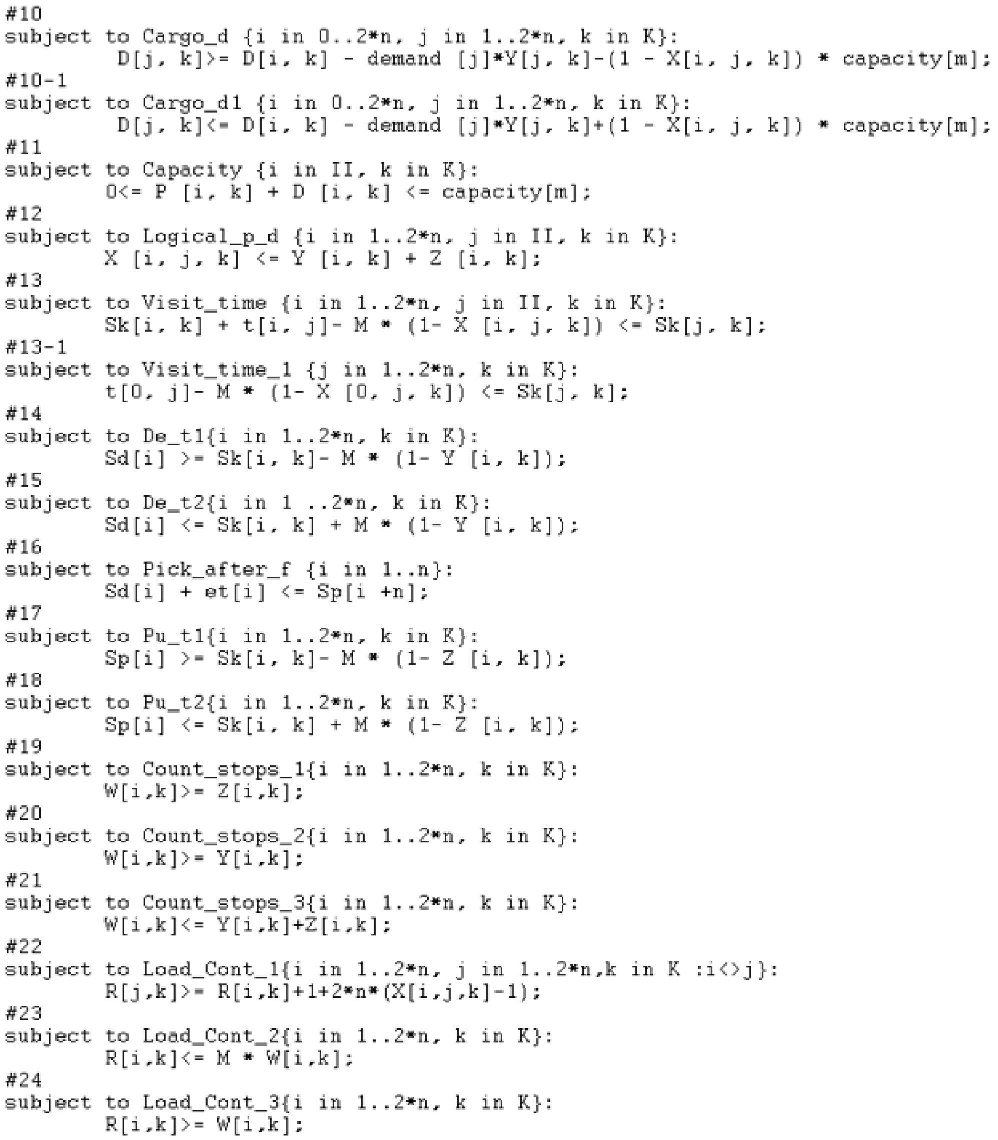
```
param n;

set ARCS := {i in 1..n, j in 1..n: i<>j};

param cost {ARCS} >=0;

var Route {ARCS} binary;
var Load {2..n} >=1, <= n-1;

minimize Total_Cost:
sum {(i,j) in ARCS} cost[i,j] * Route[i,j];

subject to Out_Of {i in 1..n}:
sum {(i,j) in ARCS} Route[i,j] = 1;

subject to In_To {i in 1..n}:
sum {(j,i) in ARCS} Route[j,i] = 1;

subject to Load_Continuity{i in 2..n, j in 2..n: i<>j}:
Load[j] >= Load[i] + 1+ (n-1)*(Route[i,j] - 1);
```

The Task 3.

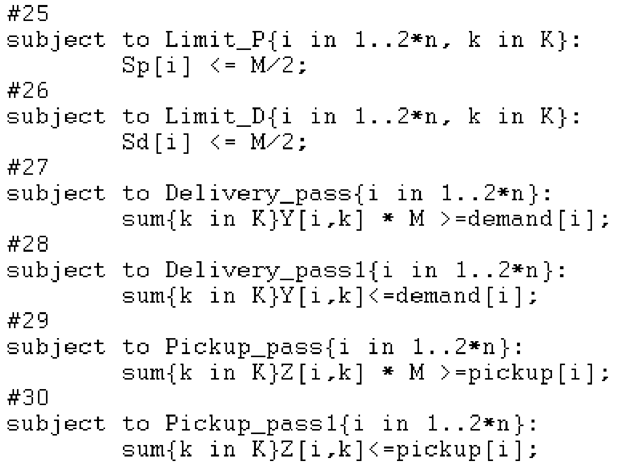
< model.File>



```
param n := 5;
param m := 2;
set K := 1..m;
set I := 1..n;
set II := 0..2*n;
set III:= 1..2*n;


param cost { II, II} >= 0;
param demand {1..2*n}>= 0;
param pickup {1..2*n}>= 0;
param capacity{1..m} >= 0;  #12
param t {i in II, j in II}>= 0;
param et{i in 1..n}>= 0;
param M; # 20

var X {0..2*n, 0..2*n, 1..m} binary;
var Y {1..2*n, 1..m} binary;
var Z {1..2*n, 1..m} binary;
var W {1..2*n, 1..m} binary;
var R {i in 1..2*n, k in K}integer,>=0;
var D {i in II, k in K}>= 0;
var P {i in II, k in K}>= 0;
var Sk {i in II, k in K}>= 0;
var Sd {i in 1..2*n}>= 0;
var Sp {i in 1..2*n}>= 0;

minimize Total_Cost:
        sum {i in II, j in II, k in K} cost [i, j] * X [i, j, k];
#2
subject to Out_De{k in K}:
        sum {j in 1..2*n} X [0, j, k] =1;
#3
subject to Balance_F{i in II, k in K}:
        sum { j in II } X [i, j, k] = sum { j in II } X [j, i, k];
#4
subject to Ex_Po {i in 1..2*n}:
        sum {k in K, j in II: (j<>i)}X [i, j, k] =1;
#5
subject to Logical_d{i in 1..2*n, k in K}:
        sum {j in II: (j<>i)}X [i, j, k]>=Y[i,k];
#6
subject to Logical_d1{i in 1..2*n, k in K}:
        sum {j in II: (j<>i)}X [i, j, k]>=Z[i,k];
#7
subject to Initial_p{k in K}:
        P [0, k] = 0;
#8
subject to Cargo_p {i in II, j in 1..2*n, k in K}:
        P[j, k]>= P[i, k] + pickup[j]*Z[j, k]-(1- X[i, j, k]) * capacity[m];
#9
subject to Initial_d{k in K}:
        D [0, k]= sum {i in 1..n} demand[i]*Y[i, k];
```



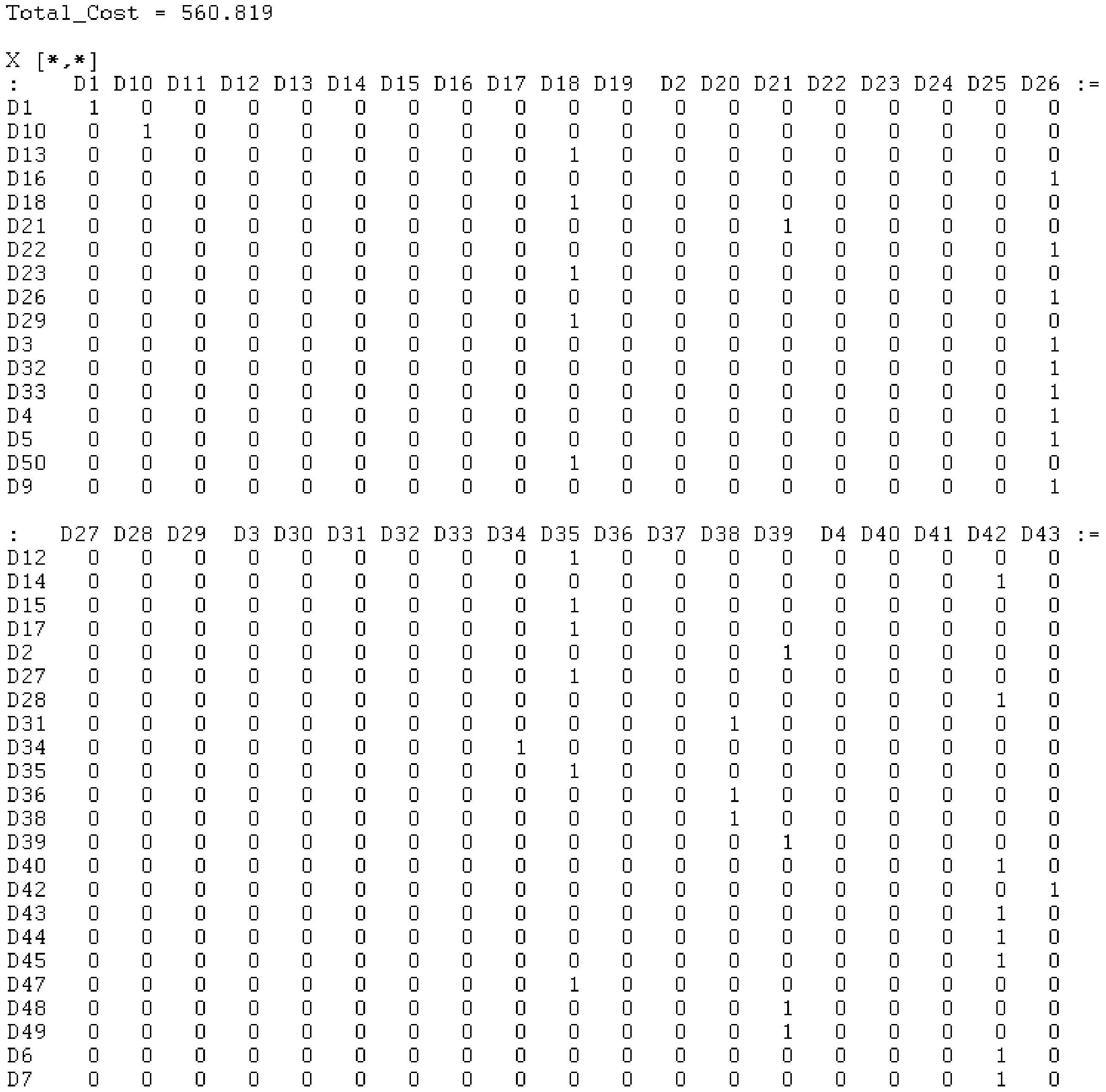
```
#10
subject to Cargo_d {i in 0..2*n, j in 1..2*n, k in K}:
         D[j, k]>= D[i, k] - demand [j]*Y[j, k]-(1 - X[i, j, k]) * capacity[m];
#10-1
subject to Cargo_d1 {i in 0..2*n, j in 1..2*n, k in K}:
         D[j, k]<= D[i, k] - demand [j]*Y[j, k]+(1 - X[i, j, k]) * capacity[m];
#11
subject to Capacity {i in II, k in K}:
        0<= P [i, k] + D [i, k] <= capacity[m];
#12
subject to Logical_p_d {i in 1..2*n, j in II, k in K}:
        X [i, j, k] <= Y [i, k] + Z [i, k];
#13
subject to Visit_time {i in 1..2*n, j in II, k in K}:
        Sk[i, k] + t[i, j]- M * (1- X [i, j, k]) <= Sk[j, k];
#13-1
subject to Visit_time_1 {j in 1..2*n, k in K}:
        t[0, j]- M * (1- X [0, j, k]) <= Sk[j, k];
#14
subject to De_t1{i in 1..2*n, k in K}:
        Sd[i] >= Sk[i, k]- M * (1- Y [i, k]);
#15
subject to De_t2{i in 1 ..2*n, k in K}:
        Sd[i] <= Sk[i, k] + M * (1- Y [i, k]);
#16
subject to Pick_after_f {i in 1..n}:
        Sd[i] + et[i] <= Sp[i +n];
#17
subject to Pu_t1{i in 1..2*n, k in K}:
        Sp[i] >= Sk[i, k]- M * (1- Z [i, k]);
#18
subject to Pu_t2{i in 1..2*n, k in K}:
        Sp[i] <= Sk[i, k] + M * (1- Z [i, k]);
#19
subject to Count_stops_1{i in 1..2*n, k in K}:
        W[i,k]>= Z[i,k];
#20
subject to Count_stops_2{i in 1..2*n, k in K}:
        W[i,k]>= Y[i,k];
#21
subject to Count_stops_3{i in 1..2*n, k in K}:
        W[i,k]<= Y[i,k]+Z[i,k];
#22
subject to Load_Cont_1{i in 1..2*n, j in 1..2*n,k in K :i<>j}:
        R[j,k]>= R[i,k]+1+2*n*(X[i,j,k]-1);
#23
subject to Load_Cont_2{i in 1..2*n, k in K}:
        R[i,k]<= M * W[i,k];
#24
subject to Load_Cont_3{i in 1..2*n, k in K}:
        R[i,k]>= W[i,k];
```



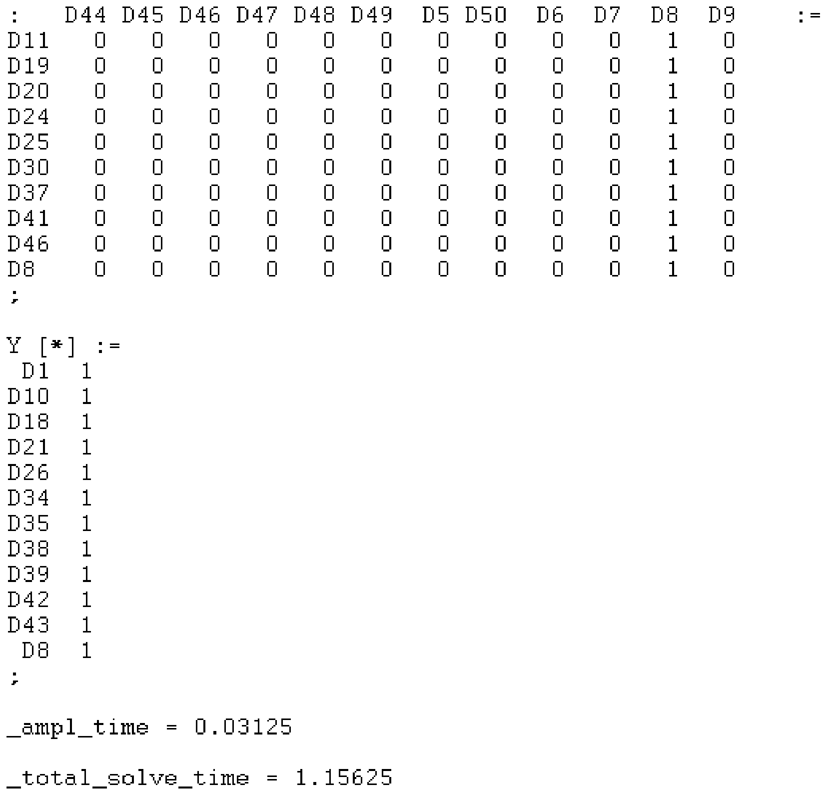
```
#25
subject to Limit_P{i in 1..2*n, k in K}:
        Sp[i] <= M/2;
#26
subject to Limit_D{i in 1..2*n, k in K}:
        Sd[i] <= M/2;
#27
subject to Delivery_pass{i in 1..2*n}:
        sum{k in K}Y[i,k] * M >=demand[i];
#28
subject to Delivery_pass1{i in 1..2*n}:
        sum{k in K}Y[i,k]<=demand[i];
#29
subject to Pickup_pass{i in 1..2*n}:
        sum{k in K}Z[i,k] * M >=pickup[i];
#30
subject to Pickup_pass1{i in 1..2*n}:
        sum{k in K}Z[i,k]<=pickup[i];
```

Appendix 2- html code for solution

The Task 1.

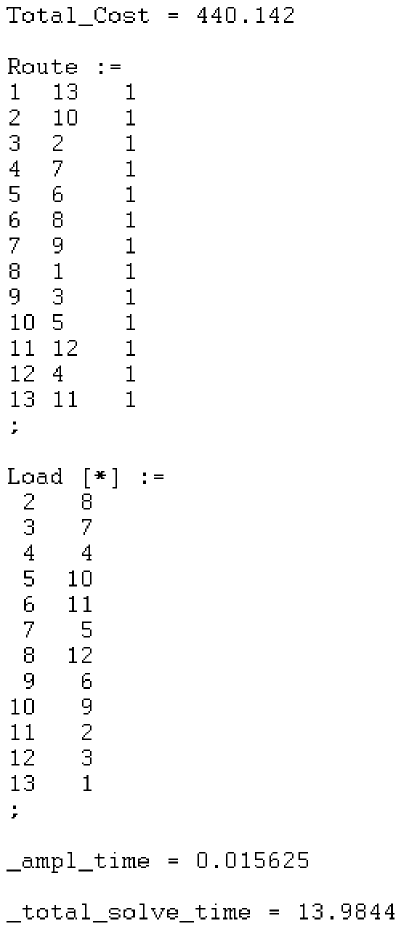


```
Total_Cost = 560.819

X [*,*]
:    D1 D10 D11 D12 D13 D14 D15 D16 D17 D18 D19  D2 D20 D21 D22 D23 D24 D25 D26 :=
D1    1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
D10   0   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
D13   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D16   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D18   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D21   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0
D22   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D23   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D26   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D29   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D3    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D32   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D33   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D4    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D5    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D50   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D9    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1

:   D27 D28 D29  D3 D30 D31 D32 D33 D34 D35 D36 D37 D38 D39  D4 D40 D41 D42 D43 :=
D12   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D14   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D15   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D17   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D2    0   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0
D27   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D28   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D31   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0
D34   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0   0
D35   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D36   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0
D38   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0
D39   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0
D40   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D42   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
D43   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D44   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D45   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D47   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
D48   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0
D49   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0   0   0   0   0
D6    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
D7    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
```



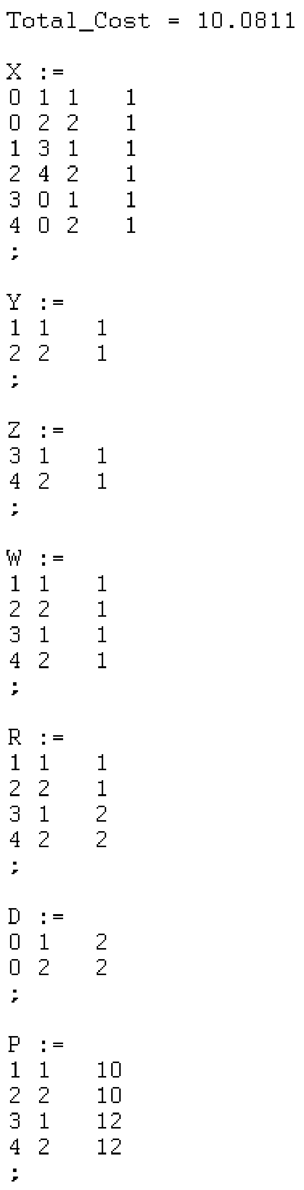
```
:   D44 D45 D46 D47 D48 D49  D5 D50  D6  D7  D8  D9    :=
D11   0   0   0   0   0   0   0   0   0   0   1   0
D19   0   0   0   0   0   0   0   0   0   0   1   0
D20   0   0   0   0   0   0   0   0   0   0   1   0
D24   0   0   0   0   0   0   0   0   0   0   1   0
D25   0   0   0   0   0   0   0   0   0   0   1   0
D30   0   0   0   0   0   0   0   0   0   0   1   0
D37   0   0   0   0   0   0   0   0   0   0   1   0
D41   0   0   0   0   0   0   0   0   0   0   1   0
D46   0   0   0   0   0   0   0   0   0   0   1   0
D8    0   0   0   0   0   0   0   0   0   0   1   0
;

Y [*] :=
 D1  1
D10  1
D18  1
D21  1
D26  1
D34  1
D35  1
D38  1
D39  1
D42  1
D43  1
 D8  1
;

_ampl_time = 0.03125

_total_solve_time = 1.15625
```

The Task 2.

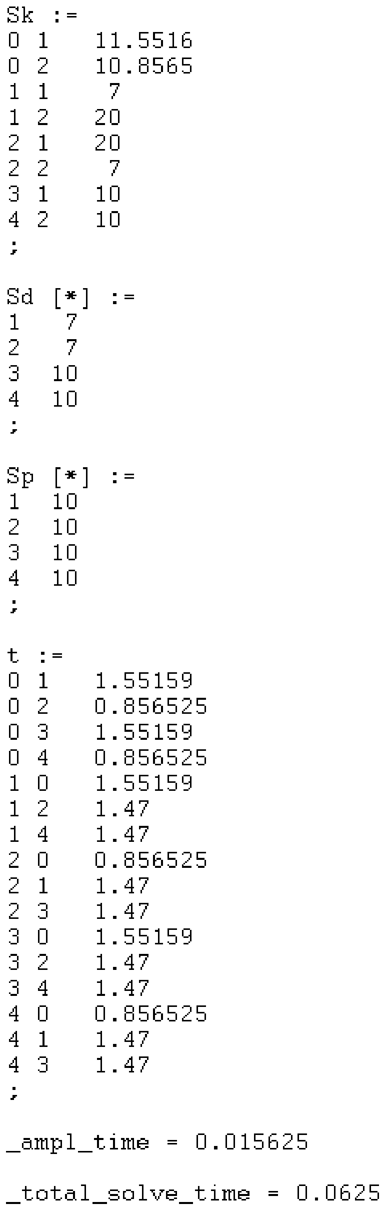


```
Total_Cost = 440.142

Route :=
1  13   1
2  10   1
3  2    1
4  7    1
5  6    1
6  8    1
7  9    1
8  1    1
9  3    1
10 5    1
11 12   1
12 4    1
13 11   1
;

Load [*] :=
 2   8
 3   7
 4   4
 5  10
 6  11
 7   5
 8  12
 9   6
10   9
11   2
12   3
13   1
;

_ampl_time = 0.015625

_total_solve_time = 13.9844
```

The Task 3.



```
Total_Cost = 10.0811

X :=
0 1 1    1
0 2 2    1
1 3 1    1
2 4 2    1
3 0 1    1
4 0 2    1
;

Y :=
1 1    1
2 2    1
;

Z :=
3 1    1
4 2    1
;

W :=
1 1    1
2 2    1
3 1    1
4 2    1
;

R :=
1 1    1
2 2    1
3 1    2
4 2    2
;

D :=
0 1    2
0 2    2
;

P :=
1 1    10
2 2    10
3 1    12
4 2    12
;
```



```
Sk :=
0 1   11.5516
0 2   10.8565
1 1    7
1 2   20
2 1   20
2 2    7
3 1   10
4 2   10
;

Sd [*] :=
1   7
2   7
3  10
4  10
;

Sp [*] :=
1  10
2  10
3  10
4  10
;

t :=
0 1   1.55159
0 2   0.856525
0 3   1.55159
0 4   0.856525
1 0   1.55159
1 2   1.47
1 4   1.47
2 0   0.856525
2 1   1.47
2 3   1.47
3 0   1.55159
3 2   1.47
3 4   1.47
4 0   0.856525
4 1   1.47
4 3   1.47
;

_ampl_time = 0.015625

_total_solve_time = 0.0625
```