UNIVERSITY OF TWENTE.

# Optimizing Purchasing and Distribution Decisions at Fugro:

## A Mathematical Programming Approach

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# Management Summary

This research was carried out together with the Purchasing & Logistics Department of Fugro Marine Services. Fugro Marine Services is the inhouse vessel manager of Fugro and is internally referred to as Fleet Services (FS). Fugro operates a fleet of vessels in different regions around the world to provide site characterization and asset integrity services. These vessels are required to be optimally equipped to fulfill their tasks.

For this research, we focused on the supply chain network of FS. The company operates over a global network consisting of many suppliers and distribution options. We limited our research to materials of type "consumables & parts". These items constitute of household goods, stationary and small hardware that are consumed regularly and periodical order groups are already introduced for them. FS believes there is a possibility to standardize their purchasing and logistics processes. We need to determine the optimal purchasing and delivery options to supply these goods to the vessels.

**Problem Description**

FS wishes to revise their global procurement operations to improve financial performance. FS has a global network consisting of a large supplier base and multiple warehouses. This renders it difficult to evaluate the costs of all alternative purchasing and distribution options. Currently, the Purchasing & Logistics Department makes purchase decisions based on experience and intuition. The degree of efficiency of this approach is not known. There is no standard methodology that provides control over the process or evaluates alternative costs. As a result, expenses are perceived to be high.

**Research Objective**

We aimed to develop a decision-making tool for consumables & parts to minimize total purchasing and logistics costs while ensuring all required goods are supplied. We answered the corresponding research question: “How to make purchasing & distribution decisions for consumables & parts to ensure efficient operation of purchasing & logistics?”.

**Approach**

We initially studied the current way of operation of FS. We identified the cost breakdown building up the purchasing and logistics costs and the applicable distribution options. We accounted for cost components displayed in Table 1. We modeled deliveries made to the agents, the central or local warehouses or directly from the supplier to the vessels. We wanted to determine the minimum cost supply and distribution option for each required item. Since the costs incurred per port call are disjoint, we formulated our model to be run for each port call separately. We limited our analysis to 15 port calls realized in 2017 based on the available data. We re-enacted these cases and compared the cost of optimal decisions for purchasing and distribution with the realized costs.

We developed a mixed integer linear programming model. Formulating a linear model enabled us to obtain an exact solution corresponding to the minimum cost supply and distribution decisions. We modeled FS’s distribution network as a directed graph and incorporated applicable distribution options. We considered these options together with procurement and freight discounts.

We built a generic model that enables updating the input data, introducing new facilities and suppliers. We also built a cost calculator that calculates the purchasing and logistics costs given the suppliers and the delivery routes selected. We formulated our model to ensure a manageable problem size. The algorithm run on average 0,355 minutes per port call. We developed the supply and distribution route determination tool using ILOG CPLEX Concert Technology with C#.

**Conclusions and Recommendations**

Analyzing the decisions made by FS in 2017, we concluded that small modifications in the purchasing and distribution decisions could yield to significant improvements (Table 1). However, due to data unavailability, we cannot project the observations based on our test cases to the whole fleet. Largest fraction of realized costs, around 81% of the total costs, are coming from product prices, followed by transportation costs corresponding to 10%. Minimizing total costs by adjusting the purchasing and distribution options can lead to a saving of 6% mostly arising from product costs.

We demonstrated that considering different and more competitive suppliers over a larger geographical region can yield to a reduction in overall costs, although this may lead to an increase in ordering and handling costs. The results suggest splitting orders among a higher number of suppliers. Consolidating goods prior to delivery to vessel in a warehouse close to the suppliers is also preferred as was already done by FS. In the optimal case, one warehouse per port call was used and use of agents was never preferred. Direct deliveries from the suppliers to the vessel were chosen when the shipment was heavy and would result in extra handling costs or when the dangerous goods and perishables were restricted from having indirect distribution. Here, we note that the decisions presented by the model are a result of the interaction of the input values like the port location, the required goods and the associated costs and therefore, are case specific.

**Table 1.** Comparison of total costs of the realized and the optimal cases for the selected 15 port calls

| | **TOTAL (€)** | | | |
|---|---|---|---|---|
| **Description** | Realized | Optimal | Saving | Saving (%) |
| **Product cost:** | 307.674 | 287.009 | 20.664 | 7% |
| **Ordering cost:** | 19.600 | 24.000 | - 4.400 | -22% |
| **Transportation cost:** | 38.914 | 36.765 | 2.149 | 6% |
| **Fixed facility cost:** | 1.918 | 1.319 | 599 | 31% |
| **Handling cost:** | 1.848 | 2.047 | - 198 | -11% |
| **Loading the vessel:** | 9.000 | 6.600 | 2.400 | 27% |
| **Total cost:** | **378.953** | **357.739** | **21.214** | **6%** |

We performed a sensitivity analysis on transportation, ordering and loading costs to test the robustness of the optimal solutions. Changing costs by -20 – +20%, affected the decisions for only slight changes in the optimal decisions. As expected, in some cases we observed that decrease in ordering costs lead to splitting orders and decrease in loading costs resulted in higher number of separate deliveries made to the vessel. Increase in transportation costs required using suppliers closer to the port region. Since only small number of items were affected by these changes, we conclude that the model is not sensitive to any of these costs. This means that in case an increase in these costs occur, the decisions of the model would remain close to optimal. Since the product costs constitute the largest fraction of total costs, we suggest negotiating for procurement discounts. Introducing various threshold discount policies, we demonstrated that savings up to 12% can be achieved.

We recognize that data availability and lack of demand planning constitute limitations for determining the supply and distribution activities for each port call. Item and supplier databases having more accurate information on price and product specifications would improve the quality of the decisions made by the model. We recommend FS to utilize the model on tactical buying level for the process of approving preferred suppliers and contracting. This would reveal the impact of purchasing locally or centrally and the applicable distribution options can be determined. Alternative logistics service providers can also be compared using the model. More accurate planning on the tactical level would help standardize processes in the operational level.

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Karen Abeniacar

Voorburg, 2018

# List of Abbreviations

| | |
|---|---|
| DDP | Delivery Duty Paid |
| ETA | Expected Time of Arrival |
| FS | Fleet Services |
| GA | Genetic Algorithm |
| ISM | International Safety Management |
| KPI | Key Performance Indicator |
| MR | Material Requisition |
| OEM | Original Equipment Manufacturer |
| NFP | Network Flow Problem |
| PO | Purchase Order |
| RFQ | Request for Quotation |
| SCND | Supply Chain Network Design |
| SKU | Stock Keeping Unit |

# Table of Contents

# Chapter 1

# Introduction

Global supply chain networks consist of alternative paths for purchasing and distribution activities. This may render it difficult for companies to evaluate the alternatives following a holistic approach. Fleet Services (FS) experiences this difficulty when submitting purchase orders (PO) and planning their logistics as well. Through this paper, we develop a mathematical model for determining the best combination of suppliers and distribution paths for required items, to supply the vessels with minimum overall supply chain costs.

This first chapter explains the context of the project. Section 1.1 provides an overview of the company, and then introduces the Purchasing & Logistics Department where the project is performed in. Section 1.2 provides the problem description and the research questions to be answered in the following chapters. Finally, Section 1.3 describes the scope of the project.

## 1.1. Company Introduction

Fugro is a Dutch multinational company providing geo-intelligence and asset integrity solutions worldwide with a focus on sustainable and efficient development. The company was founded in 1962 and currently, operates in 65 countries with 10.000 employees (Fugro, 2018c) (Figure 1.1). The headquarters is in Leidschendam, in the Netherlands.

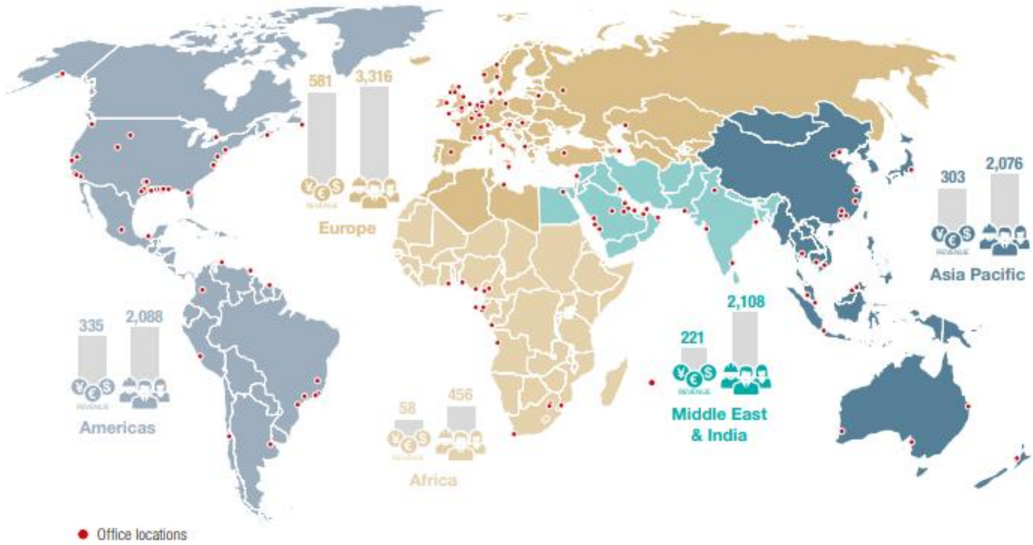


**Figure 1.1.** Fugro's five regions: revenue (EUR million), number of employees, offices in 2017 (Fugro, 2018a).

Fugro is managed through two main divisions, Land and Marine (Fugro, 2018a). These divisions offer site characterization services to determine ground and environmental conditions of project sites, and asset integrity services to determine conditions of existing constructions and infrastructure. Fugro further provides equipment and technology for exploration and transportation of natural resources, production of energy, construction and maintenance of structures and infrastructure. The company also provides services such as data acquisition, data analysis and consultancy in the related fields. The operations of the company correspond to six main markets namely oil & gas, building & infrastructure, renewables, power, nautical and mining (Fugro, 2018b). Oil companies, governments and engineering firms constitute the main customer groups of the company.

### 1.1.1. Fleet Services

FS is the business entity under Marine Division, responsible for providing Fleet Management, Fleet Development, and Fleet Personnel services to the division. This entity regulates operations of 29 vessels and accommodates various managerial branches (Appendix A). Among the responsibilities of these branches are making profit plans for regions, planning overhaul and maintenance, carrying out engineering projects such as building or conversions of the vessels, performing vessel assurance activities, and personnel planning. Moreover, the procurement and logistics activities required to outfit the vessels are planned by the Purchasing & Logistics Department within the entity. For this project we work together with this department.

### 1.1.2. Purchasing & Logistics Department

The Purchasing & Logistics Department consist of eight globally operating purchasers among which one is in the role of a tactical buyer and is responsible for establishing contact and agreements with suppliers prior to the occurrence of a material or service requirement. Other purchasers, each have several vessels assigned to them and are responsible for carrying out all the purchases related to these vessels. On a daily basis, the purchasers receive material or service requisitions through the vessel crew, vessel superintendent, Maintenance and Repair Engineering or Fleet Development Departments. Then an initial set of suppliers is selected based on experience. These suppliers are asked for a quotation. Among these suppliers, a selection is performed based on cost comparison, and a PO is placed. The department is also responsible for following the orders and maintaining contact with the third-party warehouse or suppliers for the deliveries and arranging freight transportation to the vessels. We explain the operation of the department in more detail in Section 2.3.

### 1.1.3. From Purchasing to Procurement Project

Since 2015, following the deterioration of the oil & gas market, Fugro has initiated various cost reduction projects. The “From Purchasing to Procurement” project has been introduced in 2016 by FS to establish an efficient and effective global procurement operation that would improve financial performance along with service quality. The project consists of five work packages. The first package addresses the improvement of supplier and item databases. The second introduces specializations in the procurement team, and divides purchasers in roles of either a tactical or an operational buyer. The third package focuses on managing suppliers and logistics. The remaining two packages focus on developing key performance indicators (KPI) for evaluating the employee performance and automating the procurement process. In relation to the last package, FS wishes to have a quantitative model for determining supply chain decisions. Hence, we conduct this thesis with the aim of modeling an efficient supply chain model optimizing the use of the distribution network for consumables & parts.

## 1.2. Research Plan

### 1.2.1. Problem Description

Fugro has a fleet of vessels on mission in different regions around the world all the time. These vessels are required to be optimally equipped to fulfill their tasks related to site characterization or asset integrity. Moreover, the availability of goods required by the crew such as food, clothes or medicines should also be ensured. Critical spares are mainly stored onboard, but for most consumables & parts, periodical orders are planned in advance. Currently, when requests for these orders are received by the Purchase & Logistics Department, a purchasing decision is made based on experience and intuition.

The degree of efficiency of this approach is not known. In Section 1.1.3 we have expressed that FS wishes to improve their global procurement operations to improve financial performance. FS has a global network consisting of a large supplier base and multiple warehouses that make it difficult to evaluate the costs of all alternative purchasing and distribution options. We aim to analyze the current practices and develop a structured model providing efficient purchasing ad logistics decisions. Therefore, we give the problem statement as:

“Fleet Services does not have a quantitatively founded purchasing & logistics practice that could ensure cost efficiency.”

Apart from the difficulties in making cost efficient purchasing and distribution decisions, we identified other challenges FS faces as the future locations of vessels are not fully known. When and in which harbor a vessel is to be supplied being unknown renders it difficult to make an optimal supply decision. That is, weather conditions or additional missions that are scheduled after an order is placed affect the performance. Purchasing and resupply planning is therefore limited to short term. The available storage space further restricts the type and quantity of SKUs (stock keeping unit) to be stored on board. Apart from purchase costs for consumables & parts, logistics costs including transportation and taxes should also be considered. The supply decisions should further take into account that the average waiting time of vessels at ports is typically short.

In Figure 1.2, we illustrate the above identified problems in the form of a problem cluster, using the representation introduced by Heerkens et al. (2017). The causal relationships are shown with directions of arrows. Current expenses being perceived as high and risk of downtime are final problems which FS expresses concern over. Expenses are perceived to be high as there is no standard methodology that provides control over the process and comparing alternative costs. This is also a result of FS having a complex network with many suppliers and distribution options. Furthermore, there is a risk of downtime due to product unavailability as constraints and uncertainties related to the operation of vessels may render it difficult to supply the vessels on time. The absence of a standard methodology is a core problem as it is the cause of many other problems. The lack of data and the uncertainties related to the vessel operation render it difficult to formulate a quantitative methodology, and vice versa, the absence of a systematic approach result in these issues remaining as problems. Among these problems, in this research we address high purchasing and logistics costs and propose a quantitative supply chain model to optimize the logistics pipelines. We further explain the motivation for the research direction in Section 1.3 when outlining the scope.

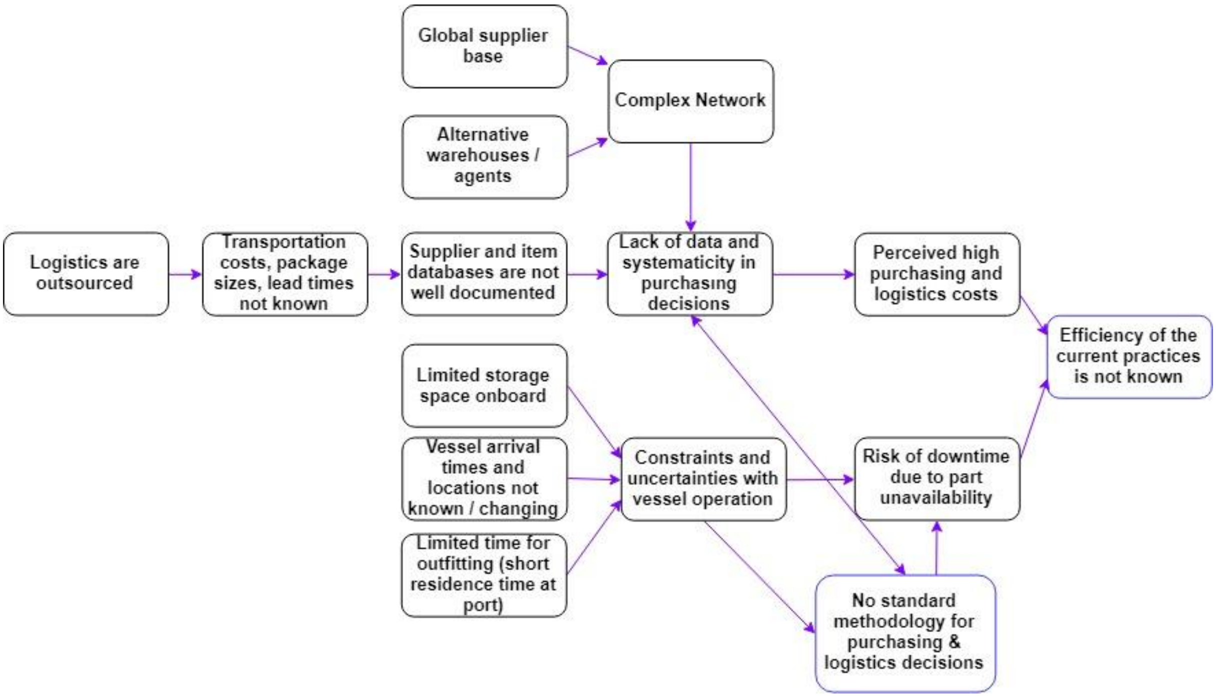


**Figure 1.2**. The problem cluster representing cause and effect relationships between identified problems

### 1.2.2. Research Objective

The desired output for the project is a model that ensures the demand is met with minimum costs. The model should determine the suppliers to submit the orders to and the optimal flow of goods in the distribution network. Therefore, we formulate our main research goal as:

“Develop a decision-making tool for consumables & parts to minimize total purchasing & logistics costs”.

We address this research objective by analyzing the current way of operation and building a tailored model for FS’s purchasing and logistics network. We further list the deliverables of this research as below:

- Insight on the current cost breakdown structure for purchasing and distribution expenses.
- A mathematical model for selecting suppliers and delivery routes for given list of orders per port call. Here, we define a port call as an intermediary stop of a vessel for loading or unloading goods. The port calls are defined along with a port location and an order list to be loaded onboard.
- An optimization tool that runs the mathematical model with generic data.
- A cost calculation tool for calculating the costs of given supply and distribution decisions.
- Analysis on the impact of the model. This analysis corresponds to insight on savings, discount and consolidation opportunities.
- Recommendations for purchasing and distribution strategies based on general rules that follow from our analysis.

### 1.2.3. Research Questions

In alignment with the problem description and project objective, we formulate a main research question and following sub-questions to outline a solution approach. The focus is on the main research question which we define as follows:

"How to make purchasing & distribution decisions for consumables & parts to ensure efficient operation of purchasing & logistics?"

Beamon (1999), defines efficiency as minimizing the utilization of resources in the system to meet the system's objectives. Here we define efficiency as minimizing purchasing and logistics costs while ensuring all required goods are supplied. In correspondence with the research questions, we organize a research framework as described in Figure 1.3. The first step of the research is analyzing the current operation of FS (Q1). Our aim is to gain an understanding of current practices; operation steps, decisions made and motivations behind them and the limitations. We perform data analysis on purchasing, stocking and transport decisions and carry out informal interviews with members of the Purchasing & Logistics Department. We also review the project documents of the "From Purchasing to Procurement Project" to analyze the operation of the internal organization. Then, we conduct a literature review on distribution network design and study alternative modeling techniques (Q2). In alignment with the information we obtain from the literature study, we formulate a distribution network approach that is applicable to FS's case. We then translate this approach into a mathematical model (Q3) and evaluate this model in comparison to the current situation (Q4). We address each research question separately in the following chapters.

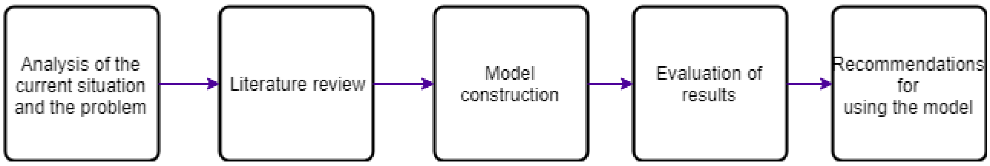


**Figure 1.3.** The research approach

Q1: How are purchasing and logistics processes handled at FS?

- How do items flow in FS's supply chain network?
- What purchasing, stocking and transport decisions are made and how are they motivated?
- What are current inefficiencies in the processes and what are the causes behind them?
- How can the efficiency of the current performance be measured?

Q2: What theory and methodologies are presented in the literature in relation to distribution network design?

- What distribution network options are covered in the literature?
- What modeling approaches have been utilized to optimize procurement and distribution strategies?

Q3: How can a quantitative model for purchasing and logistics decisions be constructed?

- What are the quantitative and qualitative trade-offs considered for constructing the model?
- How can the existing network can be translated into a mathematical model?
- What approach/ technique should we use to make purchasing and distribution decisions?
- What input data is used, and output is obtained from the model?

Q4: What are the optimal decisions for outfitting orders for the port calls?

- How can the model be validated and verified?
- How are the products procured and distributed compared to the current case?
- How significant are the improvement opportunities?
  - What are the optimal costs of purchasing and distribution and how do they compare to the current practice?
- How sensitive are the purchasing and distribution decisions to the changes in input parameters?
- What strategies should be followed for outfitting orders for a port call?

Finally, we give a summary of our findings and conclude the paper with recommendations for integrating the model to the current way of operation.

### 1.3. Project Scope

We define the scope of the project to incorporate company preferences while maintaining a manageable problem size. As the demand information can be known prior to the arrival of a vessel FS does not keep any safety inventory. The products are purchased only after items are requested by the vessel crew. Only these items that were requested by a vessel are temporarily stored in the warehouse until a port call occurs. FS wants to maintain this practice to avoid excessive inventory holding costs.

Therefore, we draw the boundaries of the project with the below statements:

- The model only addresses materials of type "consumables". Since these items constitute of household goods, stationary and small hardware that are consumed regularly, FS believes there is a possibility to standardize their purchasing and logistics processes. FS has already introduced periodical order groups for certain consumables in order to ensure availability onboard and reduce purchasing effort. We need to determine the optimal purchasing and delivery options for these goods. In the remainder of this paper we use "consumables" and “consumables & parts” interchangeably.
- We do not introduce a direct supplier selection methodology based on supplier characteristics. Suppliers FS has been working with already meet the quality requirements and comply with the delivery and payment conditions. Our selection of a supplier for a specific order is the result of the total purchase and distribution costs.
- FS states that for consumables & parts, all orders are met and downtime due to unavailability does not occur. We assume the suppliers have all the parts they have previously provided. Similarly, we assume suppliers have no capacity constraints as no issues over purchase quantities have been communicated before.
- We do not re-consider long term contracts and costs and include only the operational costs.
- For this project, FS wishes to manage the operations more efficiently using the current distribution network. We evaluate the distribution network for determining the optimal flow for each specific order. We only consider the suppliers and warehouses existing in the database.

# Chapter 2

# Analysis of the Current Situation

In this chapter, we analyze the operation of Fleet Services with respect to purchasing and logistics decisions. We provide a description of the current situation based on PO data from 2017. We limit our analysis to 15 port calls with respect to the available data. Moreover, considering all port calls would be exhaustive and would render analyzing the results difficult. These port calls are therefore selected randomly and represent various possibilities as they have different orders and different port regions. Here, we note that due to data unavailability, we cannot give a conclusion on to what extent these port calls are representative of the whole fleet. We only refer to these to evaluate the opportunity for savings. In Section 5.2.1, we describe this selection procedure in detail when discussing the experimental design.

We consider material orders of type “consumables”. These correspond to items such as accommodation necessities, stationary and medical supplies as well as production related items such as electronic components, nuts & bolts and chemicals & gases. The chapter is organized as follows: Section 2.1 starts with an introduction on FS’s distribution network; Section 2.2 provides information on demand; Section 2.3 explains purchasing processes; Section 2.4 provides information on the supplier network and Section 2.5 presents the logistics and transportation decisions. Sections 2.6 and 2.7 explain stock keeping processes and discuss the current performance. Finally, Sections 2.8 and 2.9 mention information systems used, along with present data issues. Section 2.10 presents conclusions for the chapter.

### 2.1. Current Network

In this research we focus on FS’s global supply chain network. Items can be delivered to the vessels through different suppliers and distribution routes. FS operates in four regions namely, Europe & Africa, Asia & Pacific, Middle East and Americas. We illustrate the operation of the network in Figure 2.1 using a simplified process chart following the notation of Visser and van Goor (2004), and ISO (1985). We further explain the purchasing operations in Section 2.3.

The main participants of the supply chain are: the vessels, FS (Purchasing & Logistics Department), suppliers, warehouses and agents. The vessels perform operations related to the core businesses and inform Purchasing & Logistics Department in case they need any items to be purchased for the next port call. Purchasing & Logistics Department, performs supplier selection, goes through a quote process and places POs for these items. The purchasers are also responsible for monitoring the deliveries. The suppliers are responsible for delivering the items to the specified location which may be an agent, a third-party warehouse or the port the vessel is in before the specified due date. Warehouses are responsible for receiving the goods from the suppliers and storing them until the port call. They also arrange delivery to an agent or a port. FS uses two central third party warehouses one in Rotterdam and the other in Singapore. Usually these warehouses are utilized for consolidating items before delivery to the port. Occasionally, one-time agreements can be made with local third party warehouses. Fugro operational entities can also be used as a local warehouse. FS regularly utilizes Fugro operational entities in Houston, Abu Dhabi and Macaé.

The agents may store goods temporarily and deliver them to the port as well. They are responsible for customs clearance and arranging berthing. They may also provide support with maintenance activities.

It is possible that a previously announced destination can be changed, and the vessel may arrive at a different port. In this case the same agent or other agents may need to arrange the re-location. The operation of the participants and the relations are further explained in the following sections.

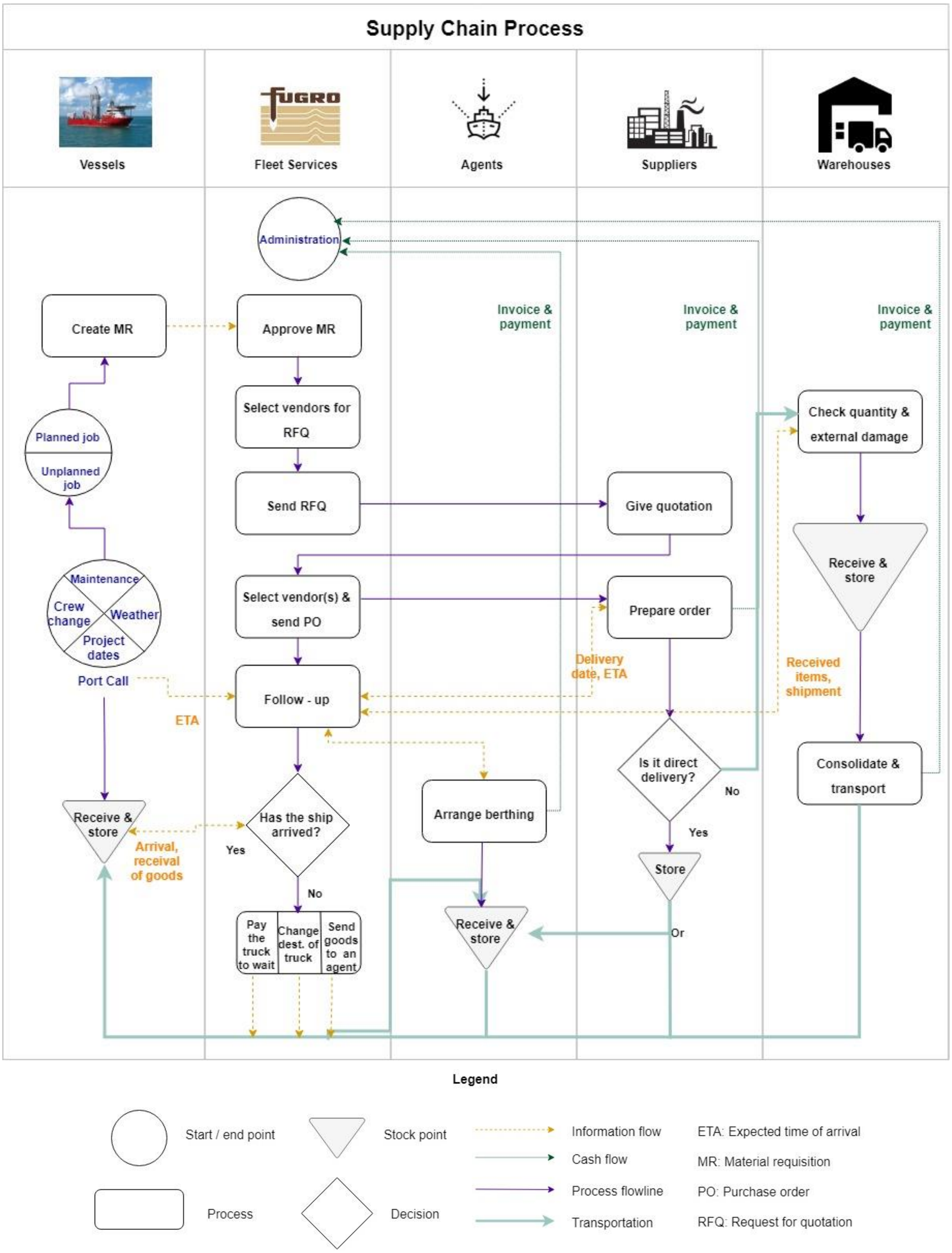


**Figure 2.1.** Supply chain process chart

### 2.1.1. Distribution Options

In this chapter, we identify distribution options based on the logistics pipelines ordered goods can flow through. Considering the current purchasing and logistics practices at FS, we map applicable purchasing strategies and distribution options, and identify alternative routes for deliveries. Currently FS, purchases most items to order, that is, after the creation of a material requisition. Periodical orders are purchased for a long time period (one year or half a year) separately for each vessel. The orders are purchased for a specific port call and stored onboard, they may only be stored in a warehouse in transit before being loaded onboard.  FS does not keep any safety stock but makes purchases with respect to the demand for the port call.

Table 2.1 displays the previously utilized delivery options. Combining these and all the possible configurations, we list the applicable distribution options as below and further discuss their trade-offs:

1. Supplier - vessel
2. Supplier – agent –vessel
3. Supplier – Rotterdam Warehouse – vessel
4. Supplier – Rotterdam Warehouse - agent –vessel
5. Supplier – Singapore warehouse – vessel
6. Supplier – Singapore warehouse - agent –vessel
7. Supplier – local warehouse – vessel
8. Supplier – local warehouse - agent -vessel

A decision on the delivery configuration should be made when placing orders. We distinguish between direct and indirect deliveries, the former corresponding to the deliveries made directly from the supplier to the agent or to the ports, and the latter corresponding to the deliveries made through an intermediary warehouse. We consider two alternatives for the use of a warehouse; local warehouses in the same region as the port call or the currently used central warehouses: the Rotterdam or the Singapore warehouse. As the ordered goods are not stored, the warehouses are used for cross-docking only. The warehouses only store goods for a short period of time from delivery from the supplier until the port call as the orders are placed specifically for a port call.

Direct deliveries can provide the supplier the flexibility to meet the delivery dates by planning in advance. However, if the delivery is made directly to the vessel, the admission and storage could be less efficient as there are more frequent shipments in smaller sizes coming from various suppliers. Still, these multiple shipments would be received in relatively close time periods since the waiting time at port is short.

Direct deliveries to the port are a requisite for delivery of certain goods. For example, fuel is delivered directly to the vessel since the delivery is made by barge or a specialized truck. Perishable goods such as food and medicine are also directly delivered as they require trucks tailored to fit their storage conditions. Similarly, certain chemicals that are marked as dangerous goods also need certain storage conditions and cannot be transported together with other goods due to safety regulations.

Direct deliveries to the vessel can also help avoid handling costs that would otherwise be incurred at the agent or warehouses. However, separate deliveries made to the vessel result in an inconvenience as the admittance of orders become difficult to trace. There are usually crew changes during port calls. The crew being busy handing over the work to the new crew makes it difficult for them to devote time to the admittance of deliveries. Similarly, there are many other operations going on onboard such as maintenance activities that require the attention of the crew. Separate deliveries slow down the operations as they require separate admittance, they cause traffic cause at the harbor, and the loading operations may be repeated since the deliveries are not synchronized. In case the agency is providing a crane service for loading based on an hourly rate, this results in extra costs. Similarly, in case there are many individual deliveries, trucks coming from the warehouses are admitted after these individual orders are cleared because they constitute of smaller orders. This results in extra charges corresponding to the waiting time of the truck.

On the other hand, delivering to the agents or using an intermediary warehouse, enables consolidating items ordered from different suppliers, so the vessel gets a single delivery. Although an increase in coordination is required, this may result in lower transportation costs as products are consolidated. However, transportation costs may also be higher than that of direct delivery if the warehouse is located far from the vessels.

From Table 2.1, we can observe the distribution decisions made previously. As we have stated above, this observation only reflects the selected port calls and consumables & parts. We refer to each distinct item as a stock keeping unit (SKU), we can observe that the number of SKUs ordered differ for each port call. We further describe the generation of demand in Section 2.2. Rotterdam Warehouse is used quite often and for any region, in comparison to the Singapore warehouse or the local warehouses. This choice is related to the proximity of the selected suppliers to the warehouses. In Section 2.5 we also examine the supplier locations. Direct deliveries from suppliers to the vessel and the agents are also commonly used. These are a result of the available time, the agreements with suppliers or separate delivery requirements for certain type of goods as explained above. Details of the port calls in terms of the suppliers used, and the configuration of the distribution network can be found in Section 5.2.2 and in Appendix B.

**Table 2.1.** Number of SKUs with respect to the distribution options that have been used for the port calls

| | | | Distribution Options | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Port Calls | Port Country | #SKUs | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | United Arab Emirates | 161 | 135 | | 26 | | | | | |
| 2 | United Arab Emirates | 41 | | | 5 | | | | 36 | |
| 3 | United Arab Emirates | 120 | | | | | 2 | | 118 | |
| 4 | Singapore | 155 | 1 | 151 | 3 | | | | | |
| 5 | Kenya | 41 | 4 | 17 | 20 | | | | | |
| 6 | The Netherlands | 144 | | | 144 | | | | | |
| 7 | United Kingdom | 51 | | 2 | 49 | | | | | |
| 8 | United Kingdom | 42 | | 13 | 29 | | | | | |
| 9 | United Kingdom | 104 | | | 104 | | | | | |
| 10 | United Kingdom | 33 | | | 33 | | | | | |
| 11 | United Kingdom | 61 | | 1 | 60 | | | | | |
| 12 | Malaysia | 44 | 44 | | | | | | | |
| 13 | The Netherlands | 57 | 2 | | 55 | | | | | |
| 14 | Germany | 46 | | | 46 | | | | | |
| 15 | The Netherlands | 207 | | | 207 | | | | | |

## 2.2. Demand

Most orders are purchased after an MR is created for some set of items while some consumables are purchased in grouped orders periodically per vessel. These periodical orders are ordered at a fixed time for a longer period. When there is demand for a certain item or service, an MR is created to trigger the purchasing process. Since, the orders are mostly placed after the demand information is known, we refer to the purchase data as “demand data” for the analysis.

There are planned jobs called "work orders" for the crew which correspond to "to do lists". The items needed for an execution and their quantities are specified on the work orders. In case some of these items are not available, an MR is created by the crew. Unplanned jobs such as machine break downs or new projects also result in need for items. Requisitions can be made at the office by the vessel superintendents as well.

For frequently used consumables "periodical orders" are placed per vessel as planned in advance, these items constitute 39.12% of all the orderlines of purchases in 2017. These items are replenished one to four times per year. The order quantities are determined by the vessel crew based on experience, and there are no pre-defined re-order levels. The order quantities also depend on the convenience of re-supplying in the next destinations (in terms of price, availability, customs) and varies for each port call (Figure 2.2). For periodical orders, MRs can be created in advance. On the other hand, especially when there is an urgency or uncertainty about specifications, some requisitions are first communicated with the purchasers, and are registered in the system later.

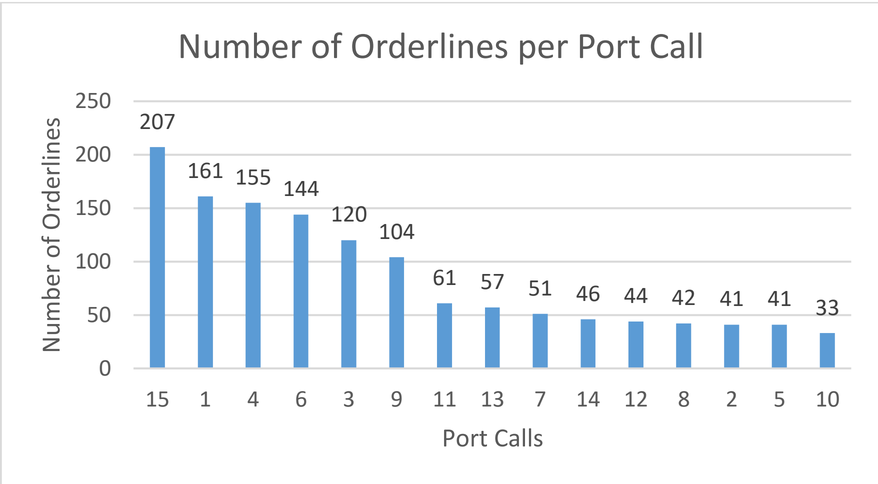


**Figure 2.2.** Number of orderlines for consumables & parts for selected port calls

### 2.3. Purchasing Process

Purchasing & Logistics Department carries out procurement processes such as selecting vendors, asking for quotation, awarding quotes, placing orders and following the placed orders. Looking at the whole 2017 data for consumables & parts, we observed that **9.976** SKUs were bought from a total of **401** suppliers. For the purchases, **2.715** POs were issued with a total of **19.806** orderlines. This corresponds to an average of 7,29 orderlines per PO.

The demand from ship level is fulfilled through the purchasing processes. As explained above, the purchasing process starts after receiving an MR (Figure 2.1). After the MRs are created, depending on the prices quoted by the suppliers, POs are placed for the required items. A PO corresponds to a single vessel and is submitted to a single supplier, and it can cover multiple items. Items needed for different MRs can also be combined in the same PO if they are to be ordered from the same supplier.

Before asking suppliers for quotation, an initial set of suppliers are selected based on experience, past purchase history and intuition. The purchasers place an order immediately after receiving an MR to ensure the goods will be delivered on time. Usually these goods are consolidated in the warehouse in advance to ensure timely delivery to the vessel. Generally, for consumables the cheapest supplier is selected while the original equipment manufacturer (OEM) is preferred for spare parts. If an order is expected to be more expensive than €3000, at least three suppliers are asked for quotation in order to prevent excessive orders and to ensure budget constraints are not exceeded. Moreover, each PO must be approved by a vessel superintendent. When there is more than one supplier, whether awarding the lowest-cost quote or splitting the order among the suppliers is more economical is checked to reduce expenses. This is done considering only the product prices. The information system has a function to highlight the cheapest supplier per item. Given this, the purchasers decide whether it is more convenient to split the order to have savings or whether to issue a single PO for reducing the purchasing effort. The purchasers may ask the supplier for discount if they perceive the total amount to be high. The purchasers stated that suppliers sometimes apply a 5% or a 10% discount over the total PO amount in these cases.

**2.4. Supplier Information**

In 2017, orders for consumables & parts were placed to 401 suppliers, in 40 countries. A large fraction of the purchase volume is sourced from the Netherlands (40,7%), followed by Germany (16,8%) and Singapore (11,4%) (Figure 2.3). Although some suppliers are original equipment manufacturers, some serve as intermediary firms. The exact purchase locations of the goods are not always known, yet transportation costs are sometimes provided by the suppliers.

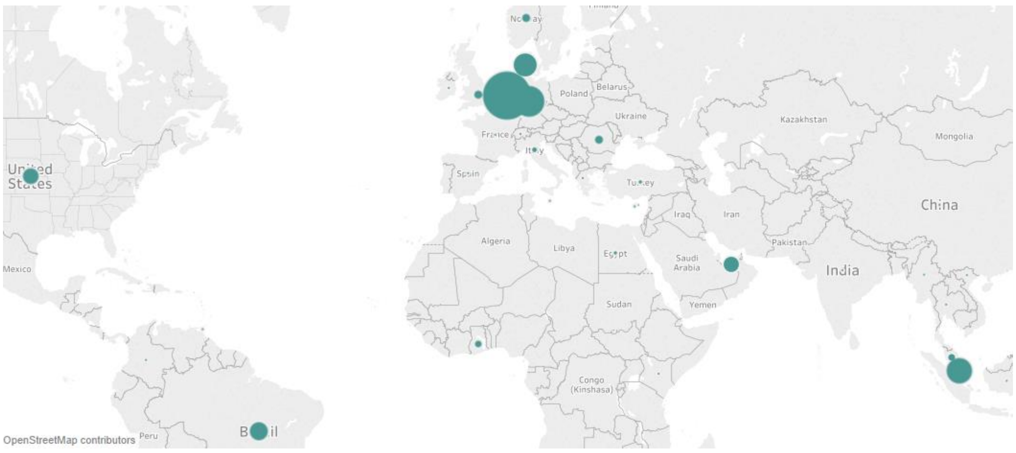


**Figure 2.3.** Map displaying supplier locations (countries) with respect to total purchasing spend over 2017

For the 15 port calls we selected, we examine the number of substitute suppliers the items have (Figure 2.4). The suppliers are referred to as substitutes if an item can be purchased from any of these suppliers without distinguishing among them. We observe that out of 1426 items, 582 have been purchased from only one supplier in the past year. Due to data availability, we include only the suppliers that were awarded a quote before and we do not know to what extend these selections considered other suppliers. However, for our model, we refer to supplier substitutability as this would affect the decisions. Having a small number of alternatives, limits the supply options and this may limit the applicable delivery options as well. Since the supply decisions are already fixed for these items, the decisions for the other items would be made in correspondence to these to ensure savings. For better performance, the model should be run with all candidate suppliers, leaving out the suppliers that are definitely not to be used.

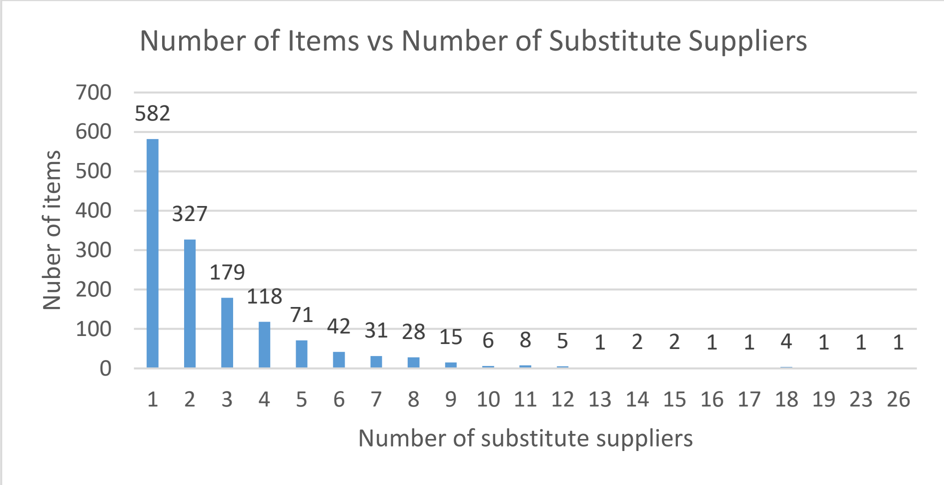


**Figure 2.4.** Number of items for given number of substitute suppliers

## 2.5. Logistics and Transportation

A third-party warehouse located in Rotterdam is used as a central depot where most orders are received, stored in, and later consolidated to be delivered to the ships. Around 30% of all the POs were ordered to the warehouse in 2017. in case certain storage conditions or time limits should be met, some orders can also be ordered to be directly delivered to local agents. Similarly, in case of a time limit or a port arrival, items can be ordered directly to the vessel. However, since there is a long-term contract with the warehouse, transportation and holding costs for alternative locations are usually not considered when placing orders.

Transport modes are chosen by the supplier when delivering orders and by the third-party warehouse when delivering goods to the ships. Truck or airfreight can be used for deliveries. In case there is an emergency order, a courier is arranged immediately, and the delivery is arranged in the fastest way applicable, usually disregarding the cost aspects as they are not comparable to day rates of the vessels.

When moving the goods from the warehouse to the ports, the transport mode is selected by the warehouse and FS receives an invoice accordingly. In case a full truck load is achieved, direct delivery to the vessel is preferred. Otherwise, the goods may be sent to a local agent for storage. If the ship does not arrive at the pre-stated time, following actions can be taken: the waiting time of the truck can be paid for, the destination of the truck can be changed, or an agent can be paid to receive the goods.

After an arrival day for the vessel is decided on, an expected arrival day is shared with the offices and is updated daily by the vessel crew. This ensures the outfitting will be planned accordingly. As we stated above, arriving to a port is referred as “port call” and can occur due to following reasons: crew changes, project start and end dates, maintenance (planned or unplanned) and weather conditions. An announced port location can also be changed in case the port does not have available space or weather conditions render it difficult to enter the port.

## 2.6. Inventory and Storage

In the FS database, on hand stock level is kept through following the POs and MRs. Every time a PO is finalized (items are received onboard and the invoices are paid), stock count is increased by one in the system. Similarly, after the completion of a “work order” at the vessel, the onboard stock levels of the items used for the job are reduced in the system. Since registering these activities in the system takes time, actual inventory levels may sometimes be different than the ones shown in the system.

As we mentioned in Section 2.2, periodical consumables are stored on board of the ships to cover the consumption for half a year or one year. Critical items are stored on board of the ships as well, the stock quantity is determined by the experience of the crew together with the recommendations of the supplier. Critical parts correspond to parts the failure of which would result in hazardous situations to the safety at sea, human safety or the protection of the environment, and are determined with respect to International Safety Management (ISM) standards. Other critical parts are ones that are critical for the continuation of the operation and are determined by the Maintenance and Repair Engineering Department. However, for most parts there is no inventory planning, and as mentioned above, orders are placed when demand is known.

The storage locations within the vessel are determined by the crew. Items received at the warehouse are reported daily. However, the packages are not checked after they are received from the supplier, and missing items may end up being registered as “received” in the system. The degree of regulation during outsourced repair and maintenance operations is not known either. For example, the party offering the service may use parts from the stock of the vessel, and this may end up not being reported. Big ships have dedicated stock keepers onboard who ensure that stock is counted and receivals are registered on system accurately. However, for smaller ships, aforementioned problems occur more frequently. As the ships are at the port for outfitting only on certain time periods, orders that are placed early wait in the warehouse resulting in warehousing costs. However, warehousing performance and inventory age are not tracked.

### 2.7. Current performance

Purchasing & Logistics Department adds value through ensuring the required items are procured in a cost and time efficient way. Purchasing & Logistics Department follows certain internal KPIs. For example, average number of request for quotation (RFQ) drafts should not be higher than 7 and the percentage of unmet promised deliveries has a limit of 95%.

A certain amount of saving should be made from procurement costs as well. This saving corresponds to the gain from choosing cheaper suppliers or distributing orders among multiple suppliers. However, as mentioned above, the supply chain performance in terms of warehousing or supplier lead times, which may be more important for attaining savings, is not accurately tracked. Data related issues regarding this process is further covered in Section 2.9.

Although there is no data available, it was expressed by the company that part - availability haven’t caused downtime in the past years, orders are always managed through emergency deliveries contacting the suppliers. As mentioned above, in case of urgent orders, purchasing and transportation costs may be disregarded, and stock-outs are prevented. Budget targets are calculated referring to the expense data of the last year, then foreseen expenses for additional maintenance activities and the crewing-budget are added to this amount. Budget does not serve as a hard constraint but an indicator for the business for budget allocation. The necessity of an MR is judged with respect to the available budget and purchasing decisions are made accordingly.

As explained above, purchasing and logistics operations are performed on spot and which decisions are made are difficult to generalize over port calls. Section 5.2.2 and Appendix B provides illustrations on the network configurations. For example, generally, if central purchases are made, orders are consolidated at a warehouse close to the suppliers and then transported to the port region. However, for Port Calls 1 and 5, the Singapore Warehouse was not used for consolidation. We observe that for port calls in Europe only suppliers in this region were considered. For port calls in Middle East or Asia, suppliers from Europe and these regions are used together.

We identify the components building up the total costs of purchasing and logistics. Combining the information in the previous chapters, we illustrate the cost components with a fishbone diagram in Figure 2.5. Below we list these costs and provide a short description. In Chapter 4, we explain in detail how these costs are quantified and applied.

- Product cost: Amount spent on the products, refers to the summation of product prices
- Ordering cost: Cost of submitting an order to a supplier, refers to the cost of personnel involving in the procure to pay process
- Transportation cost: Cost of transporting goods between locations
- Fixed facility cost: Cost of utilizing a facility per port call, refers to cost of admission and documentation
- Handling cost: Cost of handling goods at a facility
- Loading the vessel: Cost of loading each arriving shipment to the vessel, refers to the cost of the loading equipment and the personnel

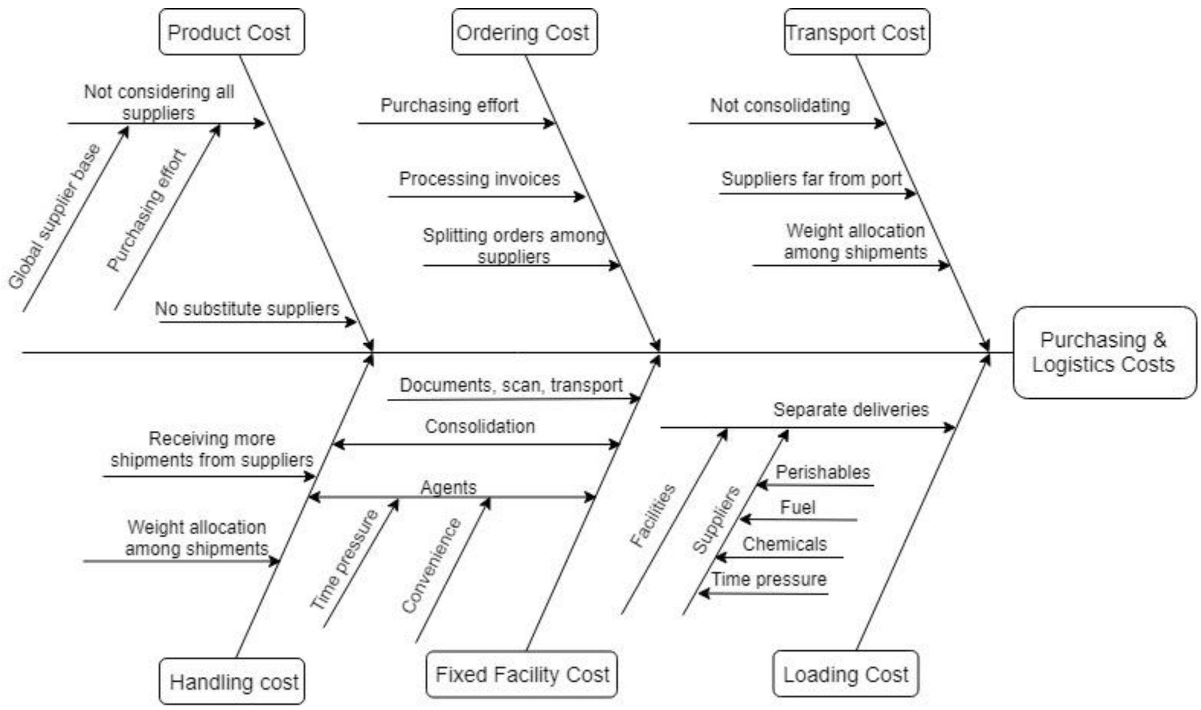


**Figure 2.5.** Cause and effect diagram for total purchasing and logistics costs

Below we study the cost breakdown of the 15 port calls. In Chapter 4, we explain how these costs are estimated. Looking at the distribution of the costs (Table 2.2), we conclude that the product costs constitute the largest fraction of the total costs and we evaluate opportunities for procurement discounts in Chapter 5. FS has already initiated negotiations with suppliers for reducing product prices. Similarly, we observe that the transportation costs are the second highest influencer on the total costs. This also emphasizes the importance of taking the economies of scales into consideration while planning deliveries. We want to evaluate the saving impact of such decisions.

**Table 2.2.** Estimated purchasing and logistics costs for the 15 port calls in the current situation

| Description | Europe (9 Port Calls) | Non Europe (6 Port Calls) | Total Costs | Percentage of Total Costs |
|---|---|---|---|---|
| **Product cost:** | 127.535 | 180.139 | 307.674 | 81,2% |
| **Transportation cost:** | 7.044 | 31.870 | 38.914 | 10,3% |
| **Ordering cost:** | 13.000 | 6.600 | 19.600 | 5,2% |
| **Loading the vessel:** | 4.200 | 4.800 | 9.000 | 2,4% |
| **Handling cost:** | 1.334 | 514 | 1.848 | 0,5% |
| **Fixed facility cost:** | 840 | 1.078 | 1.918 | 0,5% |
| **Total cost:** | 153.953 | 225.000 | 378.953 | |

We inspect the logistics costs in more detail with respect to the port locations. Here, we refer to the total cost of transportation and facilities together as logistics costs. Looking at our test cases of 15 port calls, on average, logistics costs for a port call outside Europe (5.577€) is 5,4 times more expensive than that of a port call in Europe (1.024€). As we have explained in Section 2.4, more than 50% of the purchase volume is in Europe and many products have been purchased only from Europe based suppliers. Dependency on suppliers in Europe requires more inter-continental deliveries resulting in higher transportation costs. Therefore, there may be a higher potential for savings from economies of scales for port calls outside of Europe.

### 2.8. Information Systems

Item information is stored in StarIPS, the database system which is available for the crew onboard. Planned works including planned maintenances of vessels, equipment trees (bill of materials) along with tactical accounts and part specifications are available in the system. The database is updated hourly. Work orders and MRs are created in this database. MRs are received and processed by purchasers and vessel superintendents through another system, StarFSM (Fleet Supply Management). This database allows creating RFQs and POs and includes a supplier database and a past purchase history per item.

Currently, there are two databases, one for purchasers (starFSM) and one for the Finance Department. The Finance Department registers suppliers when a receipt arrives. Both databases are manually filled in and this manual entry, together with the duplicity of databases, may result in double entries. The system will be changed so that only the Finance Department will have access to the database and their entries will be linked to the orders.

### 2.9. Data Issues

In this section some issues regarding the data accuracy are summarized. Some of them already are recognized for hindering purchasing processes. However, others are not given high attention yet. Such issues would make accurate evaluation of the performance difficult. Data on the delivery times and cost breakdown with respect to the logistics are not well documented.

A delivery date is set when placing a purchasing order. Some vendors provide a new expected delivery date together with their order confirmation. However, usually such a date is not provided and a promised delivery date for the order is manually entered in the system by the purchaser. This date is manually postponed if the vendor is contacted in the meantime. Therefore, the punctuality of the vendors is not fully known. Moreover, MR and PO creation dates do not always represent reality as some requisitions and orders are first communicated with the vessel crew / suppliers before they are officially created in the system.

Freight forwarders and facilities usually provide an overall quote, and the tariff structure and the pricing criteria used is usually not clearly presented. In Chapter 4, we describe the assumptions we made and limitations regarding data availability. Spend amounts may also be wrongly entered in the system. When a PO is created, costs given in the quotation are considered. Invoices are booked later after the completion of the delivery. However, it happens relatively often that the PO amount and the invoice amount do not match. This could happen because of errors with manual entry, suppliers updating the quotations or transportation costs being added later.

### 2.10. Conclusion

This chapter allowed us to answer the first research question: "*How are purchasing and logistics processes handled at FS?*". We observed that FS does not have a standard methodology for selecting suppliers nor distribution options. The discounts are attained rather randomly and possible discount options that could arise from purchasing larger quantities from the same supplier are not considered when placing orders. Similarly, economies of scales in transportation, or agency and warehousing costs arising from consolidating shipments are not accounted for in advance. We observed that procurement costs constitute 81% of the total costs followed by transportation costs that correspond to 10%. We contemplate that procurement and freight discounts present an opportunity for improvement and should be taken into consideration systematically.

Given above observations, we conclude that in order to minimize total costs and ensure all required goods are ordered, we should present an integrated approach for selecting suppliers and determining logistics pipelines to be followed per order. We should build a realistic model considering all identified cost components and the applicable distribution options. We can further explore consolidation strategies to receive discounts on purchasing and transportation, as well as to reduce the purchasing effort resulting from contacting many suppliers. Trade-offs between ordering from different suppliers and using different delivery options could be better evaluated considering the whole distribution process. In the next section we perform a literature review on distribution options and methodologies for network optimization.

# Chapter 3

# Literature Review

The problem described in Chapter 2 can be summarized as not having a method for evaluating alternative purchasing and distribution options. To determine how to select purchasing and distribution strategies for FS, we perform a literature study. We give a brief introduction in Section 3.1., with basic information on global sourcing and trade-offs in distribution networks which reflects the conceptual background of this research. Here we explain the trade-offs between the options we identified in Chapter 2. Next, in Section 3.2. we explain related work on network optimization and illustrate classical supply chain design models. We conclude this chapter in Section 3.3 by presenting the solution methodology that will be followed.

## 3.1. Introduction

Supply chain is a complex network of all facilities and organizations involved in moving a product or service from the manufacturer to the customers. Simchi-Levi et al. (2003), define supply chain management as a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements. The efficient operation of the company depends on the procurement decisions and the pipeline structure of the distribution network (Ross and Jayaraman, 2008).

### 3.1.1. Global Sourcing

Acquiring part or all of the required goods from suppliers from countries all over the world has become a trend as it yields to cost controls and possibility to attain savings (Crainic et al., 2013). This worldwide integration of engineering, operations and logistics to meet procurement requirements is defined as global sourcing (Trent and Monczka, 2003). Acquiring goods from countries with low manufacturing costs and tailoring logistics networks accordingly has become usual practice for many industries (Crainic et al., 2013, Christopher et al., 2006). Still, Christopher et al. (2006) states that low cost sourcing strategies can result in high-cost supply chain outcomes. They emphasize that the transportation costs should not be overlooked. Network operations require costs to be considered along with transport and lead time efficiency. When evaluating supply chain performance, Simchi-Levi et al. (2003) emphasize that a systems approach should be taken, and all stages should be considered together.

### 3.1.2. Distribution Network

Distribution refers to the steps taken to move and store a product from the supplier stage to a customer stage in the supply chain (Chopra & Meindl, 2014). Distribution occurs between many stages in the supply chain. Supply chains consisting of multiple locations that products can be distributed through are referred to as multi – echelon supply chains. Different goods may participate in several often different supply chains (Christopher et al., 2009). Each path followed by a product; the channels of transport, warehousing, handling, and control through which goods flow is also referred to as a logistics pipeline (Fuller et al.,1993). Traditionally, number of delivery pipelines and the range of products flowing down each channel to the destination have been determined by intuition (Christopher et al., 2009).

Combining the distribution network design classifications made by Chopra and Meindl (2014) with practices followed by FS, we group the distribution options in three configurations: (1) supplier storage with direct shipping, (2) supplier storage with direct shipping and in-transit merge and (3) distributor storage with last-mile delivery (Figure 3.1). Suppliers delivering directly to the vessel corresponds to the first option. FS uses warehouses and agents for transit. Long term storage is not used, and no safety stock is kept, therefore utilization of the facilities corresponds to the second option.

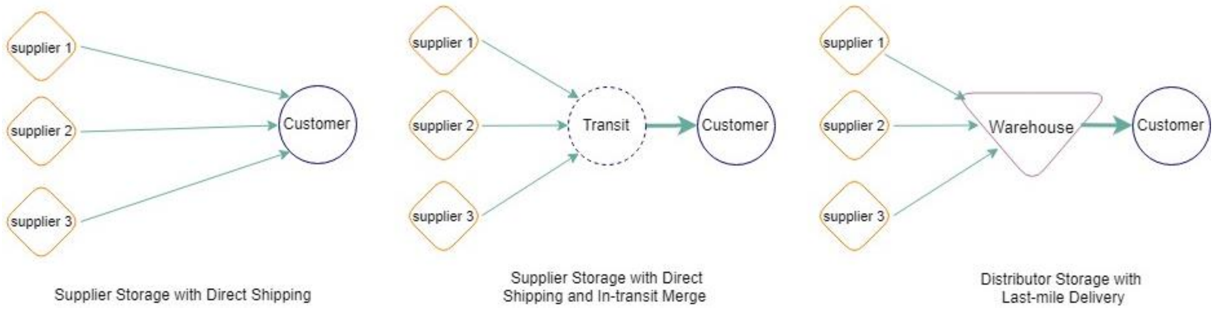


**Figure 3.1.** Distribution network configurations

With supplier storage with direct shipping, the items can be shipped directly from the supplier to the vessels. Since the orders are placed on demand and per vessel, the supplier would keep the inventory separately. Therefore, there is no risk pooling advantage for the supplier, yet this gives the supplier the opportunity to plan in advance and manage their internal lead time more efficiently (Simchi-Levi et al., 2003). This configuration generally requires significant investment in information infrastructure as synchronization is needed among different stages of the supply chain (Chopra & Meindl, 2014).

A disadvantage of supplier storage with direct shipping could be that the items ordered from different suppliers are not consolidated, and the receival and storage could be less efficient for the vessel as there are more frequent shipments in smaller sizes. Still, these multiple shipments would be received in relatively close time periods as the vessel is at port only for a short time.

Unlike the first option, under which each product in the order is sent directly to the vessels, supplier storage with direct shipping and in-transit merge combines pieces of the order coming from different suppliers, so the vessel gets a single delivery. The process is completed relatively fast and no inventory is kept. Although an increase in coordination is required, in-transit merge may decrease transportation costs relative to direct delivery by aggregating the final delivery. Still, higher overall handling costs are incurred. This network configuration is also referred as cross-docking (Simchi-Levi et al., 2003). Gue (2007), states that cross-docking is applicable when customers are willing to wait for their orders. Since, in our case the vessels have to wait until arriving to a port to be re-supplied, this configuration may be applicable. Moreover, both option 1 and option 2, can help shifting the storage costs to the supplier while giving the supplier flexibility to meet the delivery dates by planning in advance (Ross and Jayaraman 2008).

Under the distributor storage with last-mile delivery option, inventory is sent to intermediate warehouses by the supplier and stored there, and transportation to the vessels is also arranged by the warehouse. Transportation costs may be higher than the former two options are the warehouse is located far from the customers or if many small orders are to be delivered to the customers (Chopra & Meindl, 2014). Since in this research, there is a limited number of vessels and they require bulk deliveries, this configuration may be applicable.

### 3.2. Supply Chain Network Optimization

#### 3.2.1 Supply Chain Model Classification

Supply chain models incorporate many levels regarding the mathematical formulations and managerial aspects. To classify the problem at hand, we refer to Huang et al. (2003) and Mula et al. (2010). Huang et al. (2003) proposed four criteria for classification, namely, supply chain structure, decision level, modeling approach and shared information. Here, we refer to the first three as we do not consider information sharing between the different participants in the supply chain.

The supply chain structure refers to the relationships between the organizations in the supply chain. Four types of network structure can be defined as below (Beamon and Chen, 2001, Mula et al., 2010):

- Convergent: each location in the chain has one successor and non or several predecessors.
- Divergent: each location has one predecessor and non or several successors.
- Conjoined: a combination of each convergent chain and one divergent chain.
- Network: this cannot be classified as convergent, divergent or conjoined, and is more complex than the three previous types

Decision levels are mainly classified by the extent or effect of the decision to be made in terms of time (Mula et al., 2010). In supply chain network problems, the strategic level covers decisions made in relation to selecting number, capacity and location of facilities as well as contracting decisions. The tactical level corresponds to determining the distribution planning, transportation modes, amount and type of purchases and managing safety inventories. Finally, replenishment and delivery operations are made at the operational level (Huang et al., 2003, Farahani et al., 2014). Linear programming, fuzzy programming, stochastic programming and, heuristic algorithms have been used for network optimization problems (Huang et al., 2003, Mula et al., 2010).

Given above, we identify the model we present in this research as a network structure as we have a multi-echelon network with flows going skipping or through intermediary steps as we identified in Chapter 2. The model will serve for tactical planning as the decisions concern submitting purchases and determining the distribution of the purchased items through the facilities. We follow an exact approach and formulate the problem as a mixed integer linear programming model in Chapter 4.

#### 3.2.2. Related Work

First, we give an outline of the literature review process and explain how the articles relevant to our research were selected. We primarily used Scopus as the literature database as it includes articles from many publishing portals such as Elsevier, Taylor & Francis, Wiley or Emerald. We list the search terms used below. We initially make an abstract review on these primary resources to assess their relevance and, then also review the relevant references listed in these articles. We used Google scholar for articles that were not accessible via Scopus.

- "distribution network optimization" AND "supply chain"
- “distribution network design” AND "supply chain"
- "supply chain network design" AND distribution
- “supply chain network optimization”
- “supply chain network design problem”
- “supply chain” AND “network models”
- "supply chain" AND "flow problem"

Supply chain network design (SCND) problem aims to construct an efficient network structure or to reengineer an existing network (Gan et al., 2014). The network structure to be determined may correspond to the number, location or capacity of manufacturing or distribution facilities. After the network structure is determined, the flow of the goods in the network is optimized. The goal is to make this decision while meeting demand requirements of the network. These decisions concern various costs such as shipping cost, resource cost, manufacturing cost, advertising cost, and ordering cost. Most related studies in this area selects minimization of total costs as the objective (Ebrahimi, 2018). Integrated models, considering decisions on production, inventory and distribution simultaneously are studied widely in literature (Mula et al., 2010).

Owing to the high importance of the SCND, there are a relatively large number of review papers in this field. Farahani et al. (2014), propose a comprehensive review for the SCND in different categories such as solution approaches, model types, and applications. Melo et al. (2009), compare various articles on facility location with respect to supply chain structure, planning period, decisions considered and application area.

There are many studies using exact mathematical techniques. Linear programming is widely used for network optimization problems (Mula et al., 2010). Karabakal et al. (2000), customized the facility location model to generate acceptable scenarios minimizing the costs of transportation and facility operation for the number and location of automobile distribution and processing centers. Gümüş and Bookbinder (2004), present a linear programming model to minimize total costs of operation and transportation in a three- echelon network, consisting of manufacturers, cross docks and customers. Graves et al. (2007), combines freight consolidation with network design. They formulate an integer linear optimization model to decide on the number, location and operation of consolidation hubs minimizing the total logistics costs for the network. De Keizer et al. (2014), developed a mixed integer linear programming model to investigate the benefits of logistics orchestration in three scenarios. In these scenarios, the effects of network design and logistics consolidation on logistics costs, working times and carbon dioxide emissions are quantified.

Apart from exact models, heuristic models providing near optimal solutions are widely presented for SCND problems. Heuristics algorithms are preferred when the model size is large, and an exact solution cannot be obtained with commercial solvers in an acceptable time (Eskandarpour et al., 2017). Altıparmak et al. (2006), presented a multi-objective model that tries to minimize the total cost and maximizes the customer service and equity using to determine which candidate facilities to operate and the shipment quantities between them. They developed a genetic algorithm (GA) based on new solution procedure to find the set of Pareto-optimal solutions and show that their developed GA has a better performance compared to simulated annealing. Ross and Jayaraman (2008), presented a location planning model for the cross-dock and distribution centers using simulated annealing. For their network, they conclude that simulated annealing should be combined with TABU search for results with better solution time, quality, and convergence. Sarrafha et al. (2015), developed a multi-periodic SCND integrating procurement of raw materials from suppliers with production and distribution. They incorporate a flow-shop scheduling model in manufacturing part and propose a bi-objective model minimizing the total supply chain costs as well as minimizing the average tardiness of product to distribution centers. They developed a novel algorithm, called multi-objective biogeography-based optimization with tuned parameters to find a near-optimum solution.

As we already stated above in general, distribution networks are analyzed in two groups: (i) best configuration of the facilities to operate and (ii) distribution and transfer of goods along with their related logistics (Ambrosino and Scutella, 2005, Ebrahimi, 2018). In Section 3.2.3, we present the formulation of two typical SCND problems concerning these two operations respectively: The capacitated (fixed- charge) facility location model and the minimum cost network flow problem. As explained above, we give a customized network model with intermediary locations. The decision whether to operate facilities correspond to the decision of using them for a port call in our case. The purpose of our model is also minimizing total cost of item flows and we model our network as a directed graph.

### 3.2.3. Classical Network Optimization Problems

**The capacitated facility location model**

The capacitated (fixed- charge) facility location model is a classical optimization model that focuses on minimizing the cost of meeting demand while satisfying capacity constraints of each candidate plant (Chopra & Meindl, 2014). Whether the plants will be operated and what will be the flow from each plant to a customer are the main decisions addressed by the problem. Below we provide the typical formulation of the model:

The decision variables $y_i$ represents whether plant $i$ is open and, $x_{ij}$ the quantity shipped from plant $i$ to market $j$. $f_i$ is the annual fixed cost of operating facility $i$, and $c_{ij}$ is the cost of producing and shipping one unit from plant $i$ to market $j$.

Objective:

$$\min \sum_i f_i y_i + \sum_i \sum_j c_{ij} x_{ij} \qquad (1)$$

subject to:

$$\sum_i x_{ij} = D_j \qquad \forall j \qquad (2)$$

$$\sum_j x_{ij} \leq K_i y_i \qquad \forall i \qquad (3)$$

$$y_i \in \{0,1\} \qquad \forall i \qquad (4)$$

$$x_{ij} \geq 0 \qquad \forall i,j \qquad (5)$$

The objective function minimizes the total costs of operating the plants and the network. Constraint (2) ensures the demand at each market is satisfied. Constraint (3) states that no plant can supply more than its capacity.

**Minimum Cost Network Flow Problem**

If the network structure is given and the aim is to allocate the flow of goods in the network, the problem is defined as a network flow problem (NFP) (Ahuja et al., 1993, Bompadre and Orlin, 2008). The problem aims to find the best delivery route from a factory or a supplier to a warehouse where the road network has some capacity and cost associated. A flow network (also known as a transportation network) is a directed graph where each edge has a capacity and each edge receives a flow (Figure 3.2.). The items enter the network through sources which may represent suppliers or production facilities and are transported to sinks (or demand points) through arcs. Between the sources and the sinks are intermediate nodes through which materials can be shipped to other intermediate nodes or to the sinks (Gan et al., 2014).

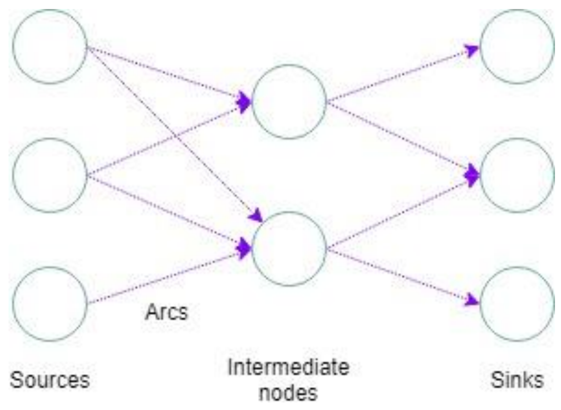


**Figure 3.2.** A general flow network

If the goal is to determine a least cost shipment of a commodity through a network in order to satisfy demands at certain nodes, the problem is named as minimum cost flow problem. The flow problem is called a multi-commodity flow problem if there are multiple flow demands (Ahuja et al., 1993). This can correspond to demand for multiple SKUs in a logistics network. To formulate this problem mathematically, the following notation is used. The notation is based on graph theory as a flow network can be modeled as a directed graph and written as a linear model (Ahuja et al., 1993, Bompadre and Orlin, 2008).

We set G = (N, A) as the directed graph defined by the sets N of n nodes and A of m arcs. Arcs are in the form of (i, j), i representing the start node and j, the end node. Each arc (i, j) ∈ A is associated with a cost per unit flow, Cij and a capacity Uij. There are commodities represented with *k* and the supply/ demand for commodity k is represented by $b^k$. Finally, the decision variable is $x_{ij}^k$, the flow (quantity) of commodity k transported on arc (i, j) ∈ A.

Objective:

$$\min \sum_{(i,j)\in A} \sum_k c_{ij} * x_{ij}^k \qquad (1)$$

subject to:

$$\sum_k x_{ij}^k \leq u_{ij} \qquad \forall (i,j) \in A \qquad (2)$$

$$\sum_{(i,j)\in A} x_{ij}^k - \sum_{(j,i)\in A} x_{ji}^k = b(i)^k \qquad \forall k \in K, i \in N \qquad (3)$$

$$0 \leq x_{ij}^k \leq u_{ij}^k \qquad \forall k \in K, (i,j) \in A \qquad (4)$$

Constraint (2) ensures that the arc capacity is not exceeded. Constraint (3) is referred to as mass balance constraints. The first term in this constraint for a node represents the total outflow of the node (i.e., the flow emanating from the node) and the second term represents the total inflow of the node (i.e., the flow entering the node). The mass balance constraint states that the outflow minus inflow must equal the supply/demand of the node. Constraint (4) states that the capacity restriction for each commodity on each arc should be met.

The network flow problems can have different characteristics. The problem is referred to as uncapacitated if the arcs do not have any capacity restrictions (Ahuja et al., 1993). If the network flows are not allowed to be split into arbitrary sizes traveling through the network on different paths, the problem is called a single-source unsplittable flow problem (Du and Kolliopoulos, 2005).

### 3.3. Conclusion

In this chapter, we carried out a literature review to answer our second question "*What theory and methodologies are presented in the literature in relation to distribution network design?"*. We observe that there are many studies on supply chain network optimization using exact or heuristic solutions, but customized adjustments might be necessary to accurately model the network we have at hand. Since the available facilities are pre-determined, our goal is to optimize the flow of demanded items through suppliers and these facilities. The method we use for purchasing and delivery decisions must be able to incorporate the distribution options we have identified in Chapter 2, must account for economies of scales and minimize the total costs.

We conclude that we can maintain a manageable problem size to solve our distribution network design problem to optimality. Since the costs for port calls are disjoint we can formulate a model to be run for each port call separately. Since FS has a complex network of suppliers and distribution options, we decide to model this network as a directed graph in order to have an adjustable network. This also facilitate applying transportation and facility costs as arcs and locations can be referred to as separate entities. We have an unsplittable flow as FS wants to work with one supplier per SKU. This would enable us to have binary decision variables for modeling whether a supplier is used instead of modeling the quantity allocated to the suppliers. Moreover, since the demand for consumables is mostly known in advance, a deterministic model can be constructed. We provide a discussion on modeling choices in Section 4.2.1 as well. Considering the requirements stated above together with these approaches, we decide to build a mixed integer linear programming model for determining minimum cost purchase and distribution decisions.

# Chapter 4

# Model Construction

In this chapter, we describe how we developed our mathematical model by translating the situation of FS into a mixed integer linear programming problem. In Section 4.1. we explain the conceptual model with the problem description and the trade-offs considered by the model. In Section 4.2, we translate the network and pricing structures into a mathematical model. Next, in Section 4.3, we explain the input and output structures of the model along with the assumptions we made. Finally, in Section 4.4, we present the conclusions of the chapter.

## 4.1. Conceptual Model

In this section we describe the structural concept that we will be modeling for the mathematical model presented in Section 4.2. to be better understood. The model determines the delivery routes for a single port call. This corresponds to a static model as the decision is made for a single time period.

### 4.1.1. Problem Description

As we have stated in Chapter 1, our objective is to "Develop a decision-making tool for consumables & parts to minimize total purchasing & logistics costs". In this chapter, we address this objective quantitatively by connecting it to a specific model.

FS's network has many global sourcing and delivery options that makes it difficult to determine a low-cost strategy considering all alternatives. Because the demand for consumables can be known in advance, for these groups of items we can build a model for selecting the minimum cost option. A model with demand information, the network structure along with supplier and delivery options can be used to determine the minimum cost flows. For a more accurate evaluation of the options and saving opportunities, we should incorporate the possible economies of scales arising from purchasing, handling and transporting items together as well. We need to ensure all required items are purchased and delivered to the vessel. Moreover, items that belong to certain categories; fuels, perishables or chemicals must be directly delivered to the port by the supplier since they require special storage or delivery conditions.

### 4.1.2. Key Trade – offs Considered

Each supply and distribution decision leads to savings from one cost aspect while resulting in extra costs in another. The model provides an optimal solution that corresponds to the balance between these trade-offs such that the overall costs are minimized. Of course, the decisions are interrelated in terms of the costs and the optimal result is a combination of all costs. We have already explained how the costs build up in Section 2.7. Here, we list the main trade-offs taken into account by the model as below:

1. Product costs vs. transportation costs:

For a given port location, there is a trade-off between purchasing and distribution costs. Purchasing locally may be more cost efficient because the transportation costs are less. However, purchasing from a geographically far supplier may turn out to be more cost efficient if product costs are cheap enough and savings from transportation can be achieved by consolidation.

2. Ordering costs vs. product costs:

Splitting orders may result in savings if the product costs vary largely among the available suppliers. However, working with more suppliers would yield additional organizational costs we refer as ordering cost. Therefore, splitting is only profitable when the ordering costs can be covered.

3. Facility costs vs. transportation costs:

Consolidating goods at a facility generally reduces transportation costs in comparison to separate deliveries as economies of scales can be attained. The impact of economies of scale grows with distance. However, use of the facility would result in extra costs for documentation and handling. The trade-off for using a facility should also be considered together with the loading costs.

4. Facility costs vs. loading costs:

Each delivery made to the vessel results in extra costs as the admittance and loading requires time of the personnel. Whether consolidating the goods at a warehouse before delivery to vessel is more profitable depends on the difference between the facility costs incurred and the loading costs.

#### 4.1.3. The Network Structure

In this chapter we provide a recap of Chapter 2 to better illustrate the distribution network that we will be modeling in the next chapter. As we have described in Chapter 2, FS's distribution network consists of many suppliers, two central warehouses (Rotterdam and Singapore), multiple local warehouses, and port agents. The network is a multi-echelon supply chain as it consists of suppliers upstream, followed by central warehouses, local warehouses, agents and finally the vessel downstream the supply chain. We refer to each link between the locations in Figure 4.1. as an arc and any combination of SKUs sent from one location to the other as a shipment.

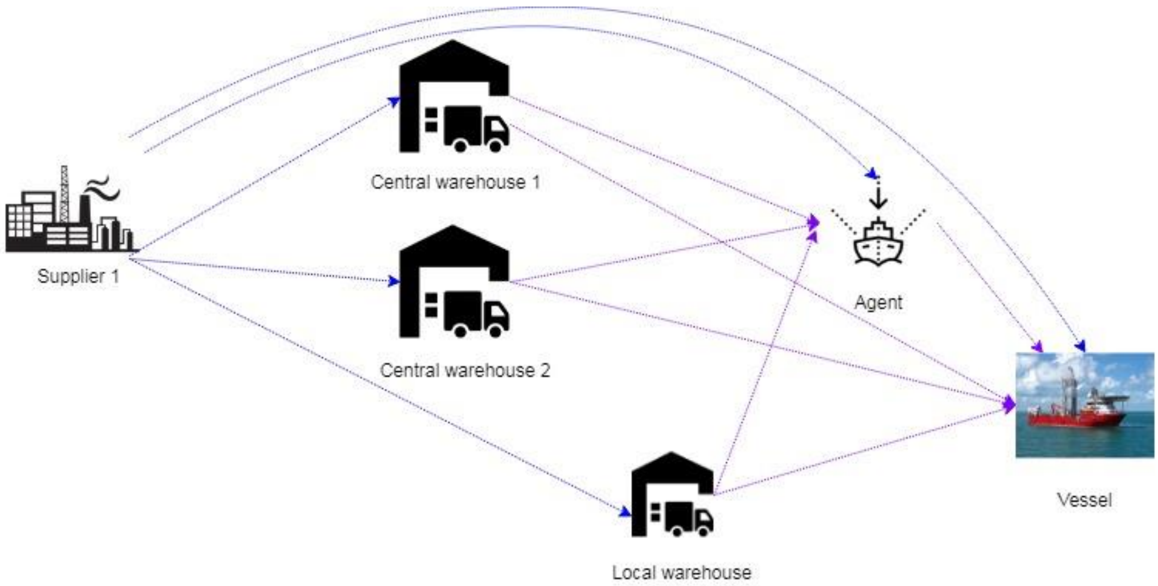


**Figure 4.1**. Supply and delivery route options for a port call.

An item can be distributed through the network either following the supply chain stages in order or skip certain stages. Figure 4.1. illustrates the part of FS's network used for a port call. We illustrate the paths with only one supplier for simplicity. In the model we consider multiple suppliers. FS uses one agent and at most one local warehouse per port call. The local warehouses can belong to the Fugro entity or be a private freight forwarder. Each port call has suppliers as the start nodes and the vessel as the end node. While defining the network structure for the model, we assume the suppliers are delivering goods from their main locations and not from any facility located in a different country as it is usually the case.

Two central warehouses, one in Europe (Rotterdam) and one in Asia & Pacific (Singapore), are available for use for each port call. Since these warehouses are accessible in these regions, additional local warehouses are not utilized. Other regions all have local warehouses. Central and local warehouses along with agents serve as cross-docking locations. They consolidate the received items and deliver them to the pre-determined location. Here, we give a recap of Chapter 2, and list the applicable delivery route options:

1. Supplier - vessel
2. Supplier – agent –vessel
3. Supplier – Rotterdam Warehouse – vessel
4. Supplier – Rotterdam Warehouse - agent –vessel
5. Supplier – Singapore Warehouse – vessel
6. Supplier – Singapore Warehouse - agent –vessel
7. Supplier – local Warehouse – vessel
8. Supplier – local Warehouse - agent -vessel

### 4.2. Mathematical Model

Following the literature review we carried out and the distribution scenarios we identified, we build a mixed integer linear programming model adapting all unit quantity discount models for procurement and transportation prices to allocate orders to the suppliers and to applicable delivery options. Since the costs incurred for each port call are disjoint, we formulate the model per port call so that the decisions can be optimized running the model separately for each port call. Considering multiple port calls together could enable us to evaluate savings from economies of scales for larger set of orders. However, this is not applicable to the current way of operation at Fugro as we discuss in Section 6.3. We assume each port has a single agent and, if the port is not in Europe or Asia, one local warehouse assigned for use. Here we explain in detail how the mathematical model is built, and we provide FS with a user manual as shared in Appendix C explaining the usage of the tool.

#### 4.2.1. Modeling Choices

Before introducing the model, we first explain certain modeling choices we have made along with the programming choices. Although the model is only run for a single port call, the large distribution network and the cost structures lead to some complications that should be addressed. We aim to have a generic model that can run with different set of facilities and suppliers.

The first complexity arises from FS's network structure having a lot of combinations of suppliers and delivery options. Moreover, we need to model the pricing structures for product, transportation handling costs. As we observed in Chapter 2, when purchasing products, threshold discounts are applicable. For handling costs, when examining the contracts made with the warehouses, we observe that different prices are applied with respect to certain weight intervals. We follow a similar structure for transportation costs. As we have discussed in Section 3.3, we aim to build a linear model and we introduce discrete weight intervals corresponding to different prices. We explain the pricing structures and how we quantify the parameters in detail in Section 4.3.1. Another complexity arises from translating all these statements into a mathematical model while ensuring a small as possible problem size. After introducing the model, we examine the magnitude of the model in more detail referring to the number of decision variables and constraints needed in Section 4.2.7. In Chapter 5, we run the model with port calls of different number of variables.

The number of variables in a model affects the computational difficulty of an integer programming model considerably (Babayev and Mardanov, 1994). In order to reduce the number of decision variables and the problem size, we run the model for each port call instead of optimizing them jointly as the purchase and logistics costs are applied separately for each. We also formulate our model in a way to ensure fewer number of decision variables. The decision we want to make with the model is to select a supplier and a distribution option per required SKU. Therefore, we initially consider modeling our main decision variable as:

$$X_{i\ ,s,m} = \begin{cases} 1 \text{ if item i is purchased from supplier s and distributed using option m} \\ 0 \text{ otherwise} \end{cases}$$

We run the model for the 200 suppliers in our dataset even though some cannot supply any of the items for some port calls to ensure that the model can support additional suppliers (Suppliers that cannot provide an item are given a very large product cost to ensure they will not be selected). As we have mentioned in Section 2.4, many items have been purchased from a single supplier. We do not know to what extend this is the result of experience or a supplier selection procedure. Therefore, we need to ensure the model can support additional suppliers. Depending on the availability of a local warehouse we have six or eight distribution options as given in Section 4.1.3. Therefore, this way of modeling would result in 200 * 8 = 1600 or 200*6= 1200 decision variables per SKU. In our test cases, we have a port call in the United Arab Emirates (Port Call 1) with 161 SKUs resulting in 161 * 200 * 8 = 257.600 decision variables and a case in the United Kingdom (Port Call 10) with 33 SKUs resulting in 33 * 200 * 6 = 39.600 decision variables. From this example, we can conclude that the change in the number of SKUs, suppliers or options (facilities) can result in large changes in the model size which would affect the run time and the usability of a commercial solver. The other decision variables are auxiliary variables defined based on this main decision variable and are not as influential on the model size.

Considering alternative modeling approaches and the literature review, we decide to model the network as a directed graph. We refer to each link between entities in Figure 4.1 as arcs:

1. Supplier – Vessel
2. Supplier – Agent
3. Supplier – Rotterdam Warehouse
4. Supplier – Singapore Warehouse
5. Supplier – Local Warehouse
6. Rotterdam Warehouse – Agent
7. Rotterdam Warehouse – Vessel
8. Singapore Warehouse – Agent
9. Singapore Warehouse – Vessel
10. Local Warehouse – Agent

11. Local Warehouse – Vessel
12. Agent - Vessel

Therefore, we base our decision variable on the arcs instead of the distribution options:

$$X_{i,a} = \begin{cases} 1 \text{ if item i is distributed using arc } a \\ \quad\quad 0 \text{ otherwise} \end{cases}$$

When we have 200 suppliers in the network, for port calls in the regions with local warehouses we have 1.007 arcs and in regions without local warehouses we have 805. With this way of modeling, for the first example given above we would have 161 * 1007 = 162.127 decision variables and for the second, 33 * 805 = 26.565. Since for larger number of SKUs and suppliers this method would require less decision variables we formulate our model based on this configuration. We need to translate all possible routes consisting of alternative suppliers and delivery options to the arcs when modeling. To interpret the output of the model, we re-configure which options were applied referring to the arcs used.

Modeling the network as a directed graph also facilitates the programming process and enables having a more flexible model. Having less decision variables reduces the memory usage as each variable defined consumes a certain number of bits. Therefore, this also helps reducing the run time.

Modeling the arcs separately and re-configuring the distribution options later renders changing scenarios and introduction of new warehouses to be easier. When the tool is started to be used it could be realized that some suppliers can only apply some of the delivery options or different number of facilities may be available for use for a port call. For example, some suppliers may prefer sending goods to a warehouse because they do not have the expertise to handle documentations for customs or the assigned agent may not have a storage space to receive goods. With the previously considered formulation, when we add a new scenario or a facility we need to define which costs are needed for a scenario and change the code accordingly. Here, only changing the input files enables running the model with different scenarios as the model works with any arcs and facilities given as input.

The transportation costs and facility costs can be modeled with less effort in this formulation as well. These costs are incurred with respect to the shipment weight on the arcs and having arcs defined as separate sets leads to a generic formulation. We explain how the model is formulated and the notation used in the following sections.

**4.2.2. Sets and indices:**

We consider the below sets to define our model. We model the network as a directed graph G = (Y, A) where *Y*, the set of nodes, includes the sets $S, F, V$. The set of arcs, *A,* includes all possible links between the nodes. This corresponds to all the transportation paths we have previously defined (Figure 4.1). We define each arc together with a start and end node. Facilities, F, correspond to the central warehouses, the local warehouse in the region of the port call, and the pre-assigned agent. We assume similar transportation rate structures for each node and, take the same number of price brackets (R) for each arc. Similarly, we assume all the facilities use the same number of price brackets (H) for handling costs. This is convenient for programming different instances at once and, in case the number of brackets differ, dummy price brackets can be used as explained in Appendix C.

$I$ = Items ordered for the port call: $\{1, \dots i \dots . . I\}$
$I'$ = Subset of $I$, consisting of fuels, perishables and chemicals
$S$ = Suppliers: $\{1, \dots \text{s} \dots . . S\}$

$F$ = Facilities: $\{1, \ldots \mathrm{f} \ldots \ldots F\}$
$V$ = The vessel
$A$ = Arcs in the network: $\{1, \ldots \mathrm{a} \ldots \ldots A\}$ such that each $\mathrm{a} = (j_a, k_a) \in \mathrm{A}$
$R$ = Weight intervals for the freight rates: $\{1, \ldots r \ldots \ldots \mathrm{R}\}$
$H$ = Weight intervals for the handling rates: $\{1, \ldots h \ldots \ldots \mathrm{H}\}$

**4.2.3. Parameters:**

Here we list the parameters that serve as inputs for the model. In Section 4.3, we explain in detail how this input data is collected.

$C_{i,s}$ = Unit procurement cost for item $i$ when bought from supplier $s$
$D_s$ = Discount percentage on procurement cost applied by supplier $s$
$E_s$ = Minimum amount supplier $s$ requires to be spent to apply discount, in €
$M$ = A large number
$W_i$ = Weight of item $i$, in kg
$Q_i$ = Quantity of item $i$ to be purchased
$T_{a,r}$ = Unit cost (per kg) for transporting goods on arc $a$, if the weight falls in interval $r$, in €
$L_{a,r}, U_{a,r}$ = Lower and upper end points of weight interval $r$ for transportation on arc $a$, in kg
$H_{f,h}$ = Cost for handling goods at facility $f$, if the received weight falls in interval $h$, in €
$LH_{f,h}, UH_{f,h}$ = Lower and upper end points of weight interval $h$ for handling in facility $f$, in kg
$F_f$ = Fixed cost per use for facility $f$
$CO$ = Ordering cost per PO, in €
$CL$ = Loading cost per delivery to vessel

**4.2.4. Decision Variables:**

In this section we list the decision variables that constitute the output of the model. Our main decision in the model is the delivery routes - which arcs to use for the distribution of each item. This is indicated by the below decision variable. Referring to the value of this decision variable, we will determine the preferred suppliers, facilities used, procurement and freight consolidation options along with the costs incurred.

$$X_{i,a} = \begin{cases} 1 \text{ if item i is distributed using arc a} \\ \quad 0 \text{ otherwise} \end{cases}$$

Below we introduce auxiliary decision variables. Unlike above, these do not represent an action that we would take but they are still outputs of the model as their value is based on that of $X_{i,a}$. We use them to translate the conditional statements we explained in the previous section into mathematical formulations. We need to correctly incur the costs for the distribution options. For example, we need to know the total weight on an arc since the transportation costs are incurred with respect to it. The total weight on each arc is an output of the model as it is a result of supply and distribution decisions the model makes for the items. Similarly, whether a discount is received or not is an output of the model as it is a result of the total purchase spent. We explicitly formulate these statements into an objective function and set of constraints in the following sections.

$TC_s$ = Total cost (without discounts) paid to supplier $s$, in €
$Z_s$ = Total cost paid to supplier $s$ that receives a discount, in €

$Y_s$ = $\begin{cases} 1 \text{ if supplier } s \text{ applies discount} \\ 0 \text{ otherwise} \end{cases}$

$V_s$ = $\begin{cases} 1 \text{ if supplier } s \text{ is used} \\ 0 \text{ otherwise} \end{cases}$

$K_f$ = $\begin{cases} 1 \text{ if fixed facility costs are incurred by facility } f \\ 0 \text{ otherwise} \end{cases}$

$WT_a$ = Total weight transported on arc $a$ , in kg

$W_{a,r}$ = Total weight transported on arc $a$, corresponding to the weight interval $r$, in kg

$B_{a,r}$ = $\begin{cases} 1 \text{ if the total weight of shipment on arc } a \text{ falls in the weight interval } r \\ 0 \text{ otherwise} \end{cases}$

$WF_{a,f}$ = Total weight of shipment sent through arc $a$ to facility $f$, in kg

$WH_{a,f,h}$ = Total weight of shipment sent through arc $a$ to facility $f$, corresponding to the weight interval $h$, in kg

$BH_{a,f,h}$ = $\begin{cases} 1 \text{ if the total weight of shipment sent through arc } a \text{ to facility f falls} \\ \text{in the weight interval } h \\ 0 \text{ otherwise} \end{cases}$

$SV_s$ = $\begin{cases} 1 \text{ if supplier } s \text{ delivers a shipment to the vessel} \\ 0 \text{ otherwise} \end{cases}$

$FV_f$ = $\begin{cases} 1 \text{ if facility f delivers a shipment to the vessel} \\ 0 \text{ otherwise} \end{cases}$

#### 4.2.5. Objective:

The objective function is minimization of the total costs of purchasing and logistics. The costs are evaluated for all items. Below we state the objective function and explain all relevant components building up the costs.

minimize total costs =

$$\begin{aligned}
&\textstyle\sum_i \sum_s \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} - \sum_s D_s * Z_s && (obj.1)\\
&+ CO * \textstyle\sum_s V_s && (obj.2)\\
&+ \textstyle\sum_a \sum_r T_{a,r} * W_{a,r} && (obj.3)\\
&+ \textstyle\sum_f F_f * K_f && (obj.4)\\
&+ \textstyle\sum_f \sum_{a:k_a=f} \sum_h H_{f,h} * BH_{a,f,h} && (obj.5)\\
&+ CL * \left(\textstyle\sum_s SV_s + \sum_f FV_f\right) && (obj.6)
\end{aligned}$$

Expression (obj.1) represents the total procurement cost to be spent as the total product cost minus the discounted amount. Next, we add the ordering cost arising from placing orders, this cost is incurred per each supplier used. With expression (obj.3), for each arc, we add the transportation costs with respect to the price corresponding to the weight on the arc. Transportation costs are applied per kg transported. We also add the flat fee for utilizing the facilities (obj.4). Next, we add the handling costs incurred by facilities. Handling costs are applied with respect to the total weight of a shipment received from a supplier (obj.5). Finally, we add the loading cost for each separate delivery made to the port from suppliers and facilities (obj.6). We explain the calculations related to the purchase, freight and handling cost discount schemes in the next section through the constraints.

#### 4.2.6. Constraints:

Here, we list the constraints that define the relationships between the decision variables that translate the situation explained in the previous section into a mathematical notation.

Network connections:

$\sum_s \sum_{a:j_a=s} X_{i,a} = 1$ $\quad \forall\, i \in I$ (1)

$\sum_s \sum_{a:j_a=s,k_a=v} X_{i,a} = 1$ $\quad \forall\, i \in I'$ (2)

$\sum_{a:k_a=f} X_{i,a} = \sum_{\alpha:j_a=f} X_{i,a}$ $\quad \forall i \in I, f \in F$ (3)

Utilization of suppliers and facilities:

$\sum_{a:j_a=s} X_{i,a} \leq V_s$ $\quad \forall\, i \in I\,, s \in S$ (4)

$\sum_{a:\,k_a=f} X_{i,a} \leq K_f$ $\quad \forall\, i \in I\,, f \in F$ (5)

Discount structure for product cost:

$TC_s = \sum_i \sum_{a:j_a=\,s} C_{i,s} * Q_i * X_{i,a}$ $\quad \forall\, s \in S$ (6)

$TC_s \leq E_s + M * Y_s$ $\quad \forall\, s \in S$ (7)

$TC_s \geq E_s * Y_s$ $\quad \forall\, s \in S$ (8)

$Z_s \leq TC_s$ $\quad \forall\, s \in S$ (9)

$Z_s \geq TC_s - M * (1 - Y_s)$ $\quad \forall\, s \in S$ (10)

$Z_s \leq M * Y_s$ $\quad \forall\, s \in S$ (11)

Transportation cost structure:

$WT_a = \sum_i Q_i * W_i * X_{i,a}$ $\quad \forall a \in A$ (12)

$\sum_r B_{a,r} = 1$ $\quad \forall a \in A$ (13)

$W_{a\,,r} \geq L_{a,r} * B_{a,r}$ $\quad \forall a \in A, r \in R$ (14)

$W_{a\,,r} \leq U_{\,a,r} * B_{a,r}$ $\quad \forall a \in A, r \in R$ (15)

$W_{a\,,r} \leq WT_a$ $\quad \forall a \in A, r \in R$ (16)

$W_{a,r} \geq WT_a - M * \left(1 - B_{a,r}\right)$ $\quad \forall a \in A, r \in R$ (17)

Handling cost structure:

$WF_{a,f} = \sum_i Q_i * W_i * X_{i,a}$ $\quad \forall\, f \in F, (.\,, f) \in A$ (18)

$\sum_h B_{\,a,f,h} = 1$ $\quad \forall\, f \in F, (.\,, f) \in A$ (19)

$WH_{a,f,h} \geq LH_{f,h,} * BH_{\,a,f,h}$ $\quad \forall\, f \in F, h \in H, (.\,, f) \in A$ (20)

$WH_{a,f,h} \leq U_{Hf,h} * BH_{\,a,f,h}$ $\quad \forall\, f \in F, h \in H, (.\,, f) \in A$ (21)

$WH_{a,f,h} \leq WF_{a,f}$ $\quad \forall\, f \in F, h \in H, (.\,, f) \in A$ (22)

$WH_{a,f,h} \geq WF_{a,f} - M * \left(1 - BH_{\,a,f,h}\right)$ $\quad \forall\, f \in F, h \in H, (.\,, f) \in A$ (23)

Deliveries made to the vessel:

$X_{i,a} \leq SV_s$ $\quad \forall\, i \in I, s \in S\,, (s, v) \in A$ (24)

$X_{i,a} \leq FV_f$ $\quad \forall\, i \in I, f \in F\,, (f, v) \in A$ (25)

Range constraints:

$X_{i\,,a} \in \{0,1\} \;\; \forall\, i \in I, a \in A\,, Y_s, V_s, SV_s \in \{0,1\} \;\; \forall\, s \in S, TC_s, Z_s \geq 0 \,\forall\, s \in S,$
$FV_f,\, K_f \in \{0,1\}, \quad \forall\, f \in F, WT_a, \geq 0 \,\forall\, a \in A\,,\, W_{a\,,r} \geq 0 \,\forall a \in A, r \in R,$
$B_{a,r} \in \{0,1\} \,\forall a \in A, r \in R, WF_{a,f} \geq 0 \,\forall a \in A, f \in F\,,$
$WH_{a,f,h} \geq 0 \,\forall a \in A, f \in F, h \in H, BH_{\,a,f,h} \in \{0,1\} \,\forall a \in A, f \in F, h \in H$ (26)

Constraint (1) makes sure all items are supplied from exactly one supplier. Constraint (2) ensures that all the items that require to be delivered directly to the vessel are delivered accordingly: through one of the arcs connecting the suppliers and the vessel. With constraint (3), we state the balance equations for the network: for each facility, if an item enters in, it will also get out. Constraint (4) ensures $V_s$ gets the value of one if supplier $s$ is used, and constraint (5) ensures $K_f$ gets the value one if facility $f$ is used. These enable the associated costs to be incurred as given in the objective function.

With constraints (6) – (11), we formulate the purchase discount structure we identified in Chapter 2: Supplier $s$ applies a discount of a certain percentage $D_s$, if the total purchase cost spent exceeds a certain threshold $E_s$. Below, we explain explicitly how the expressions for the constraints are constructed:

$$\text{Total procurement cost at supplier s} = \begin{cases} \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} & if\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} < E_s \\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * (1 - D_s) * X_{i,a} & if\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} \geq E_s \end{cases}$$

Therefore, we can introduce an auxiliary variable $Z_s$ to refer to the condition and model the total procurement cost at supplier *s* as:

$$\sum_i \sum_s \sum_{a:j_a=s} C_{i,s} * X_{i,a} - \sum_s D_s * Z_s$$

$$\text{where } Z_s = \begin{cases} 0 & if\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} < E_s \\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} & if\ \sum_i \sum_{a:j_a=s} C_{i,s} * Q_i * X_{i,a} \geq E_s \end{cases}$$

We define $TC_s$ as an auxiliary variable representing the total procurement cost without discount for clearer notation. The total cost can be either below or above the threshold, we introduce the binary variable $Y_s$ to correspond to this situation and, link $TC_s$ and $Y_s$ using below constraints. Similarly, above we have defined $Z_s$ to be equal to $TC_s$ or to 0. Constraints (9) – (11) ensure $Z_s$ and $Y_s$ are linked.

With constraints (12)-(17) and (18)-(23), we model the transportation and handling costs in a similar way as above. Here, we introduce weight intervals as we will explain in Section 4.3.1. The formulation is similar to the discount structure explained above but, here we introduce lower and upper bounds for each weight interval and ensure that the weight falls in only one.

Constraints (24) ensures $SV_s$ gets the value of one when there is a delivery from the supplier to the vessel. Similarly, constraint (25) does the same for deliveries to the vessel from facilities. Finally, we state the non-negativity and binary restrictions on the decision variables (26) and complete the model.

### 4.2.7. Model Size

We run the model formulated above for 15 port calls of different number of variables and constraints. The model initially performs a data processing operation in milliseconds reading the input data from the given files. We only note the solution time for the solver engine to run the optimization algorithm and observe that the average run time per port call is 0,355 minutes (Appendix D). We can conclude that we have a relatively fast model that can be used efficiently for tactical planning of 29 vessels. Below we list the details of two exceptional cases of the largest and smallest sizes. We have also referred to them when discussing the modeling choices in Section 4.2.1. We provide the model size for Port Call 1 in the United Arab Emirates and Port Call 10 in the United Kingdom (Table 4.1). We run both port calls with 200 suppliers. We have seven weight intervals (including a dummy interval for 0 weight) for handing costs for each facility and six for transportation cost brackets for each arc.

**Table 4.1.** Model size for Port Call 1 and 10

| Port Call | # SKUs | # Arcs | # Decision Variables | # Constraints* | Run Time (min) |
|---|---|---|---|---|---|
| 1 | 161 | 1007 | 236.646 | 117.976 | 4,437 |
| 10 | 33 | 805 | 74.261 | 53.720 | 0,013 |

* Number of constraints exclude the range constraints. Each decision variable is defined with a range resulting in range constraints equal to the number of decision variables.

CPLEX, the solver we use to define and optimize the model, uses branch and cut algorithm to solve mixed integer programming models [(1)]. The speed of the algorithm can be affected by the values and the interaction of the input parameters since the algorithm is applied iteratively with respect to those values. The interested readers can refer to Mitchell (2002) for explanation on branch and cut algorithm.

### 4.2.8. Software and Solver

We used the solver IBM ILOG CPLEX version 12.6 to solve the problem. CPLEX is an advanced software for mathematical optimization problems which is free for academic use and is commonly used to solve supply chain network optimization problems (Ebrahimi, 2018). The delivery route determination tool is developed on Visual Studio using ILOG CPLEX Concert Technology with C#.

## 4.3. Model Input and Output

In this section, we list the elements of the existing setting that we incorporate in our model. We explain our assumptions regarding the model and how we collected the required input data. We re-state the cost breakdown structure that constitutes the output of the model as well. In Chapter 5, we will run the model with this input to get numerical results.

### 4.3.1. Input Requirements

**Demand**

We need to have a list of required SKUs per port call to be able to plan the supply and the distribution decisions. We refer to the purchase data of 2017 and the purchase invoices along with the data file for daily operation and movement of the vessels to identify for which port call and at what quantities the items were ordered. We aim to have an overview on applicable purchase decisions and take the demand for consumables to be known. This is usually the case as there are periodical orders planned in advance for consumables & parts as explained in Chapter 2.

[1] https://www.ibm.com/support/knowledgecenter/SSSA5P_12.6.2/ilog.odms.cplex.help/refcppcplex/html/branch.html

**Product Prices**

We determine the unit price for each item – supplier pair. We obtain the average unit price by weighing the prices by the quantity purchased at that price in order to have prices that better represent the overall purchases as previous grouping of items or negotiations may have led to different prices.

The suppliers usually apply a discount of a certain percentage if the costs of goods purchased exceed a certain threshold per order (placed per port call). In order to have a more accurate comparison with the current situation we run the base case with 0 discounts in Chapter 5. Then we run a sensitivity analysis to gain insights on possible saving options through purchasing discounts.

**Product Weights**

Product weights are needed to be able to calculate handling and transportation costs. Because FS does not keep data on product weights, we contacted some suppliers and searched weights of certain items online.

In practice, freight forwarders use a freight rate calculation structure based on both physical weight and volume weight. Volume weight is calculated based on the packaging size and the greater of the two weights is called the “chargeable weight” as the pricing structure is applied to this value. Here, due to data unavailability on item and packaging sizes, we assume the handling and transportation costs are incurred based on physical weight only. The Europe Warehouse generally applies charges with respect to the physical weight as well.

**Facility Costs**

Fixed costs are incurred by each facility when their services are used. This corresponds to a flat fee consisting of administration, dispatching and transportation to be paid every time the facility is used regardless of the size of the received shipments.

We refer to the rates of the Europe Warehouse for determining the input values for the model as we have a contract available with clearly defined pricing structures. We assume the Singapore Warehouse and local warehouses in any region are identical in terms of facility costs. Studying the invoices and consulting the Purchasing & Logistics Department for expert opinion, we take the agents to be 15% more expensive. Looking at the past invoices, we conclude that airfreight was used for different regions. We assume the same for the model and add the associated fixed costs if the warehouse is in a different region than that of the port. In this case we take 159,5 (70 + 89,5) as the fixed facility cost in the model (Table 4.2 and 4.3).

**Table 4.2. and 4.3.** Fixed costs applied per use of facility

| Fixed Costs (€) | |
|---|---|
| Custom documents | 48 |
| Administration and communication fee | 20 |
| Scanning | 2 |
| **Total** | **70** |

| Fixed Costs for Airfreight (€) | |
|---|---|
| Export treatment | 61 |
| Security Check | 28,5 |
| **Total** | **89,5** |

Handling costs are incurred when admitting goods in the facilities as well as dispatching them for delivery. We assume the handling costs are applied for each delivery made to a facility, with respect to the total weight of this shipment (Table 4.4).

**Table 4.4.** Handling cost per shipment with respect to the weight brackets

| Handling Cost (€) | | |
|---|---|---|
| Lower Bound (Kg) | Upper Bound (Kg) | Cost |
| 0 | 5 | 2,5 |
| 5,01 | 25 | 11,5 |
| 25,01 | 100 | 22,5 |
| 100,01 | 500 | 34 |
| 500,01 | 1000 | 57 |
| 1000,01 | - | 68 |

We do not consider storage costs as the facilities are used for cross docking only. The facilities do not apply charges if the goods are in transit for a certain amount of time, for the Rotterdam this duration is three months. Therefore, planning the deliveries in advance, FS can avoid storage costs. This has usually been the case with their current practice as well.

### Transportation Costs

Because FS uses 3rd party freight providers, a calculation scheme for freight rates used is not available. We refer to the transportation costs of the Europe warehouse in our calculations for the model as their invoices are well documented and have clear descriptions for destination, origin and price information. After consulting the Europe Warehouse, the purchasers and checking the transportation invoices, we confirm that there are economies of scales in transportation; that is the transportation price applied per unit weight (kg) becomes less when the shipment is heavier (Figure 4.2).

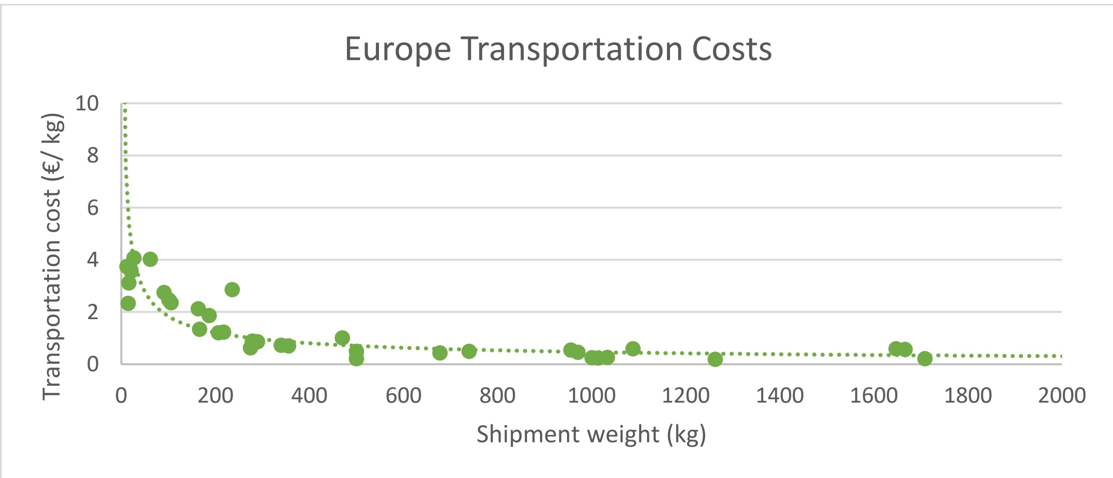


**Figure 4.2.** Unit transportation costs applied by the Europe warehouse for deliveries in Europe

As we have discussed in Section 3.3, we aim to have a linear model. The model is linear if the objective function and all the constraints are linear combinations of the decision variables (Winston and Goldberg, 2004). In order to have a linear rates structure and to incorporate economies of scales in the model, we introduce discrete weight intervals. All-weight unit discount models have been commonly studied in literature and are used by some freight forwarders for pricing (Moussourakis and Haksever, 2013, Şen et al.,2010). For our model, we assume the corresponding rate is applied with respect to the interval shipment weight falls in (Table 4.5).

**Table 4.5.** Transportation rates calculated averaging costs per kg for the corresponding weight interval, for shipment sent over distances between 0 -500 km

| Lower Bound (kg) | Upper Bound (kg) | Rate (€/kg) |
|---|---|---|
| 0 | 25 | 5,00 |
| 25,01 | 50 | 4,60 |
| 50,01 | 100 | 4,21 |
| 100,01 | 500 | 1,40 |
| 500,01 | 1000 | 0,98 |
| 1000,01 | - | 0,84 |

We have enough data points only for deliveries in Europe, and the Rotterdam Warehouse only has Rotterdam as origin. We divide the data into distance intervals of 500 km with respect to the distances between all origin and destination points. We calculate the average rate paid for shipments for each distance and weight interval. To fill the other values, we assume the rate is linearly increasing over the distance intervals as transportation costs are co-related with distance travelled (Hummels, 2007).

Here, we list other assumptions regarding the transportation in the network:

- We assume the suppliers deliver all items ordered together and we apply the transportation rates for all the items ordered from the supplier jointly.
- We assume a symmetric transportation cost matrix. That is, we assume the cost of transport is the same between any two locations regardless of the starting point.
- We assume the transportation cost structure is the same for all entities in the network.
- Suppliers transport delivery duty paid (DDP) for deliveries within their countries meaning that no transportation costs are incurred. However, agents and warehouses apply transportation costs even if they are in the same region as a result of the transportation service they provide.

**Ordering Costs**

We associate an ordering cost for each order submitted to a supplier. This corresponds to a quantification of the purchasing effort for processing a PO and the associated invoice along with the personnel and equipment costs. We assume ordering cost is the same for dealing with any supplier for orders of any size. We decided to assume a cost of 200€ per PO by quantifying the time purchasers, account officers and managers spend per PO and add a cost of overhaul consulting the Purchasing & Logistics Department for expert opinion [(2)].

[2] We refer to industry benchamarks for total cost of placing purchase orders from https://www.nextlevelpurchasing.com/blog/cost-of-a-purchase-order-the-great-mystery-of-procurement.html

**Loading Costs**

We include the average service cost per delivery made to the vessel as each separate delivery incurs extra costs corresponding to the loading equipment used and the working hours of the personnel. Generally, a crane is rented on an hourly rate. Studying agent invoices and consulting the Purchasing & Logistics Department, we assume the loading cost per delivery made to vessel to be 300€ [(3)].

**Other Assumptions**

Below we list additional assumptions and limitations:

- We do not consider transport modes as a decision as it is generally determined by the supplier or the facilities based on the time and the distance to be travelled. Here, we assume the influence of transport mode is covered through the transport prices.
- Since FS utilizes 3rd party freight providers, and states that they have not experienced availability issues for consumables before, we assume there are no capacity constraints for the number of goods that can be provided by the suppliers or the total weight of goods that can be transported on an arc.
- Similarly, we assume that all pieces of the same SKU are ordered from the same supplier and are delivered together. In other words, we assume one PO is issued per supplier as this would be the case if orders are submitted in advance.
- We only consider the suppliers that were awarded a quote before and were submitted a PO to because of data availability. We also assume these suppliers comply with Fugro's quality standards and are to be considered in the model for purchase decisions.

### 4.3.2. Model Output

Since our objective for the project is to determine the suppliers the items should be purchased from and the distribution paths items should follow, such that the total costs of purchasing and logistics are minimized, the desired result of the model should be the supply and delivery route per item. As we have explained in Section 4.2.1, we translate the results of our model into supply and distribution decisions. The output format can be seen in Appendix C in the user guide.

We measure the performance of the decisions based on the cost components we have identified in Section 2.7. We will compare the results of the model to the current situation to evaluate the possible impact of the model. We give a recap of the purchasing and logistics cost breakdown structure below:

- Product cost: Amount spent on the products, refers to the summation of product prices
- Ordering cost: Cost of submitting an order to a supplier, refers to the cost of personnel and overhaul
- Transportation cost: Cost of transporting goods between locations
- Fixed facility cost: Cost of utilizing a facility per port call, refers to cost of admission and documentation
- Handling cost: Cost of handling goods at a facility
- Loading the vessel: Cost of loading each arriving shipment to the vessel, refers to the cost of loading equipment and personnel

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[3] Example rates for renting a crane https://www.vertikal.net/uploads/tx_filelinks/ca_2017_9_p24-35.pdf

We also calculate the saving from changing the supply and delivery routes. We refer to the supply and delivery route decisions made in 2017 as the “realized case” and the decisions made by the model as the “optimal case”. The difference between the estimated total costs of the realized and the optimal case is a potential saving. We further explain how these costs are quantified and incurred in the next chapters through numerical examples.

### 4.4. Conclusions

In this chapter we combined our observations in FS’s Network as explained in Chapter 2 and our knowledge on network optimization as obtained in Chapter 3 to develop a tailored mixed integer linear programming model. We design the model to be run for each port call and adapt our decision variables to ensure a problem size that can be solved to optimality. With this approach we answer our third research question *“How can a quantitative model for purchasing and logistics decisions be constructed?”.*

We take into consideration the cost of products, submitting orders to suppliers, transportation, using facilities, handling goods at facilities and loading goods to a vessel. The model enables comparing tradeoffs by accounting for the costs related to each distribution option and possible savings from economies of scale. Through these discount structures and fixed costs, we are able to evaluate supplier and freight consolidation options prior to submitting orders. The cost minimizing combination of purchasing and distribution options is the output of the model. In the next chapter, we will present a numerical implementation of this model comparing its results to the current practices followed.

# Chapter 5

# Computational Experiments

In this chapter, we provide the results of the model we built in Chapter 4 in terms of total purchasing and logistics costs and delivery routes. We start with explaining the verification and validation of the model in Section 5.1. We select a set of port calls for our experimental design and share the numerical results in Section 5.2 along with illustrating the trade-offs evaluated with example cases. Next, in Section 5.3, we perform a sensitivity analysis on input parameters we have estimated and evaluate opportunities for purchasing discounts. Finally, we conclude this chapter in Section 5.4.

### 5.1. Verification and Validation

Before we start our computations, we perform validation and verification of our model to ensure correct and reliable outcomes. Verification is ensuring the paper model and the programmed model are the same, whereas validation is ensuring the programmed model represents the reality accurately (Law, 2015). We visualize this relation in Figure 5.1.

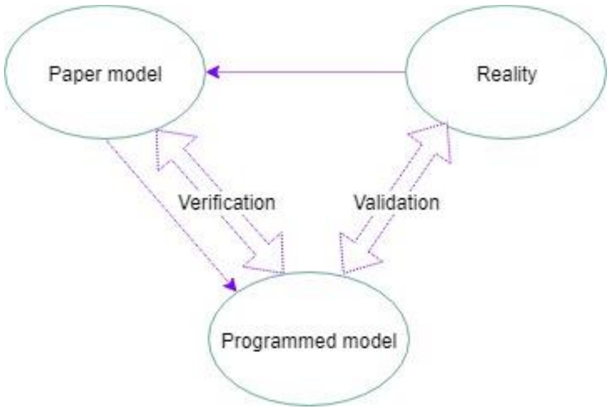


**Figure 5.1.** Definition of verification and validation

We formulate the model referring to the reality. We identify the purchasing and distribution options along with the purchasing process for port calls as we explained in Chapter 2. We study past port calls and determine the procurement discounts, handling and transportation costs referring to the available data as explained in Chapter 4. We regularly contacted the purchasers for information exchange and often planned meetings with the manager of the Purchasing & Logistics Department. In these meetings, we confirmed the validity of assumptions and decisions made.

After, transforming the paper model into a programmed model, this model was verified with the paper model and validated with reality.  We built the program using an incremental approach: we checked the correctness of every newly added step of the model. While programming, cost values are also recalculated by hand. Moreover, the cost results of the optimization problem are tested with the cost calculation model using the same delivery routes for cross-checking. Also, we used dummy data to check the optimality of the results.

## 5.2. Model Results

### 5.2.1. Experimental Design

As we have stated in Chapter 2, we limit our analysis to 15 port calls realized in 2017 as considering all would be exhaustive and would render it difficult to analyze the results. We select these port calls based on the available data. The total number of port calls and the corresponding orders are not separately documented by FS. Only for some port calls, we could obtain the list of consumables & parts that were loaded onboard. Among these we select the top 15 that had the highest number of orderlines to ensure relatively large test cases as we need to ensure that the model can support such large number of variables. These correspond to port calls with more than 30 orderlines. Moreover, the impact of the model is more visible for large cases as the complex network and interaction of joint costs make it more difficult to assess the decisions without calculations. These port calls represent various possibilities as they have different orders and different port regions. We note that due to data unavailability, we cannot know how representative these port calls are with respect to the whole fleet. We only refer to these port calls to gain insight on the potential for savings. Our goal is to re-enact these cases and see what the cost optimal decisions for purchasing and distribution would be.

The details of these port calls, such as the number of SKUs required, total weight of the orders, port location can be seen in Section 5.2.2 and in Appendix B. As we have explained in Chapter 2, we only consider the consumables & parts, a general description of the goods is also provided within that chapter. We do not provide a detailed list of items as it would be too exhaustive. These port calls have port locations in Asia, Middle East and Europe (Table 5.1). Following the selection procedure described above, we ended up with nine port calls in Europe and six outside Europe. At the end of this chapter, we give general conclusions based on these test cases and in Chapter 6, we give recommendations on data collection to be able to apply the model to any port call.

Ideally, the model enables running cases with different set of item requirements and different costs used as input. As explained in Chapter 4, for the 15 port calls selected, the average time is 0,355 minutes, which renders the analysis feasible in terms of the run time.

**Table 5.1.** Number of SKUs with respect to the distribution options that are used per port call in the optimal configuration

| | | | Distribution Options | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Port Calls | Port Country | #SKUs | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | United Arab Emirates | 161 | 117 | | 36 | | 8 | | | |
| 2 | United Arab Emirates | 41 | | | | | | | 41 | |
| 3 | United Arab Emirates | 120 | | | | | | | 120 | |
| 4 | Singapore | 155 | 4 | | | | 151 | | | |
| 5 | Kenya | 41 | | | 41 | | | | | |
| 6 | The Netherlands | 144 | 3 | | 141 | | | | | |
| 7 | United Kingdom | 51 | | | 51 | | | | | |
| 8 | United Kingdom | 42 | 1 | | 41 | | | | | |
| 9 | United Kingdom | 104 | | | 104 | | | | | |
| 10 | United Kingdom | 33 | | | 33 | | | | | |
| 11 | United Kingdom | 61 | | | 61 | | | | | |
| 12 | Malaysia | 44 | 44 | | | | | | | |
| 13 | The Netherlands | 57 | | | 57 | | | | | |
| 14 | Germany | 46 | | | 46 | | | | | |
| 15 | The Netherlands | 207 | | | 207 | | | | | |

### 5.2.2. Computational Results

We run the model for the 15 port calls with the optimization model running separately for each. We initially display an overview of the delivery options used per port call in Table 5.1 as stated above, and then analyze the change in the total costs (Table 5.2). Subsequently, we investigate the optimal solution of three port calls in more detail to comprehend the joint effect of the decisions.

Comparing the delivery options used in the realized (Table 2.1) and optimal cases (Table 5.1), we can conclude that the options selected are similar. Every port call that utilizes the Rotterdam Warehouse in the optimal case have also utilized it in the realized case. Similarly, for Port Call 2 and 3 the local warehouse are used in both cases. Port Calls 1, 4, 12 have direct deliveries made from the supplier to the vessel in both cases as well. The only major difference is on the use of agents as in the optimal case the agents were never used. Other than this change, in the optimal case, Port Call 1 uses the Singapore Warehouse, Port Call 2 uses the Rotterdam Warehouse and there are differences in the deliveries made directly to the vessel from the suppliers. The number of SKUs allocated to the distribution decisions differs compared to the realized case as the model yields the cost optimal selection.

In Table 5.2, we provide a comparison on the total costs for these port calls. We estimate the costs for the realized and optimal cases using the data as explained in Chapter 4. Similarly, we run the model with this input and obtained the results displayed under the “Optimal” column. As mentioned earlier, we refer to the difference between the realized and optimal costs as “saving” as it is an indicator for an opportunity for saving.

Looking at the overall cost breakdown structure in Table 5.2, we conclude that significant savings can be achieved from total costs spent per port call. We observe that the 97% of the savings come from the product costs. As we have discussed in Chapter 4, ordering costs and product costs constitute a trade-off as reducing one may increase the other. The savings from the product costs together with the increase in the ordering costs, suggest that splitting the orders over more suppliers can be more cost efficient. We further observe that the facilities are used less in the optimal configuration resulting in savings from fixed facility costs. We have already stated above that the agents are not used in the optimal case unlike the realized case (Table 2.1 and 5.1). Overall, using less facilities to deliver to the vessel reduces the loading costs, but we can infer that splitting orders and the change in shipment sizes sent from the suppliers in the new configuration leads to extra handling costs.

**Table 5.2**. Comparison of total costs of the realized and the optimal cases for the selected 15 port calls

| | **TOTAL (€)** | | | |
|---|---|---|---|---|
| **Description** | Realized | Optimal | Saving | Saving (%) |
| **Product cost:** | 307.674 | 287.009 | 20.664 | 7% |
| **Ordering cost:** | 19.600 | 24.000 | - 4.400 | -22% |
| **Transportation cost:** | 38.914 | 36.765 | 2.149 | 6% |
| **Fixed facility cost:** | 1.918 | 1.319 | 599 | 31% |
| **Handling cost:** | 1.848 | 2.047 | - 198 | -11% |
| **Loading the vessel:** | 9.000 | 6.600 | 2.400 | 27% |
| **Total cost:** | **378.953** | **357.739** | **21.214** | **6%** |

Below we inspect three port calls in detail to exemplify the trade-offs considered by the model. We further compare the purchasing and supply decisions that were made previously with the optimal configurations. We select the below port calls to discuss in detail because they illustrate the complexity and the multidimensionality of trade-offs clearly as they have more items and in the optimal solution more delivery options are used. These ports are also in three different regions. Details of the remaining port calls can be found in Appendix B. We examine the total cost results based on the key trade-offs discussed in Chapter 4:

1. Product costs vs transportation costs
2. Ordering costs vs product costs
3. Facility costs vs transportation costs
4. Facility costs vs loading costs

We then analyze how these costs are built based on savings, number and weight of items to be supplied, change in selected suppliers, the number of suppliers used (splitted orders) and change in delivery options used.

We should note that the model results present the minimum cost solution considering all above criteria jointly. Therefore, the solution is a result of the given input; location of port call, costs, demand list. That is, an exact conclusion on optimal strategies cannot be made. We only refer to the common patterns in the port calls we have selected. Below we discuss case specific examples and draw general conclusions in Section 5.4 on alternative strategies that FS could considered.

**Example Case 1:**

Here, we investigate the decisions made for Port Call 1 in more detail. This is a port call in United Arab Emirates with 161 items. Looking at Figure 5.2 and 5.3, along with Table 5.3 and 5.4, we observe that in the optimal case, orders are allocated differently among the suppliers; a higher number of suppliers from a wider geographical spectrum is used. Some SKUs previously purchased from Singapore and the United Arab Emirates are now purchased from Europe and Brazil. Total costs suggest that cheaper product costs cover for additional costs of transportation or ordering (Table 5.5).

In the optimal case, the Singapore Warehouse is used as well. Less purchase is made from Singapore resulting in lower transportation costs and making extra facility costs still feasible to add. As both Rotterdam and Singapore Warehouses are utilized for supplies in proximity, we can infer that consolidating purchases in a warehouse close to the suppliers and then transporting the shipment to the port is more cost efficient as it enables benefiting from economies of scale. For suppliers located far from both central warehouses, as in the case for supplier S46, the optimal configuration may suggest splitting the orders in order to gain maximum benefit from consolidation (Figure 5.3 and Table 5.4).

Here, suppliers S188 and S183 deliver directly to the vessel because they deliver chemicals that are restricted from being consolidated at the warehouses. These items cannot be transported together with other items.  Supplier S183 needs to supply both dangerous and non-dangerous goods. However, since the total shipment is relatively heavy, direct delivery is preferred for all orders from this supplier rather than paying extra handling costs at the warehouse.


**Figure 5.2.** Realized distribution for Port Call 1

**Table 5.3.** Realized supply and delivery decisions for Port Call 1

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S190 | Norway | 1 | 1 | 339 | 11 |
| S185 | Singapore | 1 | 15 | 4.786 | 12.371 |
| S62 | Singapore | 1 | 6 | 13.226 | 4.902 |
| S117 | The Netherlands | 3 | 1 | 1.169 | 7 |
| S146 | The Netherlands | 3 | 15 | 4.747 | 106 |
| S30 | The Netherlands | 3 | 7 | 653 | 6 |
| S85 | The Netherlands | 3 | 3 | 2.817 | 35 |
| S58 | United Arab Emirates | 1 | 113 | 6.409 | 1.132 |


**Figure 5.3.** Optimal distribution for Port Call 1

**Table 5.4.** Optimal supply and delivery decisions for Port Call 1

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S46 | Brazil | 3 | 1 | 410 | 2 |
| | | 5 | 3 | 802 | 4 |
| S65 | Germany | 3 | 1 | 166 | 40 |
| S188 | Norway | 1 | 2 | 295 | 2.436 |
| S190 | Norway | 3 | 1 | 339 | 11 |
| S101 | Singapore | 5 | 1 | 6.708 | 3.536 |
| S62 | Singapore | 5 | 4 | 3.671 | 1.326 |
| S117 | The Netherlands | 3 | 1 | 1.169 | 7 |
| S146 | The Netherlands | 3 | 10 | 3.074 | 94 |
| S183 | The Netherlands | 1 | 13 | 3.622 | 9.935 |
| S30 | The Netherlands | 3 | 19 | 1.689 | 13 |
| S85 | The Netherlands | 3 | 3 | 2.817 | 35 |
| S58 | United Arab Emirates | 1 | 102 | 4.899 | 1.129 |

**Table 5.5.** Comparison of total costs of the realized and the optimal case for Port Call 1

| | Port Call 1 | | |
|---|---|---|---|
| | 161 items, United Arab Emirates | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 34.146 | 29.663 | 4.483 |
| **Ordering cost:** | 1.600 | 2.400 | - 800 |
| **Transportation cost:** | 27.854 | 26.713 | 1.140 |
| **Fixed facility cost:** | 160 | 319 | - 160 |
| **Handling cost:** | 80 | 243 | - 164 |
| **Loading the vessel:** | 1.500 | 1.500 | - |
| **Total cost:** | **65.338** | **60.838** | **4.500** |

**Example Case 2:**

Here, we examine Port Call 4, a port call in Singapore with 155 items. We observe again that the optimal configuration uses suppliers in a wider geographical region (Figure 5.4 and 5.5) and orders are split over a larger set of suppliers (Table 5.6 and 5.7). Looking at the change in cost breakdown structure, we can conclude that selection of different suppliers could result in important savings (Table 5.8). Similarly, in the realized case the Rotterdam Warehouse and the agents are used resulting in higher facility costs than using only the Singapore warehouse as in the optimal case.

Looking at the optimal configuration, we can conclude that generally suppliers closer to the port region are preferred. This results in lower transportation costs as distance travelled is less. Moreover, suppliers deliver without additional transportation costs within their countries. Similarly, the Singapore warehouse is utilized for this port call which is in the same country. Consolidating items arriving from other countries would result in economies of scales in transportation and consolidating the items arriving from within Singapore would reduce the loading costs that would be incurred if these were delivered directly. However, the supplier S110 delivers directly to the vessel. There is a trade-off between the handling costs and transportation costs applied by the warehouse and the loading cost for delivering to the vessel. Looking at this case, we can conclude that for heavy deliveries made with DDP it can be cheaper to have the supplier deliver directly.

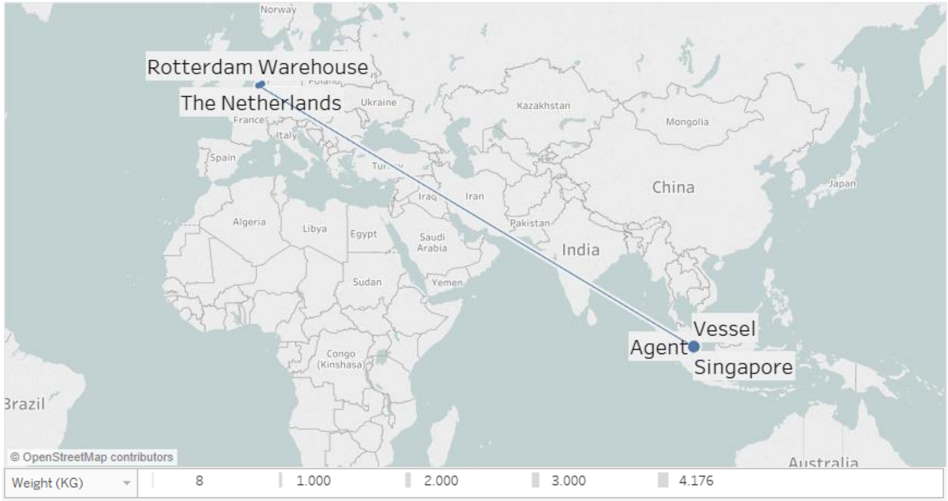


**Figure 5.4.** Realized distribution for Port Call 4

**Table 5.6.** Realized supply and delivery decisions for Port Call 4

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S110 | Singapore | 2 | 6 | 8.745 | 3.446 |
| S135 | Singapore | 2 | 34 | 1.238 | 47 |
| S139 | Singapore | 2 | 2 | 205 | 15 |
| S164 | Singapore | 2 | 1 | 253 | 2 |
| S194 | Singapore | 1 | 1 | 10.6704 | 206 |
| S45 | Singapore | 2 | 9 | 215 | 4 |
| S96 | Singapore | 2 | 99 | 8.537 | 662 |
| S30 | The Netherlands | 3 | 3 | 708 | 8 |


**Figure 5.5.** Optimal distribution for Port Call 4

**Table 5.7.** Optimal supply and delivery decisions for Port Call 4

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S65 | Germany | 5 | 2 | 532 | 162 |
| S110 | Singapore | 1 | 4 | 7.233 | 3.284 |
| S135 | Singapore | 5 | 22 | 343 | 40 |
| S139 | Singapore | 5 | 3 | 267 | 15 |
| S164 | Singapore | 5 | 1 | 253 | 2 |
| S45 | Singapore | 5 | 10 | 402 | 8 |
| S57 | Singapore | 5 | 9 | 190 | 17 |
| S96 | Singapore | 5 | 87 | 7.924 | 643 |
| S30 | The Netherlands | 5 | 2 | 241 | 4 |
| S197 | United Arab Emirates | 5 | 14 | 360 | 9 |
| S61 | United Arab Emirates | 5 | 1 | 104.986 | 206 |

**Table 5.8.** Comparison of total costs of the realized and the optimal case for Port Call 4

| | Port Call 4 | | |
|---|---|---|---|
| | 155 items, Singapore | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 126.605 | 122.731 | 3.874 |
| **Ordering cost:** | 1.600 | 2.200 | - 600 |
| **Transportation cost:** | 1.467 | 1.358 | 109 |
| **Fixed facility cost:** | 230 | 70 | 160 |
| **Handling cost:** | 200 | 199 | 2 |
| **Loading the vessel:** | 900 | 600 | 300 |
| **Total cost:** | **131.001** | **127.157** | **3.844** |

**Example Case 3:**

Finally, we examine Port Call 9, a port call in the United Kingdom with 104 items. Here we can observe the trade-offs between procurement cost with ordering and transportation costs. We observe that savings from product costs are made in exchange for savings from ordering and transportation costs (Table 5.9). We present the optimal configuration with preferred delivery options in Figure 5.7 and Table 5.11. Compared to the realized case (Figure 5.6 and Table 5.10), we can observe that suppliers in a wider geographical spectrum are used. The majority of the suppliers used are in the Netherlands, close to the port region. However, suppliers in Singapore and Brazil are also used. These new suppliers are selected, and the orders are re-allocated among some suppliers in the Netherlands. These changes result in savings from procurement costs. However, using more suppliers increases the ordering cost as it is proportional to the number of suppliers used. Similarly, using suppliers far from the port location for small weights leads to an increase in the transportation costs. In both cases the Rotterdam Warehouse is used for consolidation. However, in the optimal case, we can infer that the change in the sizes (weights) of shipments received from the suppliers leads to a negligible increase in handling costs as the costs are applied based on shipment size.

**Table 5.9.** Comparison of total costs of the realized and the optimal case for Port Call 9

| | Port Call 9 | | |
|---|---|---|---|
| | 104 items, United Kingdom | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 10.875 | 8.936 | 1.938 |
| **Discount amount:** | - | - | - |
| **Ordering cost:** | 2.000 | 2.400 | - 400 |
| **Transportation cost:** | 566 | 754 | - 188 |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 164 | 166 | - 2 |
| **Loading the vessel:** | 300 | 300 | - |
| **Total cost:** | **13.975** | **12.626** | **1.349** |


**Figure 5.6.** Realized distribution for Port Call 9

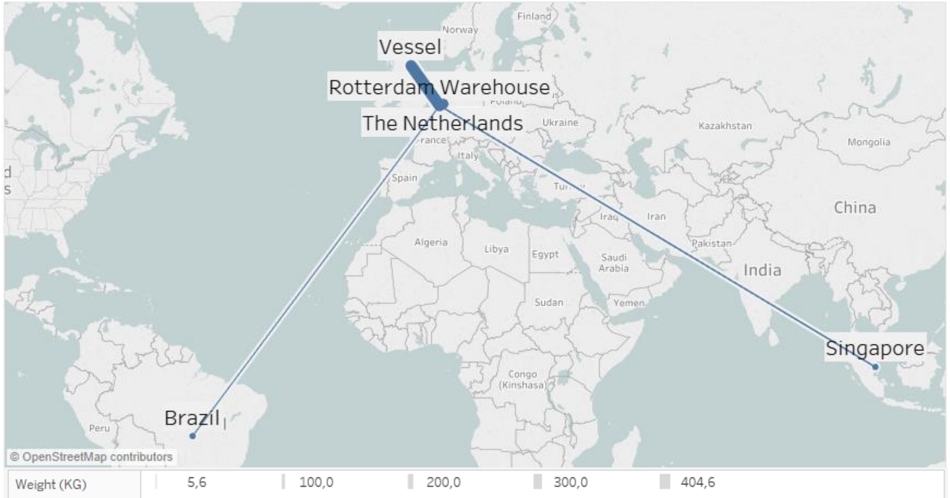


**Figure 5.7.** Optimal distribution for Port Call 9

**Table 5.10.** Optimal supply and delivery decisions for Port Call 9

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 28 | 1.292 | 142 |
| S128 | The Netherlands | 3 | 31 | 1.250 | 100 |
| S142 | The Netherlands | 3 | 3 | 744 | 43 |
| S146 | The Netherlands | 3 | 17 | 3.968 | 83 |
| S170 | The Netherlands | 3 | 2 | 655 | 3 |
| S183 | The Netherlands | 3 | 1 | 467 | 6 |
| S31 | The Netherlands | 3 | 2 | 164 | 1 |
| S35 | The Netherlands | 3 | 5 | 918 | 5 |
| S74 | The Netherlands | 3 | 7 | 190 | 10 |
| S92 | The Netherlands | 3 | 8 | 1.225 | 11 |

**Table 5.11.** Optimal supply and delivery decisions for Port Call 9

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S186 | Brazil | 3 | 1 | 36 | 6 |
| S139 | Singapore | 3 | 5 | 918 | 21 |
| S199 | Singapore | 3 | 3 | 124 | 3 |
| S100 | The Netherlands | 3 | 27 | 943 | 55 |
| S102 | The Netherlands | 3 | 7 | 432 | 4 |
| S128 | The Netherlands | 3 | 29 | 1.211 | 100 |
| S142 | The Netherlands | 3 | 3 | 744 | 43 |
| S146 | The Netherlands | 3 | 15 | 3.134 | 68 |
| S178 | The Netherlands | 3 | 1 | 468 | 88 |
| S31 | The Netherlands | 3 | 2 | 164 | 1 |
| S74 | The Netherlands | 3 | 7 | 190 | 10 |
| S92 | The Netherlands | 3 | 4 | 572 | 6 |

### 5.3. Sensitivity Analysis

We perform a sensitivity analysis on the input parameters we have estimated in order to check the robustness of the purchasing and distribution decisions made by the model. Below, we analyze the sensitivity of the results with respect to the transportation, ordering and loading costs. We refer to the realized and optimal configurations we obtained using the input values as estimated in Chapter 4 as the base case.

We initially increase and decrease the cost components one by one keeping all other input the same and examine the change in the total costs given we apply the optimal configuration of the base case. Then, we re-run the model with the new costs and observe how the optimal purchasing and distribution decisions would change. We further perform an analysis on discount percentage and threshold values the suppliers may apply, to evaluate the attainability of savings and gain insights on the negotiation terms with the suppliers.

#### 5.3.1. Transportation Costs

We initially look at the effect of increasing transportation costs on the total costs when we apply the purchasing and delivery scenarios of the optimal configuration for the base case. Since the transportation costs constitute only 10% of the total costs (Table 5.2), a 5% change in the transportation costs would result in a 0,5% change in the total costs. The change in transportation costs affect the total costs proportionally as cost components are added linearly. For example, a 10% change in the transportation costs would result in a change of 1% in total costs.

When re-running the model to optimality with the changed costs, we observe that the suppliers selected, and the optimal delivery routes do not have a significant change as out of 15 port calls, only 5 have small changes for a small number of SKUs (Table 5.12). Only port calls 8 and 15 have considerable changes when costs are increased by 10 or 20%. This again is a result of transportation costs having small influence on the overall costs. Changes result in suppliers closer to the port being used.

**Table 5.12.** Percentage of SKUs with changed optimal supply and delivery decisions given the change in transportation costs, only the changed port calls with changes are displayed

| | Change in transportation costs: | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | -20% | | -10% | | 5% | | 10% | | 20% | |
| Port Call | Supplier | Delivery Route | Supplier | Delivery Route | Supplier | Delivery Route | Supplier | Delivery Route | Supplier | Delivery Route |
| 1 | **0,62%** | **1,24%** | **0,62%** | 0% | 0% | **1,24%** | 0% | **1,24%** | 0% | **1,24%** |
| 4 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | **0,65%** | 0% |
| 6 | **0,69%** | 0% | **0,69%** | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 8 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | **7,14%** | **23,81%** |
| 15 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | **8,21%** | **0,97%** | **8,70%** |

Looking at the decisions made for Port Call 8 with respect to transportation costs increased by 20%, we observe that some orders are shifted from supplier S102 in the Netherlands to S162 in the United Kingdom where the Port Call is (Table 5.13 and Appendix B: Port Call 8). These items are also delivered directly to the vessel although they were previously taken to the Rotterdam Warehouse for consolidation. Even though this incurs extra loading costs, it is preferred in comparison to the extra transportation costs that would be incurred otherwise.

**Table 5.13.** Optimal supply and delivery decisions for Port Call 8 when transportation costs are increased by 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S29 | Denmark | 1 | 1 | 6.447 | 1.451 |
| S132 | Norway | 3 | 1 | 3.300 | 69 |
| S166 | Norway | 3 | 1 | 3.200 | 2 |
| S102 | The Netherlands | 3 | 11 | 254 | 10 |
| S20 | The Netherlands | 3 | 2 | 878 | 7 |
| S39 | The Netherlands | 3 | 1 | 49 | 0 |
| S6 | The Netherlands | 3 | 12 | 266 | 2 |
| S91 | The Netherlands | 3 | 3 | 656 | 1.677 |
| S162 | United Kingdom | 1 | 10 | 361 | 83 |

We provide the changes in the supply and distribution decisions for Port Call 15 in Appendix E and the optimal configuration for the base case can be found in Appendix B. Similar to the case of Port Call 8, for Port Call 15, when transportation costs are increased by 10%, supplier S70 which is in the Netherlands (the port country), delivers directly to the vessel. When the costs are increased by 20%, some SKUs are purchased from supplier S70 and S131 which are both in the Netherlands instead of S198 which is in the United Arab Emirates. Supplier S70 delivers directly to the vessel as well. These are to avoid the extra transportation costs resulting from the distance or the service of the warehouse.

As we just observed, the optimal supply and distributions options given the new transportation costs differ only slightly from the optimal costs in the base case. Therefore, the total costs for the new optimal configurations are also close to that of the base case (Table 5.14).

**Table 5.14.** Change in the total costs of new optimal configurations with respect to the change in transportation costs

| Change in Transportation Cost | Optimal Total Cost (€) | Change in Total Cost |
|---|---|---|
| -20% | 350.386 | -2,06% |
| -10% | 354.063 | -1,03% |
| -5% | 355.901 | -0,51% |
| Base case | 357.739 | 0,00% |
| 5% | 359.578 | 0,51% |
| 10% | 361.409 | 1,03% |
| 20% | 365.041 | 2,04% |

### 5.3.2. Ordering Cost

In this section we test the robustness of the decisions with respect to the changes in ordering cost as we have estimated this cost using benchmarks and expert opinion. This cost reflects the organizational costs for submitting an order to a supplier and influences the number of suppliers to be used per port call. Since ordering cost constitutes only 7% of the total costs (Table 5.2), a change of 5% in ordering costs would result in a change of 0,35% in total costs. Therefore, we expect the total costs for the new optimal configurations also to be close to that of the base case (Table 5.15).

**Table 5.15.** Change in the total costs of new optimal configurations with respect to the change in ordering costs

| Change in Ordering Cost | Optimal Total Cost (€) | Change in Total Cost |
|---|---|---|
| -20% | 352.866 | -1,36% |
| -10% | 355.333 | -0,67% |
| -5% | 356.539 | -0,34% |
| Base case | 357.739 | 0,00% |
| 5% | 358.933 | 0,33% |
| 10% | 360.199 | 0,69% |
| 20% | 362.136 | 1,23% |

When re-running the model to optimality with the changed costs, we observe that the selected suppliers and the optimal delivery routes do not have a significant change as only a small number of SKUs have a different strategy. Only for Port Call 1, a slightly larger number of SKUs have a change in their suppliers. When the ordering costs are decreased by 20% it becomes profitable to use two more suppliers (S11 and S185) (Section 5.2.2: Example Case 1 and Appendix F). Similarly, when ordering costs decrease by 10% one additional supplier (S185) is used (Appendix F). As expected, the total number of suppliers used for the port calls changes with respect to ordering costs, for the 15 port calls the changes remain relatively small (Table 5.16).

**Table 5.16.** Change in the total number of orders submitted to suppliers with respect to the change in ordering costs

| Change in Ordering Cost | Number of Orders to Suppliers |
|---|---|
| -20% | 124 |
| -10% | 122 |
| -5% | 120 |
| Base Case | 120 |
| 5% | 119 |
| 10% | 118 |
| 20% | 116 |

### 5.3.3. Loading Cost

Since we have estimated the loading costs based on expert opinion, we perform a sensitivity analysis to evaluate its influence on the supply and distribution decisions. Since the loading costs constitute only 2% of the total costs (Table 5.2), a change of 5% in loading costs would only result in a change of 0,1% in total costs. Still, having such costs and using multiple delivery options leave a possibility for attaining savings if the delivery times of separate orders can be synchronized.

When we re-run the model to optimality with the modified costs, we observe negligible change in the optimal costs (Table 5.17). We observe only small changes in optimal supplier or delivery decisions in Port Calls 1, 8 and 15. When the loading cost is reduced by 20%, for Port Call 1, Singapore Warehouse is no longer used in the optimal solution and two direct deliveries are made to the vessel as the loading costs are cheaper than the facility costs (Section 5.2.2: Example Case 1 and Appendix G). Similarly, for Port Call 8 and 15 an additional direct delivery is made as well (Appendix B: Port Call 8 and 15 and Appendix G).

**Table 5.17.** Change in the total costs of new optimal configurations with respect to the change in loading costs

| Change in Loading Cost | Optimal Total Cost (€) | Change in Total Cost |
|---|---|---|
| -20% | 356.295 | -0,40% |
| -10% | 357.049 | -0,19% |
| -5% | 357.408 | -0,09% |
| Base Case | 357.739 | 0,00% |
| 5% | 358.069 | 0,09% |
| 10% | 358.399 | 0,18% |
| 20% | 359.059 | 0,37% |

### 5.3.4. Discount Structure

As we explained in Chapter 2, consulting the purchasers, we learned that the suppliers may be willing to apply a 5% or a 10% discount over the total spent amount (per port call) if this amount is considered large. However, there is no fixed terms on this discount policy and it is at the purchasers' discretion to ask for discounts when they think that the amount is large enough. We run the model to optimality with different discount policies. As expected, the introduction of discounts leads to reduction in total costs (Figure 5.8). With a policy of discount of 5% over purchases of 3000 €, the optimal total costs can be reduced by 3%. If a discount of 10% is applied for purchases over only 1000 €, this reduction can be up to 7%.

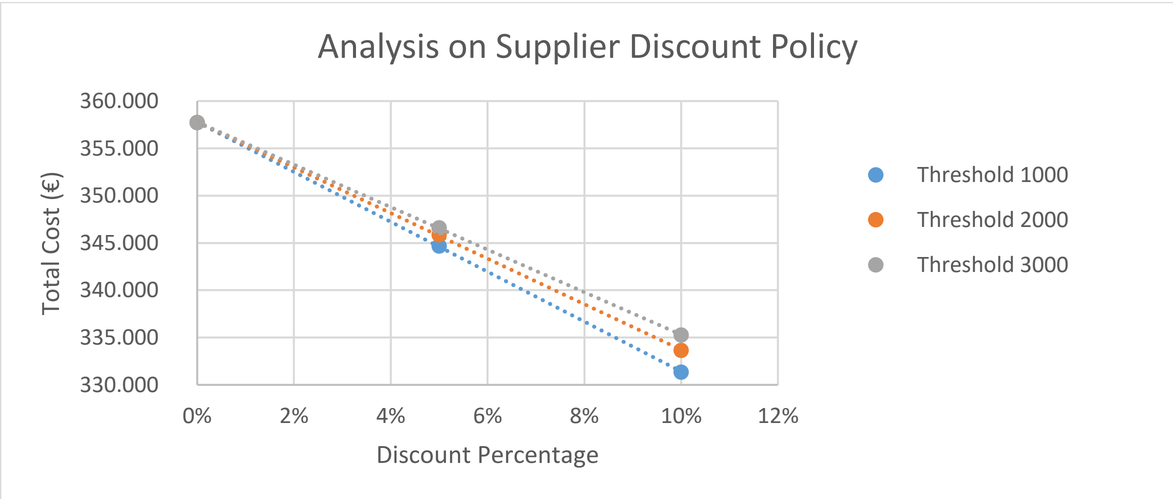


**Figure 5.8.** Optimal costs for given discount policies

Order consolidation would yield to savings from both procurement and ordering costs as a smaller number of suppliers would be used with cheaper prices. Table 5.18 presents the attainable savings compared to the current case. For the analysis we tested the cases where all suppliers apply the same discount policies. The model can be run using different discount percentages and thresholds per supplier.

**Table 5.18.** Attainable savings with respect to different threshold discount policies

| Discount | Threshold | Realized (Base Case) Total Cost | Optimal Cost | Saving | Saving Percentage | Change in Optimal Cost | Number of Suppliers |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 378.953 | 357.739 | 21.214 | 5,60% | 0,00% | 120 |
| 5% | 1000 | 378.953 | 344.684 | 34.269 | 9,04% | -3,65% | 117 |
| 5% | 2000 | 378.953 | 345.852 | 33.102 | 8,74% | -3,32% | 117 |
| 5% | 3000 | 378.953 | 346.615 | 32.338 | 8,53% | -3,11% | 120 |
| 10% | 1000 | 378.953 | 331.370 | 47.583 | 12,56% | -7,37% | 114 |
| 10% | 2000 | 378.953 | 333.660 | 45.293 | 11,95% | -6,73% | 115 |
| 10% | 3000 | 378.953 | 335.268 | 43.685 | 11,53% | -6,28% | 117 |

Looking at the changes in the optimal decisions with respect to the given discount policies, we observe that only a small number of SKUs are purchased from different suppliers. Although the supply decisions do not change for most of the SKUs, we observe that total costs have significant changes (Table 5.18). This is because, orders large enough to meet the thresholds are already being submitted to suppliers. Therefore, negotiating for discount over these quantities has a significant saving potential.

Port Calls 9, 11 and 15 have the highest percentage of SKUs that have changes in the optimal supply decisions when discounts are introduced. Here, we inspect the changes in the optimal suppliers for these port calls. When 10% discount is applied for purchases over 1000€, for Port Call 9, more orders are consolidated at suppliers S92 and S100 which already had relatively high total prices to benefit from the discounts optimally (Section 5.2.2: Example Case 3 and Appendix H). This leads to re-distribution of other orders and reduces the number of suppliers used by one.

Similarly, for Port Call 11, when 10% discount is applied for purchases over 1000€, 200€ or 3000€, the supplier S139 in Singapore is no longer used as the discounts cover for the savings obtained from the previous configuration (Appendix B: Port Call 11 and Appendix H). However, other orders are not further consolidated at suppliers. For Port Call 15, when 10% discount is applied for 3000€, some orders in the previous configuration become eligible for discount and are kept the same. These discounts enable removing suppliers S147 and S4 located in Singapore as the savings from using these suppliers are now covered. As explained in Section 2.4, the database contains substitute suppliers only for small number of items. This makes it difficult to evaluate the effect of further consolidating orders at a supplier. Benefiting from discount policies depends on the substitutability of suppliers. Moreover, the joint effect of discount percentage and the threshold value affect the decisions as whether the discount covers for the change in product costs and transportation costs is evaluated.

## 5.4. Conclusion

After analyzing our test case of 15 port calls, we got to exemplify the trade-offs we have discussed in Chapter 4 and answered our fourth research question *"What are optimal decisions for outfitting orders for the port calls?"*. We summarize our observations on differences between the realized and optimal cases as below. The reader can refer to the examples discussed in Section 5.2.2 or Appendix B for the mentioned port calls for an illustration of the cases.

- Considering cheaper suppliers located far from the port region may be more profitable. Similarly, splitting orders among cheaper suppliers may result in savings (Port Call 1,2,4,5).
- Generally, suppliers and a warehouse closer to the port region are selected. Items should be consolidated at a point close to the suppliers and then be transported to the vessel (All port calls).

- For heavy orders, direct delivery to vessel may be cheaper if the supplier is in that country and therefore delivering DDP (Port Call 4,6,8).
- If there are many separate small (light) deliveries, they are usually consolidated. If there is only a small number of items (or the total weight is very small), consolidation should be made in one facility. Starting to use a second facility would not be profitable as fixed costs would be more (Port call 2, 3,5,7).
- The use of multiple facilities was only feasible if both are used for relatively heavy loads and the suppliers are in proximity (Port Call 1).
- Although savings from transportation could be made, agents were not preferred in any of our cases as they have higher facility costs. This is actually a preferable solution since the port locations and agents may not always be known in advance or they may be updated. Using warehouses instead, reduces the dependency on the punctuality of the supplier.

Through our sample port calls, we demonstrated that significant savings can be achieved. Analyzing how the configurations differ in the realized and optimal cases, we reach conclusions on the attainability of the savings. We observed that a large fraction of the savings come from the product costs. With our test cases, we conclude that suppliers in a broader geographical region should be considered when placing orders, as cheaper product costs can cover for transportation costs. We conclude that applying the model for all the port calls would be worthwhile. We note again that the optimal configurations are a result of the given demand lists and port locations. The joint effect of the inputs can yield different optimal decisions. We share above insights with FS as a step for using the tool for decision support and adapting the operational purchases. The aim is to eventually use the tool for prior planning per port call.

We also carried out a sensitivity analysis to determine the effect of input parameters on the supply and distribution decisions. We changed one cost value at a time keeping all other input the same and observed the changes in the distribution decisions and the total costs. First, we studied how the change in transportation costs affect the optimal configuration. We observed that the model is not very sensitive to the change in transportation cost when the changes are between -20% – +20%. When the costs were increased by 20%, we observed for two port calls that using suppliers closer to the port, benefiting more from DDP deliveries and delivering directly to the vessel were preferred. Second, we recognized that the change in ordering costs does not have much influence on the optimal supply and distribution configurations. As expected, reduction in loading costs by 10 and 20% lead to an increase in the number of suppliers used but it has only affected a small number of SKUs. Next, we observed that reduction in loading costs lead to an increase in the number of separate deliveries made to the vessel. Again, this change only affected small number of SKUs. We can conclude that the model results are not sensitive to the changes in transportation, ordering or loading costs.

Since larger fraction of costs are caused by product costs, we explored how introducing threshold discount policies would affect the total costs. Benefiting from discount policies depends on the substitutability of suppliers and supplier consoldation. Moreover, the joint effect of discount percentage and the threshold value affect the decisions as whether the discount covers for the change in product costs and transportation costs is evaluated. We observe that depending on the policy, savings of up to 12% can be attained compared to the realized case.

# Chapter 6

# Conclusions and Recommendations

In this final chapter we conclude our research. In Section 6.1., we summarize our conclusions based on the results of Chapter 5. We provide recommendations for successfully implementing the model in Section 6.2. We complete the chapter by discussing the possibilities for future research in Section 6.3.

### 6.1. Conclusions

The main objective of our research was to "Develop a decision-making tool for consumables & parts to minimize total purchasing & logistics costs". We did this by studying the current way of operation of FS and building a mixed integer linear programming model. Formulating a linear model enabled us to obtain an exact solution corresponding to the minimum cost supply and distribution decisions. We modeled FS's distribution network as a directed graph and incorporated applicable distribution options. We considered these options together with procurement and freight discounts. Our goal was to minimize total costs of purchasing and distribution. We selected a test case of 15 port calls based on data availability and compared the estimated costs for the realized and optimal cases.

We observed that significant savings are attainable by re-configuring purchasing and logistics activities. The largest fraction of costs, around 81% percent of total costs, are coming from product prices followed by transportation costs corresponding to 10%. Minimizing total costs through adjusting the purchasing and distribution options can lead to a saving of 6% mostly arising from product costs (Table 6.1).

Our test cases showed that considering suppliers over a larger geographical region and procuring cheaper products can yield to a reduction in overall costs. Consolidating goods prior to delivery to vessel in a warehouse close to the suppliers is also preferred as was already done by FS. Referring to the transportation and warehousing costs together as logistics costs, we can conclude that savings up to 6% can be achieved from logistics costs. Given these observations, we conclude that applying the model for the whole fleet would result in significant savings.

We have an overview of the total cost breakdown structure in Table 6.1. The model suggests splitting orders among a higher number of suppliers. This results in additional ordering costs as well as extra handling costs as more shipments are received at the warehouse. Savings in transportation costs occur because of consolidating goods more, not using the agents and re-allocation of weights. These also result in other savings. More items are consolidated in the same warehouse rather than using agents or direct deliveries form the suppliers. Using fewer facilities reduces fixed facility costs. Moreover, having fewer number of separate deliveries at the vessel reduces the loading costs. The model also ensures the items are re-allocated among suppliers in a way to minimize both product and transportation costs.

**Table 6.1.** Comparison of total costs of the realized and the optimal cases for the selected 15 port calls

| | TOTAL (€) | | | |
|---|---|---|---|---|
| **Description** | Realized | Optimal | Saving | Saving (%) |
| **Product cost:** | 307.674 | 287.009 | 20.664 | 7% |
| **Ordering cost:** | 19.600 | 24.000 | - 4.400 | -22% |
| **Transportation cost:** | 38.914 | 36.765 | 2.149 | 6% |
| **Fixed facility cost:** | 1.918 | 1.319 | 599 | 31% |
| **Handling cost:** | 1.848 | 2.047 | - 198 | -11% |
| **Loading the vessel:** | 9.000 | 6.600 | 2.400 | 27% |
| **Total cost:** | **378.953** | **357.739** | **21.214** | **6%** |

After observing the high total product costs and the unstructured discount policies applied by suppliers, we re-run the model for the port calls assuming various threshold discount policies. We assumed suppliers would apply a certain percentage discount over the total spent amount for the port call if the amount exceeds a certain threshold. Depending on the policy applied, we observed that a saving up to 12% can be attained. In absence of discounts, the optimal solution suggests splitting orders among more suppliers. However, when discounts are introduced it would be optimal to consolidate orders at fewer number of suppliers in order to benefit from the discounts. This discount structure is applied per port call but can aid in determining negotiation conditions for the whole fleet.

We performed a sensitivity analysis on transportation, ordering and loading costs in order to test the robustness of the given optimal solutions. When the costs are changed by -20 – +20%, the optimal strategies change for only a small number of SKUs. We conclude that the model is not sensitive to any of these costs. This means that if an increase in these costs occur, the decisions made by the model would remain close to that of the lowest cost scenario. Still, higher increases in transportation costs may require using suppliers closer to the port region.

The algorithm run on average in 0,355 minutes per port call and can support up to 236.646 decision variables and 117.976 constraints. We summarize the features of the tool and the advantages it provides as below:

- We provide a generic model. Data is read from csv files that can be updated.
- The model can work with smaller or additional number of facilities. For example, for Europe and Asia, we discard local warehouses. If different arcs are fed as input additional warehouses can be considered as well.
- The model enables comparing a wide set of suppliers for the supplier selection process, given the product and transportation costs are provided by the suppliers in advance. This would reduce the effort purchasers spend on asking for and comparing quotes each time an order should be placed and enable comparing more suppliers.
- Introducing different facilities and updating the transportation cost between any arc enable comparing logistics service providers as well. The model can be re-run with the quotes of different service providers.
- We also build a cost calculator that calculates the purchasing and logistics costs given the suppliers and delivery routes selected. This would enable the users to run scenarios they prefer and to decide on how much deviation from optimal is acceptable. This would reveal the cost of bad planning as well.

### 6.2. Recommendations

This section provides recommendations for the utilization of the optimization tool. Here, we provide recommendations for the implementation of the model to the FS's way of operating. We further list suggestions for improving the accuracy of the model. We emphasize that the model reveals the impact of alternative decisions. The result would be more representative of reality and accurate if data requirements are met and prior planning can be achieved. We suggest FS to make improvements on data collection and demand planning.

We recommend the Purchasing & Logistics Department to initially use the model to gain insight on the applicability of alternative purchasing and distribution options. The model can be used at tactical buying level for the processes of approving preferred suppliers and contracting. The impact of negotiating with suppliers can be visible using the model. Similarly, the model would aid in deciding to purchase locally or centrally. The model should be used for comparing alternative suppliers and logistics service providers as well as determining applicable distribution strategies.

Application of the model requires a more tactical perspective compared to the operational purchasing processes handled daily. Improvements on data availability would increase the accuracy of the decisions made in the tactical level. This would also help tactical level decisions to be more applicable to the operational level and reduce ad-hoc decision making. In the future, products to be supplied at a port call can be planned with higher certainty. A better forecasting method for periodical orders should be applied. This early demand planning would enable benefitting from the economies of scales for product costs, handling and freight rates.

Given above, we advise FS to start collecting the input data to increase the accuracy of the decisions made by the model. We also acknowledge that this data collection would not only lead to cost savings through the model but also aid in monitoring the performance of suppliers and logistics service providers. Quotes for freight rates and product costs should be available to be able to run the model more accurately. Suppliers should be asked to provide the transportation costs along with the package dimensions and the weight of the products. Similarly, freight providers should be asked to provide their rate structures in advance. Comparing more alternatives would also yield a better evaluation. Different suppliers can be added as input for comparison. Still for running the model at an acceptable time, we advise FS to include only relevant input and keep the model size small. Removing inapplicable supplier or facility options from the data would result in a faster run time.

The model can be updated whenever new data is available by changing the input files as explained in Appendix C. Similarly, in case FS's network changes and different facilities are started to be considered for port calls, they can be defined in the model. We provide a user guide in Appendix C with explanation on how to set up and use the optimization tool. The tool we programmed and used for our analysis has its limitations for daily use. Therefore, we recommend FS to work with a software developer to build a professional tool that can be integrated to their information systems.

### 6.3. Future Research

The network optimization model we presented in this research sets an initial step for supplier selection and delivery route planning and is meant as a decision-support tool. Here, we took into account economies of scales in purchasing, transportation and facility costs and provided optimal purchasing and distribution decisions for a given set of items to be supplied for a vessel at a given location.

We formulated the model to be run separately for each port call as the costs are incurred separately for each. This also resulted in a smaller model size. We do not consider optimizing multiple port calls jointly to be worthwhile as the costs are disjoint and currently the purchasers are working per vessel. The Purchasing & Logistics Department wishes to maintain having separate purchasing and warehousing operations for each vessel. Moreover, the uncertainties with the planning of port calls also require a planning to be made in relatively short time making the joint distribution of items for multiple vessels difficult. The tool enables running multiple port calls sequentially and negotiations with suppliers can be made combining these results.

The mathematical programming model we introduced in this research can be extended to allow time constraints such that the items must be supplied and delivered onboard within a given time period for the port call. The lead times of suppliers and the planning time required by the warehouse can be considered. A quantitative supplier selection methodology can also be integrated in the model introducing alternative costs for suppliers based on lead times, expertise in customs or ease of communication. These would fasten and facilitate the implementation of the model as well. Another extension can be taking the cash flows into account. Since the order times affect the payment time and conditions, the optimal ordering times can be determined to balance the spent of the company over a certain period.

Additionally, the model can be applied to other product groups other than consumables & parts such as equipment and spare parts. This would enable better exploitation of economies of scale in purchasing, transportation and facility costs. Combining the model with a demand forecast when using it with different group of items may also be applicable as their demand is not always known.

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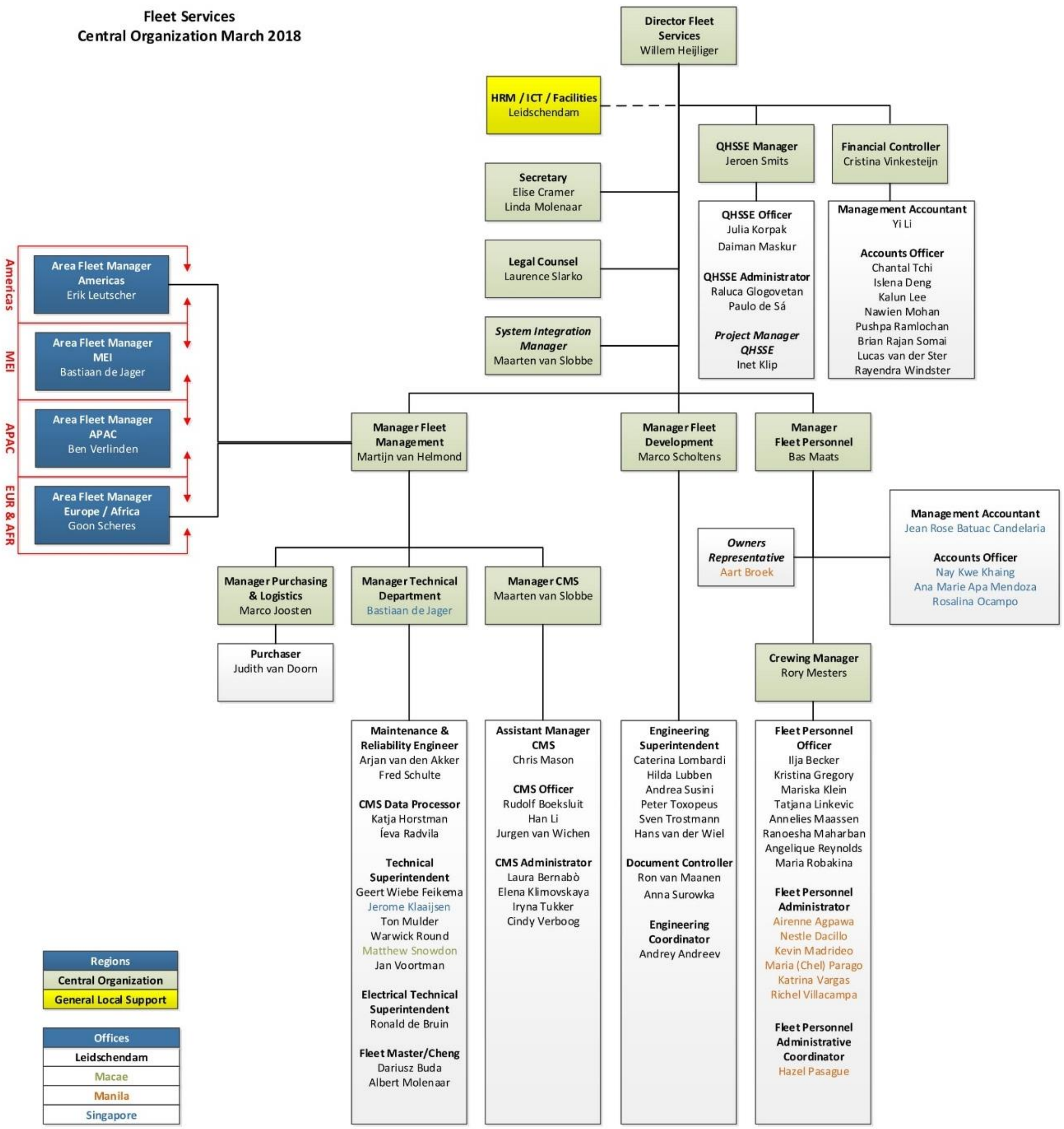
# Appendix

## **Appendix A.** Organization of Fleet Services



**Appendix B.** Details of Realized and Optimal Configurations per Port Call

Here we give an analysis on the comprison of realized and optimal supply and delivery options for each port call we have selected. We display the network flow maps using total weight as an indicator of the magnitude of the flow as transportation costs are determined with respect to the weight. The country names represent the suppliers used. For visualization purposes, we do not differentiate between the suppliers delivering from the same country, we select approximate locations for the vessels, agents (which are actually located at the port) and warehouses. The tables accompanying the maps display the suppy choices made in detail. We do not list the SKUs purchased from each supplier here as the lists would be too exhaustive. We list the port calls that were not explained in detail in Section 5.2.2. Comments on the differences between realized and optimal configurations along with the tables representing total costs are provided after the network maps. Delivery options correspond to the options identified in Section 2.1.1 and are repeated below:

1. Supplier - vessel
2. Supplier – agent –vessel
3. Supplier – Rotterdam Warehouse – vessel
4. Supplier – Rotterdam Warehouse - agent –vessel
5. Supplier – Singapore warehouse – vessel
6. Supplier – Singapore warehouse - agent –vessel
7. Supplier – local warehouse – vessel
8. Supplier – local warehouse - agent -vessel

**Port Call 2:** 41 SKUs to be ordered for vessel in United Arab Emirates


**Figure B.1.** Realized distribution for Port Call 2

**Table B.1.** Realized supply and delivery decisions for Port Call 2

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S133 | The Netherlands | 3 | 4 | 1.183 | 22 |
| S30 | The Netherlands | 3 | 1 | 132 | 1 |
| S179 | United Arab Emirates | 7 | 1 | 587 | 27 |
| S198 | United Arab Emirates | 7 | 13 | 576 | 22 |
| S58 | United Arab Emirates | 7 | 22 | 175 | 3 |


**Figure B.2.** Optimal distribution for Port Call 2

**Table B.2.** Optimal supply and delivery decisions for Port Call 2

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S133 | The Netherlands | 7 | 4 | 1.183 | 22 |
| S30 | The Netherlands | 7 | 3 | 275 | 3 |
| S179 | United Arab Emirates | 7 | 1 | 587 | 27 |
| S198 | United Arab Emirates | 7 | 10 | 194 | 20 |
| S58 | United Arab Emirates | 7 | 23 | 211 | 3 |

**Port Call 3:** 120 SKUs to be ordered for vessel in United Arab Emirates


**Figure B.3.** Realized distribution for Port Call 3

**Table B.3.** Realized supply and delivery decisions for Port Call 3

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S47 | Singapore | 5 | 1 | 1.052 | 1 |
| S7 | Singapore | 5 | 1 | 1.074 | 217 |
| S198 | United Arab Emirates | 7 | 41 | 787 | 161 |
| S58 | United Arab Emirates | 7 | 77 | 3.958 | 701 |


**Figure B.4.** Optimal distribution for Port Call 3

**Table B.4.** Optimal supply and delivery decisions for Port Call 3

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S47 | Singapore | 7 | 1 | 1.052 | 1 |
| S7 | Singapore | 7 | 1 | 1.074 | 217 |
| S198 | United Arab Emirates | 7 | 41 | 787 | 161 |
| S58 | United Arab Emirates | 7 | 77 | 3.958 | 701 |

**Port Call 5:** 41 SKUs to be ordered for vessel in Kenya


**Figure B.5.** Realized distribution for Port Call 5

**Table B.5.** Realized supply and delivery decisions for Port Call 5

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S15 | Kenya | 1 | 4 | 2.122 | 55 |
| S147 | Singapore | 2 | 17 | 3.375 | 39 |
| S126 | The Netherlands | 3 | 1 | 195 | 1 |
| S128 | The Netherlands | 3 | 3 | 152 | 15 |
| S131 | The Netherlands | 3 | 2 | 43 | 1 |
| S183 | The Netherlands | 3 | 3 | 415 | 1 |
| S39 | The Netherlands | 3 | 11 | 554 | 16 |


**Figure B.6.** Optimal distribution for Port Call 5

**Table B.6.** Optimal supply and delivery decisions for Port Call 5

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S15 | Kenya | 3 | 2 | 1.175 | 8 |
| S147 | Singapore | 3 | 6 | 535 | 13 |
| S102 | The Netherlands | 3 | 2 | 320 | 46 |
| S126 | The Netherlands | 3 | 1 | 195 | 1 |
| S128 | The Netherlands | 3 | 3 | 152 | 15 |
| S131 | The Netherlands | 3 | 2 | 43 | 1 |
| S146 | The Netherlands | 3 | 9 | 1.519 | 13 |
| S183 | The Netherlands | 3 | 3 | 415 | 1 |
| S39 | The Netherlands | 3 | 11 | 554 | 16 |
| S197 | United Arab Emirates | 3 | 2 | 54 | 13 |

**Port Call 6:** 144 SKUs to be ordered for vessel in the Netherlands


**Figure B.7.** Realized distribution for Port Call 6

**Table B.7.** Realized supply and delivery decisions for Port Call 6

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 4 | 254 | 2 |
| S102 | The Netherlands | 3 | 1 | 371 | 0 |
| S128 | The Netherlands | 3 | 24 | 1.642 | 100 |
| S131 | The Netherlands | 3 | 5 | 455 | 17 |
| S144 | The Netherlands | 3 | 52 | 965 | 43 |
| S150 | The Netherlands | 3 | 3 | 82 | 0 |
| S170 | The Netherlands | 3 | 44 | 5.939 | 1.020 |
| S183 | The Netherlands | 3 | 8 | 2.071 | 10 |
| S71 | The Netherlands | 3 | 3 | 887 | 1.250 |


**Figure B.8.** Optimal distribution for Port Call 6

**Table B.8.** Optimal supply and delivery decisions for Port Call 6

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S53 | Egypt | 3 | 3 | 64 | 2 |
| S96 | Singapore | 3 | 8 | 135 | 3 |
| S100 | The Netherlands | 3 | 4 | 254 | 2 |
| S102 | The Netherlands | 3 | 8 | 334 | 165 |
| S128 | The Netherlands | 3 | 22 | 1.616 | 99 |
| S131 | The Netherlands | 3 | 6 | 686 | 36 |
| S144 | The Netherlands | 3 | 49 | 1.686 | 70 |
| S150 | The Netherlands | 3 | 2 | 74 | 0 |
| S170 | The Netherlands | 3 | 34 | 3.665 | 808 |
| S183 | The Netherlands | 3 | 5 | 1.049 | 8 |
| S71 | The Netherlands | 1 | 3 | 887 | 1.250 |

**Port Call 7:** 51 SKUs to be ordered for vessel in the United Kingdom

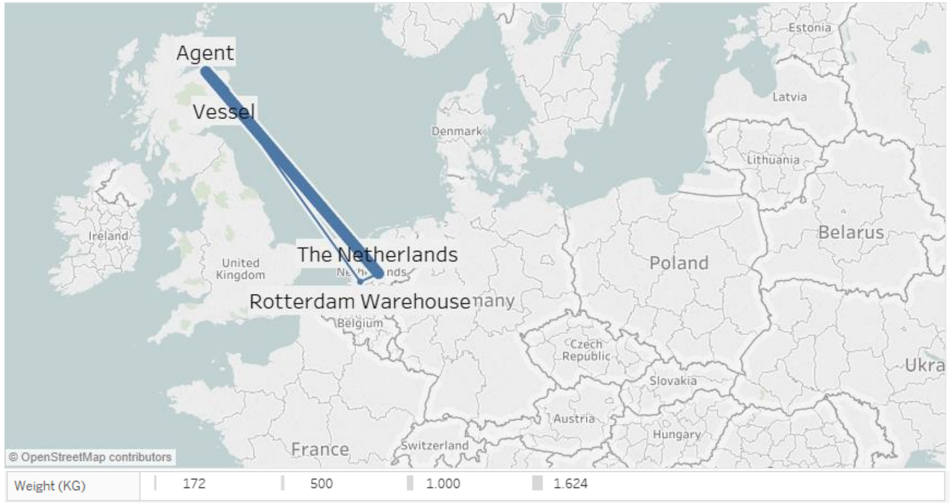



**Figure B.9.** Realized distribution for Port Call 7


**Figure B.10.** Optimal distribution for Port Call 7

**Table B.9.** Realized supply and delivery decisions for Port Call 7

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 5 | 5.140 | 97 |
| S131 | The Netherlands | 3 | 20 | 1.293 | 67 |
| S142 | The Netherlands | 3 | 1 | 221 | 2 |
| S145 | The Netherlands | 2 | 2 | 3.791 | 1.624 |
| S183 | The Netherlands | 3 | 1 | 965 | 0 |
| S30 | The Netherlands | 3 | 21 | 364 | 4 |
| S35 | The Netherlands | 3 | 1 | 246 | 1 |

**Table B.10.** Optimal supply and delivery decisions for Port Call 7

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 5 | 5.140 | 97 |
| S131 | The Netherlands | 3 | 19 | 1.275 | 67 |
| S142 | The Netherlands | 3 | 2 | 234 | 2 |
| S145 | The Netherlands | 3 | 2 | 3.791 | 1.624 |
| S183 | The Netherlands | 3 | 1 | 965 | 0 |
| S30 | The Netherlands | 3 | 21 | 364 | 4 |
| S35 | The Netherlands | 3 | 1 | 246 | 1 |

**Port Call 8:** 42 SKUs to be ordered for vessel in the United Kingdom


**Figure B.11.** Realized distribution for Port Call 8

**Table B.11.** Realized supply and delivery decisions for Port Call 8

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S29 | Denmark | 2 | 1 | 6.447 | 1.451 |
| S132 | Norway | 3 | 1 | 3.300 | 69 |
| S166 | Norway | 3 | 1 | 3.200 | 2 |
| S102 | The Netherlands | 3 | 9 | 202 | 3 |
| S20 | The Netherlands | 3 | 2 | 878 | 7 |
| S39 | The Netherlands | 3 | 1 | 49 | 0 |
| S6 | The Netherlands | 3 | 12 | 266 | 2 |
| S91 | The Netherlands | 3 | 3 | 656 | 1.677 |
| S162 | United Kingdom | 2 | 12 | 477 | 89 |


**Figure B.12.** Optimal distribution for Port Call 8

**Table B.12.** Optimal supply and delivery decisions for Port Call 8

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S29 | Denmark | 1 | 1 | 6.447 | 1.451 |
| S132 | Norway | 3 | 1 | 3.300 | 69 |
| S166 | Norway | 3 | 1 | 3.200 | 2 |
| S102 | The Netherlands | 3 | 14 | 296 | 41 |
| S20 | The Netherlands | 3 | 2 | 878 | 7 |
| S39 | The Netherlands | 3 | 1 | 49 | 0 |
| S6 | The Netherlands | 3 | 12 | 266 | 2 |
| S91 | The Netherlands | 3 | 3 | 656 | 1.677 |
| S162 | United Kingdom | 3 | 7 | 320 | 52 |

**Port Call 10:** 33 SKUs to be ordered for vessel in the United Kingdom

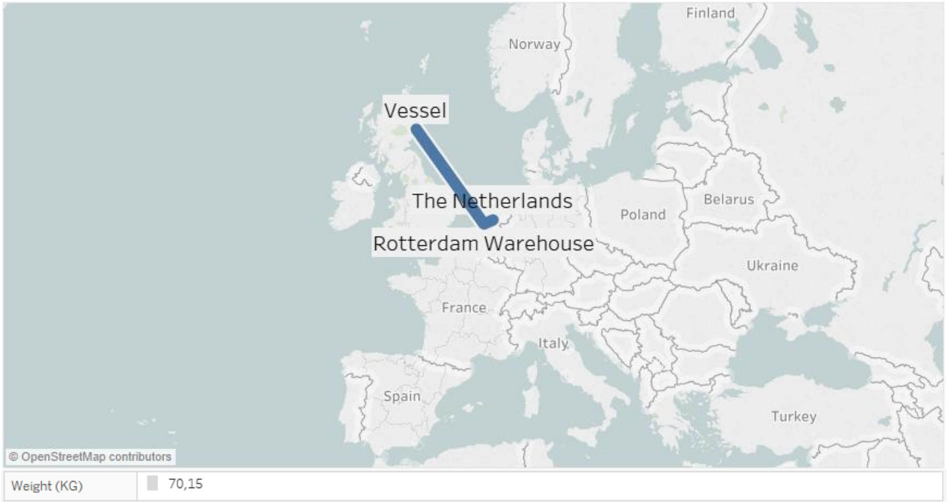



**Figure B.13.** Realized and optimal distribution for Port Call 10

**Table B.13.** Realized and optimal supply and delivery decisions for Port Call 10

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S123 | The Netherlands | 3 | 8 | 422 | 2 |
| S150 | The Netherlands | 3 | 5 | 40 | 1 |
| S170 | The Netherlands | 3 | 1 | 538 | 6 |
| S39 | The Netherlands | 3 | 19 | 1.203 | 62 |

**Port Call 11:** 61 SKUs to be ordered for vessel in the United Kingdom


**Figure B.14.** Realized distribution for Port Call 11

**Table B.14.** Realized supply and delivery decisions for Port Call 11

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S102 | The Netherlands | 3 | 19 | 1.216 | 98 |
| S128 | The Netherlands | 3 | 5 | 105 | 5 |
| S142 | The Netherlands | 3 | 1 | 383 | 13 |
| S144 | The Netherlands | 3 | 1 | 391 | 2.000 |
| S146 | The Netherlands | 3 | 32 | 4.594 | 96 |
| S31 | The Netherlands | 3 | 2 | 146 | 1 |
| S69 | United Kingdom | 2 | 1 | 30 | 1 |

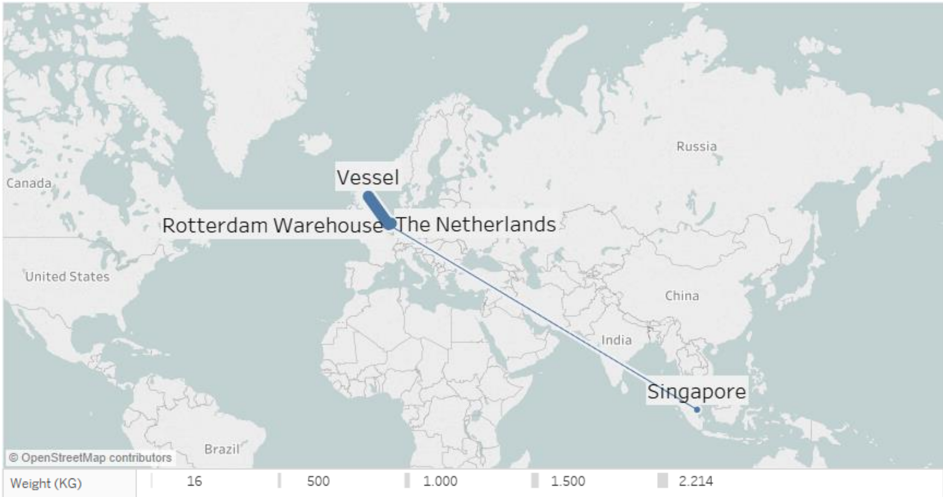



**Figure B.15.** Optimal distribution for Port Call 11

**Table B.15.** Optimal supply and delivery decisions for Port Call 11

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S139 | Singapore | 3 | 6 | 535 | 15 |
| S45 | Singapore | 3 | 2 | 103 | 1 |
| S102 | The Netherlands | 3 | 21 | 1.370 | 100 |
| S128 | The Netherlands | 3 | 5 | 105 | 5 |
| S142 | The Netherlands | 3 | 1 | 383 | 13 |
| S144 | The Netherlands | 3 | 1 | 391 | 2.000 |
| S146 | The Netherlands | 3 | 24 | 3.451 | 80 |
| S69 | United Kingdom | 3 | 1 | 30 | 1 |

**Port Call 12:** 44 SKUs to be ordered for vessel in Malaysia

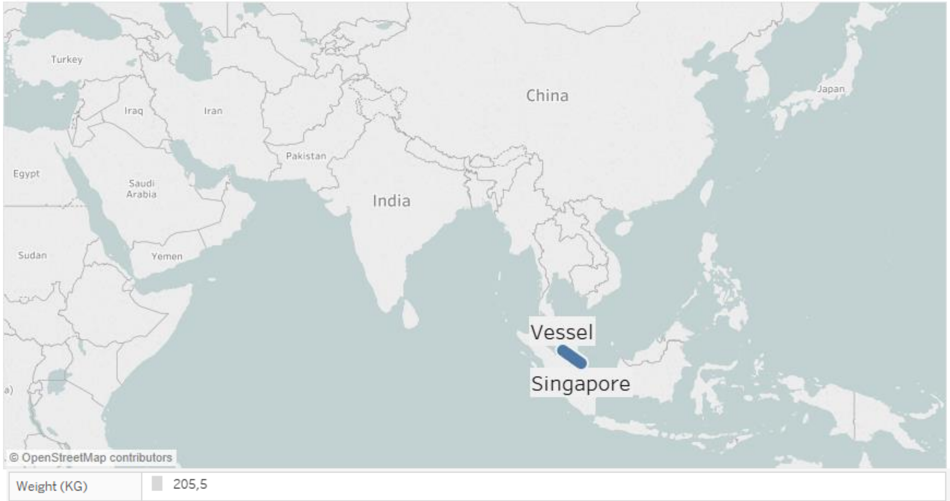



**Figure B.16.** Realized and optimal distribution for Port Call 12

**Table B.16.** Realized and optimal supply and delivery decisions for Port Call 12

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S99 | Singapore | 1 | 44 | 3007 | 205 |

**Port Call 13:** 57 SKUs to be ordered for vessel in the Netherlands


**Figure B.17.** Realized distribution for Port Call 13

**Table B.17.** Realized supply and delivery decisions for Port Call 13

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 1 | 1 | 21 | 1 |
| | | 3 | 10 | 2.296 | 74 |
| S102 | The Netherlands | 3 | 4 | 741 | 80 |
| S131 | The Netherlands | 3 | 8 | 980 | 6 |
| S146 | The Netherlands | 3 | 10 | 8.483 | 32 |
| S35 | The Netherlands | 1 | 1 | 5.980 | 154 |
| | | 3 | 3 | 765 | 2 |
| S86 | The Netherlands | 3 | 20 | 1.262 | 7 |


**Figure B.18.** Optimal distribution for Port Call 13

**Table B.18.** Optimal supply and delivery decisions for Port Call 13

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S124 | Italy | 3 | 3 | 301 | 2 |
| S100 | The Netherlands | 3 | 11 | 2.317 | 75 |
| S102 | The Netherlands | 3 | 4 | 741 | 80 |
| S131 | The Netherlands | 3 | 8 | 980 | 6 |
| S146 | The Netherlands | 3 | 10 | 8.483 | 32 |
| S35 | The Netherlands | 3 | 1 | 5.980 | 154 |
| S86 | The Netherlands | 3 | 20 | 1.262 | 7 |

**Port Call 14:** 46 SKUs to be ordered for vessel in Germany


**Figure B.19.** Realized distribution for Port Call 14

**Table B.19.** Realized supply and delivery decisions for Port Call 14

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 7 | 182 | 1 |
| S102 | The Netherlands | 3 | 32 | 2.560 | 50 |
| S128 | The Netherlands | 3 | 2 | 1.661 | 124 |
| S131 | The Netherlands | 3 | 1 | 838 | 1 |
| S146 | The Netherlands | 3 | 4 | 4.445 | 16 |

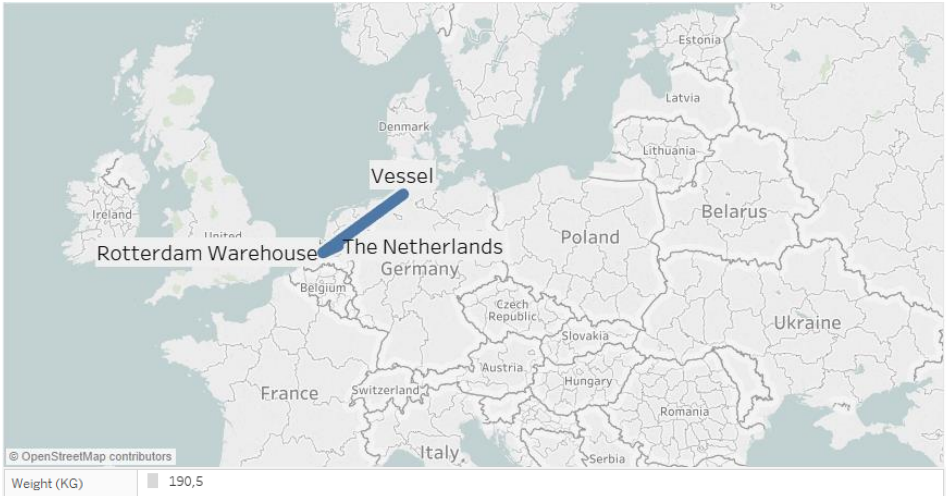



**Figure B.20.** Optimal distribution for Port Call 14

**Table B.20.** Optimal supply and delivery decisions for Port Call 14

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S100 | The Netherlands | 3 | 7 | 182 | 1 |
| S102 | The Netherlands | 3 | 31 | 2.247 | 49 |
| S128 | The Netherlands | 3 | 1 | 133 | 120 |
| S131 | The Netherlands | 3 | 2 | 908 | 1 |
| S146 | The Netherlands | 3 | 4 | 4.445 | 16 |
| S54 | The Netherlands | 3 | 1 | 626 | 4 |

**Port Call 15:** 207 SKUs to be ordered for vessel in the Netherlands


**Figure B.21.** Realized distribution for Port Call 15

**Table B.21.** Realized supply and delivery decisions for Port Call 15

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S102 | The Netherlands | 3 | 69 | 8.804 | 462 |
| S13 | The Netherlands | 3 | 37 | 2.631 | 66 |
| S131 | The Netherlands | 3 | 19 | 2.343 | 112 |
| S144 | The Netherlands | 3 | 12 | 1.427 | 197 |
| S146 | The Netherlands | 3 | 41 | 15.148 | 257 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 7 | 3.367 | 42 |
| S70 | The Netherlands | 3 | 21 | 2.552 | 709 |

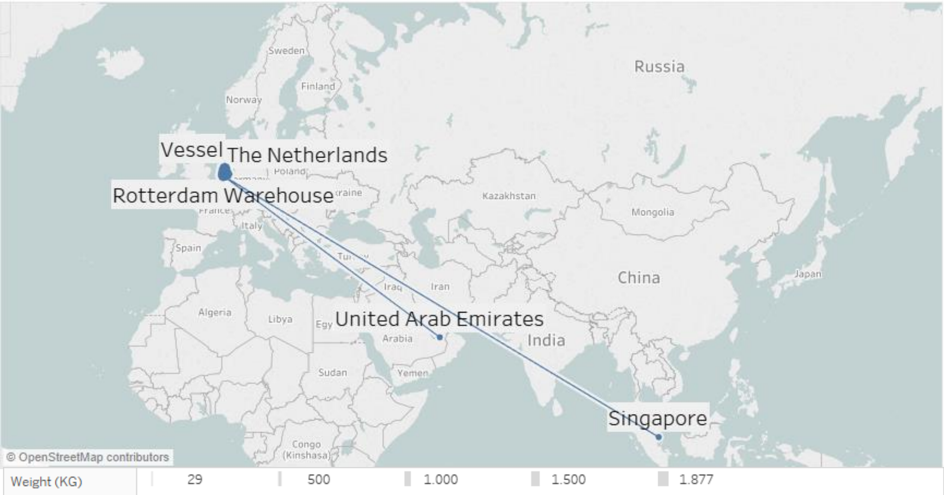



**Figure B.22.** Optimal distribution for Port Call 15

**Table B.22.** Optimal supply and delivery decisions for Port Call 15

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S147 | Singapore | 3 | 3 | 883 | 4 |
| S4 | Singapore | 3 | 4 | 116 | 5 |
| S96 | Singapore | 3 | 9 | 2.058 | 37 |
| S102 | The Netherlands | 3 | 62 | 6.483 | 471 |
| S13 | The Netherlands | 3 | 31 | 1.530 | 37 |
| S131 | The Netherlands | 3 | 14 | 2.259 | 88 |
| S144 | The Netherlands | 3 | 12 | 1.397 | 202 |
| S146 | The Netherlands | 3 | 35 | 12.219 | 243 |
| S183 | The Netherlands | 3 | 3 | 878 | 17 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 6 | 3.170 | 41 |
| S70 | The Netherlands | 3 | 17 | 1.205 | 671 |
| S198 | United Arab Emirates | 3 | 10 | 198 | 29 |

For Port Call 2, we refer to Figure B.1 and B.2 together with Table B.1 and B.2. The total costs of these configurations are displayed in Table B.23. Comparing the realized and the optimal distributions we observe that:

- Savings are relatively small in comparison to some other port calls, this is expected as the total SKUs to be purchased and the total spend is also small.
- Mostly the same suppliers are used for supplying the same items. Still, some savings from product costs are achieved by re-allocating the purchases to cheaper suppliers. In the optimal case, two SKUs previously supplied by S198 are supplied by S30, a supplier in the Netherlands and one SKU from S58, another supplier in the United Arab Emirates. The first re-allocation incurs extra transportation costs but the savings from product costs are higher.
- The local warehouse is used in both cases since the suppliers are in proximity, this consolidation prevents extra transportation and loading costs that could occur from separate deliveries.
- In the optimal case, the Rotterdam warehouse is not used, and all purchases are consolidated at the local warehouse, this reduces the loading costs that were incurred because of the delivery made from Rotterdam.

**Table B.23.** Comparison of total costs of the realized and the optimal case for Port Call 2

| | **Port Call 2** | | |
|---|---|---|---|
| | **41 items, United Arab Emirates** | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 2.653 | 2.449 | 204 |
| **Ordering cost:** | 1.000 | 1.000 | - |
| **Transportation cost:** | 348 | 455 | - 107 |
| **Fixed facility cost:** | 230 | 70 | 160 |
| **Handling cost:** | 51 | 51 | - |
| **Loading the vessel:** | 600 | 300 | 300 |
| **Total cost:** | **4.881** | **4.324** | **557** |

For Port Call 3, we refer to Figure B.3 and B.4 together with Table B.3 and B.4. The total costs of these configurations are displayed in Table B.24. Comparing the realized and the optimal distributions we observe that:

- The same suppliers are used for supplying the same items.
- Savings occur from the transportation, fixed facility costs and loading costs. These savings are the result of the decision of not utilizing the Singapore Warehouse as extra costs for utilizing the facility and bringing deliveries to the vessel are avoided. Consolidating the goods prevents additional loading costs arising from separate deliveries. The overall transportation cost is smaller when the total load is delivered from the local warehouse due to economies of scale.

**Table B.24.** Comparison of total costs of the realized and the optimal case for Port Call 3

| | Port Call 3 | | |
|---|---|---|---|
| | 120 items, United Arab Emirates | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 6.871 | 6.871 | - |
| **Ordering cost:** | 800 | 800 | - |
| **Transportation cost:** | 1.323 | 848 | 475 |
| **Fixed facility cost:** | 230 | 70 | 160 |
| **Handling cost:** | 128 | 128 | - |
| **Loading the vessel:** | 600 | 300 | 300 |
| **Total cost:** | **9.951** | **9.016** | **935** |

For Port Call 5, we refer to Figure B.5 and B.6 together with Table B.5 and B.6. The total costs of these configurations are displayed in Table B.25. Comparing the realized and the optimal distributions we observe that:

- Savings occur from all the cost components except for the ordering and handling costs.
- Ordering costs increase because the number of suppliers used is higher. SKUs previously purchased from Singapore are split between suppliers in the United Arab Emirates and the Netherlands. Similarly, some orders previously purchased from Kenya are now purchased from the Netherlands. These splits result in cheaper product coasts overall.
- In the optimal case, only the Rotterdam Warehouse is utilized. It is cheaper to make deliveries to this warehouse as a lot of the suppliers are already in the Netherlands and apply DDP. The Singapore warehouse is not utilized as the gain from economies of scales is not large enough for handling and transport of light items. Using only one warehouse reduces fixed facility costs and having a single delivery to the vessel reduces the loading costs.
- Transporting a heavy shipment results in savings from the overall transportation costs.

**Table B.25.** Comparison of total costs of the realized and the optimal case for Port Call 5

| | Port Call 5 | | |
|---|---|---|---|
| | 41 items, Kenya | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 6.856 | 4.961 | 1.895 |
| **Ordering cost:** | 1.400 | 2.000 | - 600 |
| **Transportation cost:** | 592 | 500 | 92 |
| **Fixed facility cost:** | 230 | 160 | 70 |
| **Handling cost:** | 56 | 99 | - 43 |
| **Loading the vessel:** | 900 | 300 | 600 |
| **Total cost:** | **10.034** | **8.019** | **2.015** |

For Port Call 6, we refer to Figure B.7 and B.8 together with Table B.7 and B.8. The total costs of these configurations are displayed in Table B.26. Comparing the realized and the optimal distributions we observe that:

- Savings occur from product, transportation and handling costs.
- Ordering costs increase because the number of suppliers used is higher. In the realized case, all items are purchased from suppliers in the Netherlands whereas in the optimal case,

suppliers in Egypt and Singapore are also used. Moreover, purchases are re-allocated between some of the previously used suppliers. These changes result in lower product costs.

- In the optimal case, supplier S71 delivers directly to the vessel. This is to avoid the extra handling and delivery costs incurred by the warehouse as the total weight of the items purchased is high. However, this separate delivery results in extra loading costs.

**Table B.26.** Comparison of total costs of the realized and the optimal case for Port Call 6

| | Port Call 6 | | |
|---|---|---|---|
| | 144 items, The Netherlands | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 12.666 | 10.450 | 2.217 |
| **Ordering cost:** | 1.800 | 2.200 | - 400 |
| **Transportation cost:** | 827 | 431 | 396 |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 223 | 180 | 43 |
| **Loading the vessel:** | 300 | 600 | - 300 |
| **Total cost:** | **15.887** | **13.931** | **1.956** |

For Port Call 7, we refer to Figure B.9 and B.10 together with Table B.9 and B.10. The total costs of these configurations are displayed in Table B.27. Comparing the realized and the optimal distributions we observe that:

- Savings occur from all cost components except for ordering cost.
- Ordering cost is the same in both cases as same number of suppliers are used. These are also the same suppliers. In the optimal case only one item is allocated differently (to supplier S142, instead of S131) resulting in a small saving in product costs.
- In the optimal case, only the Rotterdam Warehouse is utilized whereas the agent was used previously. Consolidating all goods supplied from the Netherlands yields to savings in transportation. Also, the transportation costs incurred by the agent are avoided. Consolidating orders at one warehouse also reduces handling and loading costs.

**Table B.27.** Comparison of total costs of the realized and the optimal case for Port Call 7

| | Port Call 7 | | |
|---|---|---|---|
| | 51 items, United Kingdom | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 12.020 | 12.014 | 6 |
| **Ordering cost:** | 1.400 | 1.400 | - |
| **Transportation cost:** | 1.340 | 608 | 732 |
| **Fixed facility cost:** | 140 | 70 | 70 |
| **Handling cost:** | 133 | 123 | 10 |
| **Loading the vessel:** | 600 | 300 | 300 |
| **Total cost:** | **15.633** | **14.515** | **1.118** |

For Port Call 8, we refer to Figure B.11 and B.12 together with Table B.11 and B.12. The total costs of these configurations are displayed in Table B.28. Comparing the realized and the optimal distributions we observe that:

- Savings occur from all cost components except for ordering and loading costs.

- Ordering cost is the same in both cases as same number of suppliers are used. These are also the same suppliers. In the optimal case only one item is allocated differently (to supplier S102, instead of S162) resulting in a small saving in product costs.
- In the optimal case, only the Rotterdam Warehouse is utilized whereas the agent was used previously. Consolidating all goods supplied from the Netherlands yields to savings in transportation. Also, the transportation costs incurred by the agent are avoided.
- In the optimal case, supplier S29 delivers directly to the vessel. This is to avoid the extra handling and delivery costs incurred by the warehouse as the total weight of the items purchased is high.
- Decisions to have one separate delivery to the vessel and not using the agent balances each other in terms of the loading costs.

**Table B.28.** Comparison of total costs of the realized and the optimal case for Port Call 8

| | **Port Call 8** | | |
|---|---|---|---|
| | **42 items, United Kingdom** | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 15.475 | 15.411 | 63 |
| **Ordering cost:** | 1.800 | 1.800 | - |
| **Transportation cost:** | 2.080 | 1.807 | 274 |
| **Fixed facility cost:** | 140 | 70 | 70 |
| **Handling cost:** | 216 | 155 | 62 |
| **Loading the vessel:** | 600 | 600 | - |
| **Total cost:** | **20.311** | **19.843** | **469** |

For Port Call 10, we refer to Figure B.13 together with Table B.13. The realized and optimal configurations turn out to be the same. The total costs of this configuration is displayed in Table B.29. We observe that purchasing from suppliers close to the port region and consolidating before delivery to vessel turns out to be optimal for this port call.

**Table B.29.** Comparison of total costs of the realized and the optimal case for Port Call 10

| | **Port Call 10** | | |
|---|---|---|---|
| | **33 items, United Kingdom** | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 2.203 | 2.203 | - |
| **Ordering cost:** | 800 | 800 | - |
| **Transportation cost:** | 295 | 295 | - |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 39 | 39 | - |
| **Loading the vessel:** | 300 | 300 | - |
| **Total cost:** | **3.707** | **3.707** | **-** |

For Port Call 11, we refer to Figure B.14 and B.15 together with Table B.14 and B.15. The total costs of these configurations are displayed in Table B.30. Comparing the realized and the optimal distributions we observe that:

- Savings occur from product, facility and loading costs.

- Ordering costs increase because the number of suppliers used is higher, now S139 and S45 are used and S31 is not. In the realized case, all items are purchased from suppliers in Europe whereas in the optimal case, suppliers in Singapore are also used. Moreover, purchases are re-allocated between some of the previously used suppliers. These changes result in lower product costs.
- Using suppliers located far from the port for small weights results in extra transportation costs.
- In the optimal case, only the Rotterdam Warehouse is utilized whereas the agent was used previously. Decision on not using the agent leads to savings from loading costs and the fixed facility costs.
- However, in the optimal case, we can infer that the change in the sizes (weights) of shipments received from the suppliers leads to a slight increase in handling costs as the costs are applied based on shipment size.

**Table B.30.** Comparison of total costs of the realized and the optimal case for Port Call 11

| | **Port Call 11** | | |
|---|---|---|---|
| | **61 items, United Kingdom** | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 6.865 | 6.366 | 499 |
| **Ordering cost:** | 1.400 | 1.600 | - 200 |
| **Transportation cost:** | 750 | 851 | - 101 |
| **Fixed facility cost:** | 140 | 70 | 70 |
| **Handling cost:** | 132 | 144 | - 11 |
| **Loading the vessel:** | 600 | 300 | 300 |
| **Total cost:** | **9.888** | **9.331** | **556** |

For Port Call 12, we refer to Figure B.16 together with Table B.16. The realized and optimal configurations turn out to be the same. The total costs of this configuration is displayed in Table B.31. We observe that purchasing from a supplier close to the port region and consolidating before delivery to vessel is optimal for this port call. Since this is a small order both in terms of the number of SKUs required and the total weight, only one supplier is used, and the items are delivered directly to the vessel to avoid extra costs of transportation or facility use.

**Table B.31.** Comparison of total costs of the realized and the optimal case for Port Call 12

| | **Port Call 12** | | |
|---|---|---|---|
| | **44, Malaysia** | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 3.007 | 3.007 | - |
| **Ordering cost:** | 200 | 200 | - |
| **Transportation cost:** | 287 | 287 | - |
| **Fixed facility cost:** | - | - | - |
| **Handling cost:** | - | - | - |
| **Loading the vessel:** | 300 | 300 | - |
| **Total cost:** | **3.795** | **3.795** | **-** |

For Port Call 13, we refer to Figure B.17 and B.18 together with Table B.17 and B.18. The total costs of these configurations are displayed in Table B.32. Comparing the realized and the optimal distributions we observe that:

- Savings occur from product and loading costs.
- Ordering costs increase because the number of suppliers used is higher, additionally S124 is used resulting in a 200€ increase. In the realized case, all items are purchased from suppliers in the Netherlands whereas in the optimal case, a supplier in Italy is also used to supply some items instead of S35.
- Using suppliers located far from the port for small weights results in extra transportation costs.
- In both cases the Rotterdam Warehouse is utilized for consolidation. However, in the optimal case, we can infer that the change in the sizes (weights) of shipments received from the suppliers leads to a slight increase in handling costs as the costs are applied based on the shipment size.
- Decision on not having a direct delivery to the vessel leads to savings from loading costs.

**Table B.32.** Comparison of total costs of the realized and the optimal case for Port Call 13

| | Port Call 13 | | |
|---|---|---|---|
| | 57 items, The Netherlands | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 20.527 | 20.064 | 463 |
| **Ordering cost:** | 1.200 | 1.400 | - 200 |
| **Transportation cost:** | 283 | 510 | -227 |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 93 | 127 | - 34 |
| **Loading the vessel:** | 900 | 300 | 600 |
| **Total cost:** | **23.073** | **22.471** | **602** |

For Port Call 14, we refer to Figure B.19 and B.20 together with Table B.19 and B.20. The total costs of these configurations are displayed in Table B.33. Comparing the realized and the optimal distributions we observe that:

- Savings occur from product costs.
- Ordering costs increase because the number of suppliers used is higher, additionally S54 is used resulting in a 200€ increase. In both cases all suppliers used are in the Netherlands. Moreover, purchases are re-allocated between some of the previously used suppliers. These changes result in lower product costs and does not lead to an increase in transportation costs.
- In both cases the Rotterdam Warehouse is utilized for consolidation. However, in the optimal case, we can infer that the change in the sizes (weights) of shipments received from the suppliers leads to a slight increase in handling costs as the costs are applied based on the shipment size.

**Table B.33.** Comparison of total costs of the realized and the optimal case for Port Call 14

| | Port Call 14 | | |
|---|---|---|---|
| | 46 items, Germany | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 9.686 | 8.541 | 1.145 |
| **Ordering cost:** | 1.000 | 1.200 | - 200 |
| **Transportation cost:** | 267 | 267 | - |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 73 | 76 | - 3 |
| **Loading the vessel:** | 300 | 300 | - |
| **Total cost:** | **11.396** | **10.453** | **943** |

For Port Call 15, we refer to Figure B.21 and B.22 together with Table B.21 and B.22. The total costs of these configurations are displayed in Table B.34. Comparing the realized and the optimal distributions we observe that:

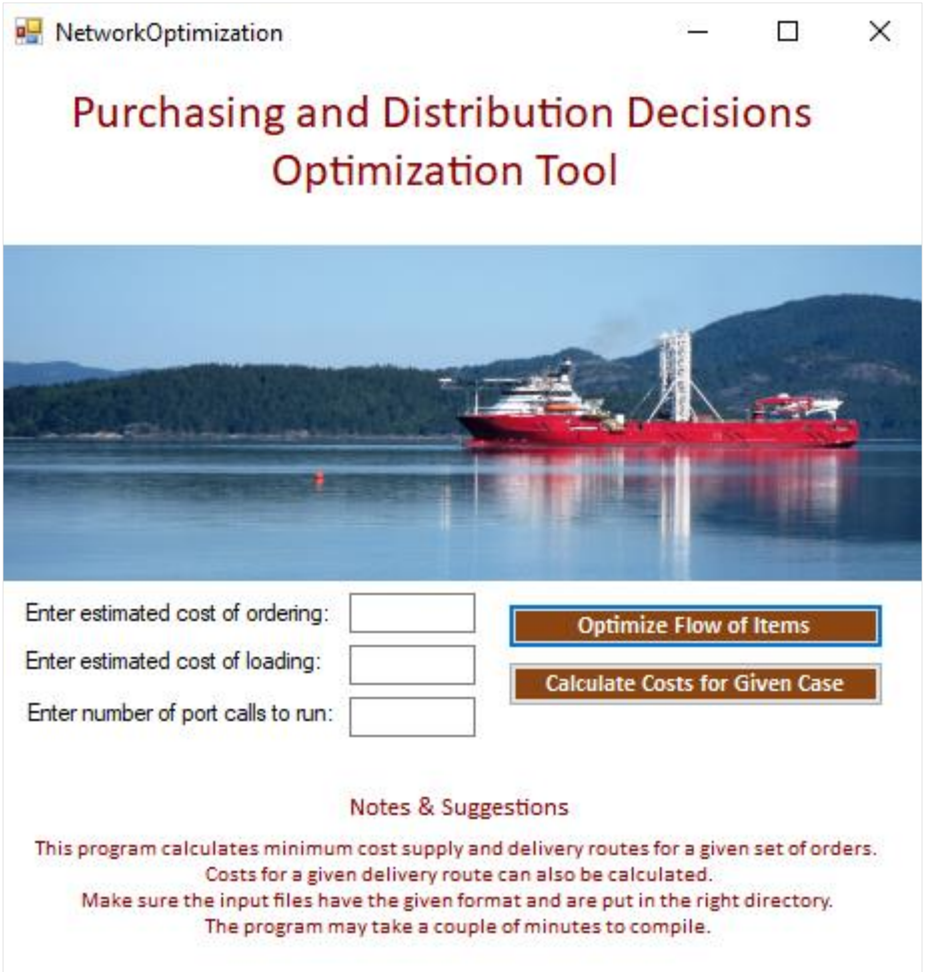
- Savings occur from product costs.
- Ordering costs increase because the number of suppliers used is higher, additionally S147, S4, S96, S183 and S198 are used resulting in a 1.000€ increase. In the realized case, all items are purchased from suppliers in the Netherlands whereas in the optimal case, suppliers in Singapore and the United Arab Emirates are used. These changes result in large savings in product costs.
- Using suppliers located far from the port for small weights results in extra transportation costs.
- In both cases the Rotterdam Warehouse is utilized for consolidation. However, in the optimal case, we can infer that the change in the sizes (weights) of shipments received from the suppliers leads to a slight increase in handling costs as the costs are applied based on the shipment size.

**Table B.34.** Comparison of total costs of the realized and the optimal case for Port Call 15

| | Port Call 15 | | |
|---|---|---|---|
| | 207 items, The Netherlands | | |
| **Description** | **Realized** | **Optimal** | **Saving** |
| **Product cost:** | 37.218 | 33.341 | 3.876 |
| **Ordering cost:** | 1.600 | 2.600 | - 1.000 |
| **Transportation cost:** | 635 | 1.081 | - 446 |
| **Fixed facility cost:** | 70 | 70 | - |
| **Handling cost:** | 261 | 320 | - 59 |
| **Loading the vessel:** | 300 | 300 | - |
| **Total cost:** | **40.083** | **37.712** | **2.371** |

**Appendix C. Purchasing and Distribution Decisions Optimization Tool User Guide**

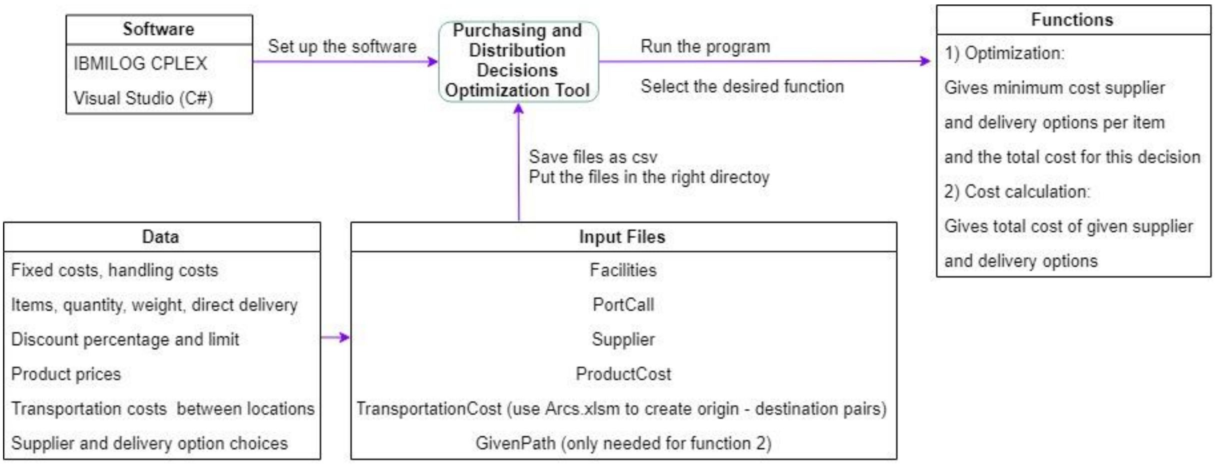
This tool provides the minimum cost supply and distribution decisions for a given list of items. For each port call, a list of items to be purchased can be given as input. The tool has two functions: (i) optimizing the supply and distribution decisions, (ii) calculating the costs of given supply and distribution decisions. It is possible to run the program for a desired number of port calls. Below the steps for setting up the program and the required file formats are described. Please refer to the Thesis document for detailed explanation on considered costs and their applications.



# Table of Contents

## Introduction

An overview of the steps needed to utilize the tool is given below. In the next sections, the required software and the input format are explained in detail. As explained above, the program can be run to obtain the minimum cost supply and distribution decisions. The total costs of a given supply and distribution option can also be calculated.




## 1. Required Programs

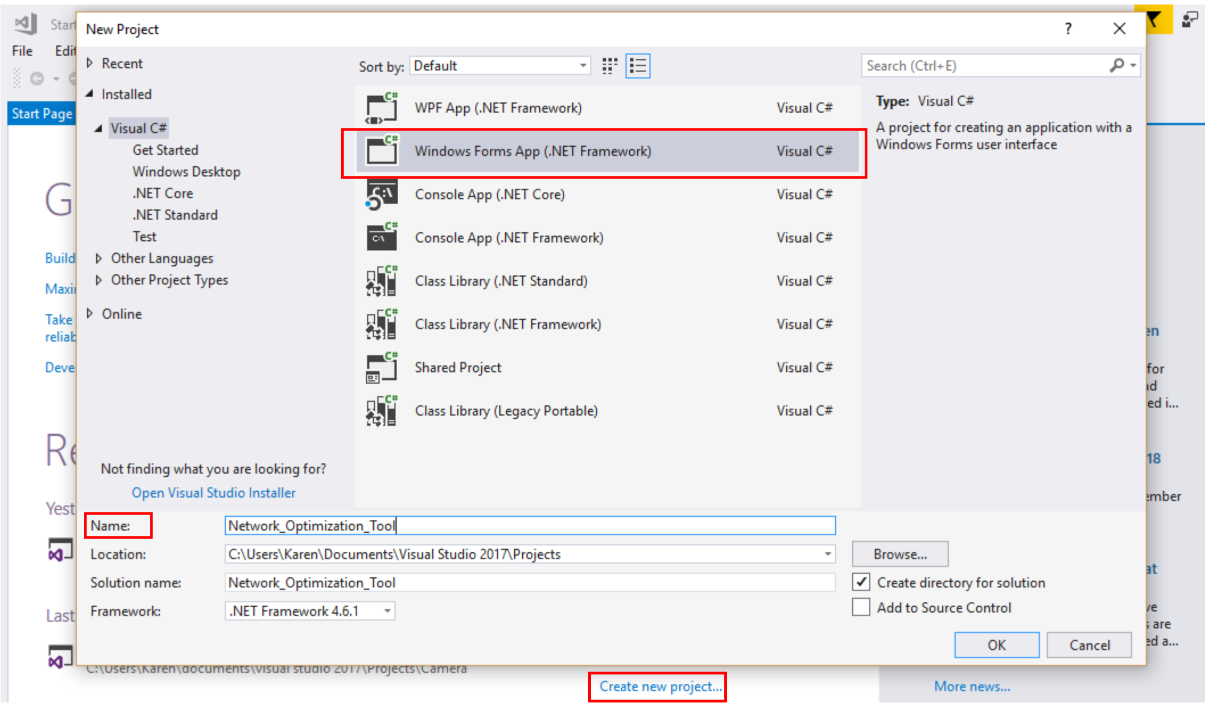
The project is prepared using Visual Studio Ultimate 2017, with the built in C# programming language, and IBM ILOG CPLEX Optimization Studio V12.6.1.0. Visual Studio is available online for public use, CPLEX is free only for academic use. Different versions or any updates may require certain changes in the code. Also, use of an integrated development environment other than Visual Studio may cause a change in the processes that are explained in the following sections.

## 2. Setting up the Software

Below processes explain how to add all the necessary files to a Visual Studio project and set the application ready to run.

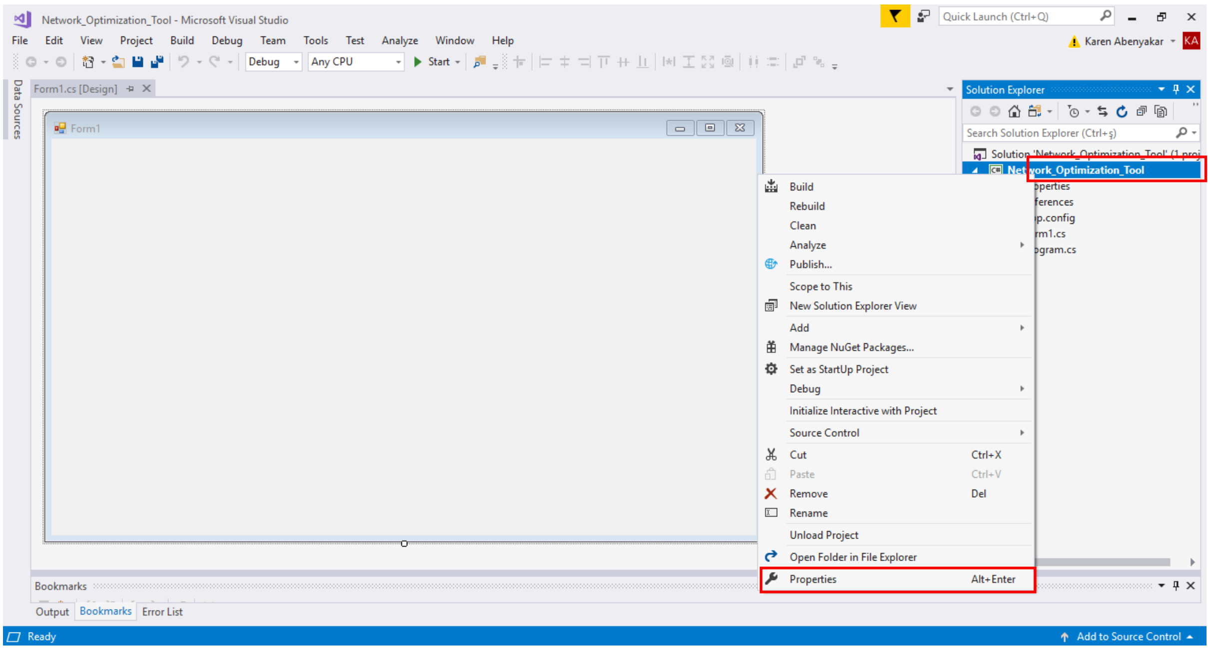
### 2.1. Opening a New Project

1. Create a new project either using the options under File section on the upper bar or using the link on the main page.
2. Enter a name for the project and make sure Form Application is selected. This is required to use the graphical user interface.

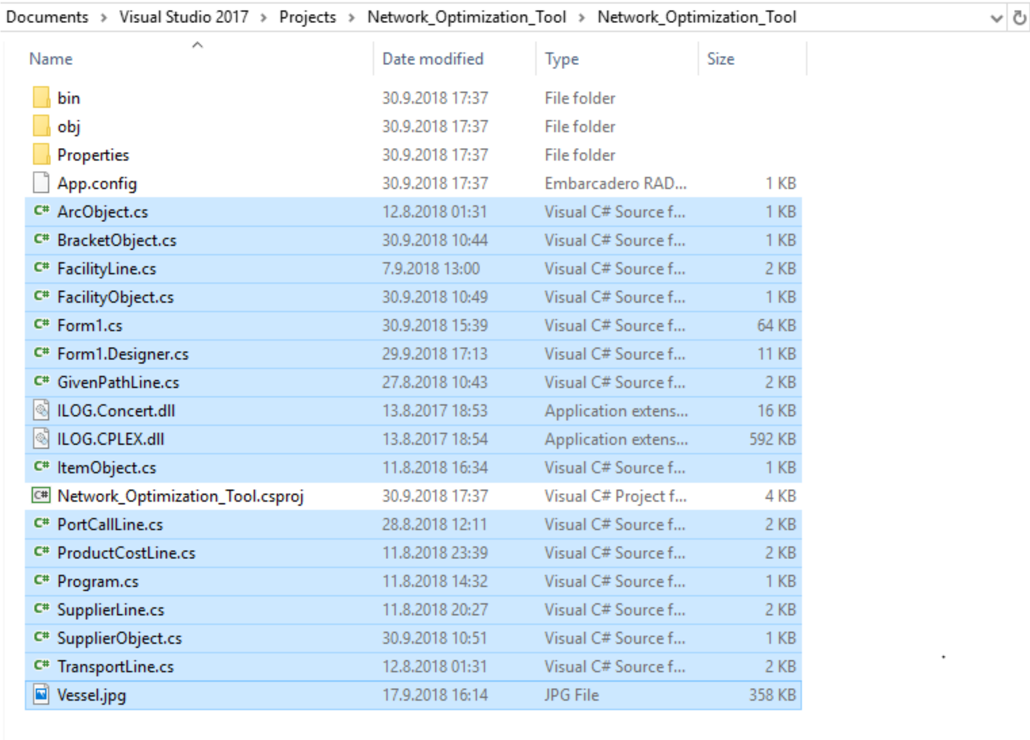



## 2.2. Adding the .cs Files

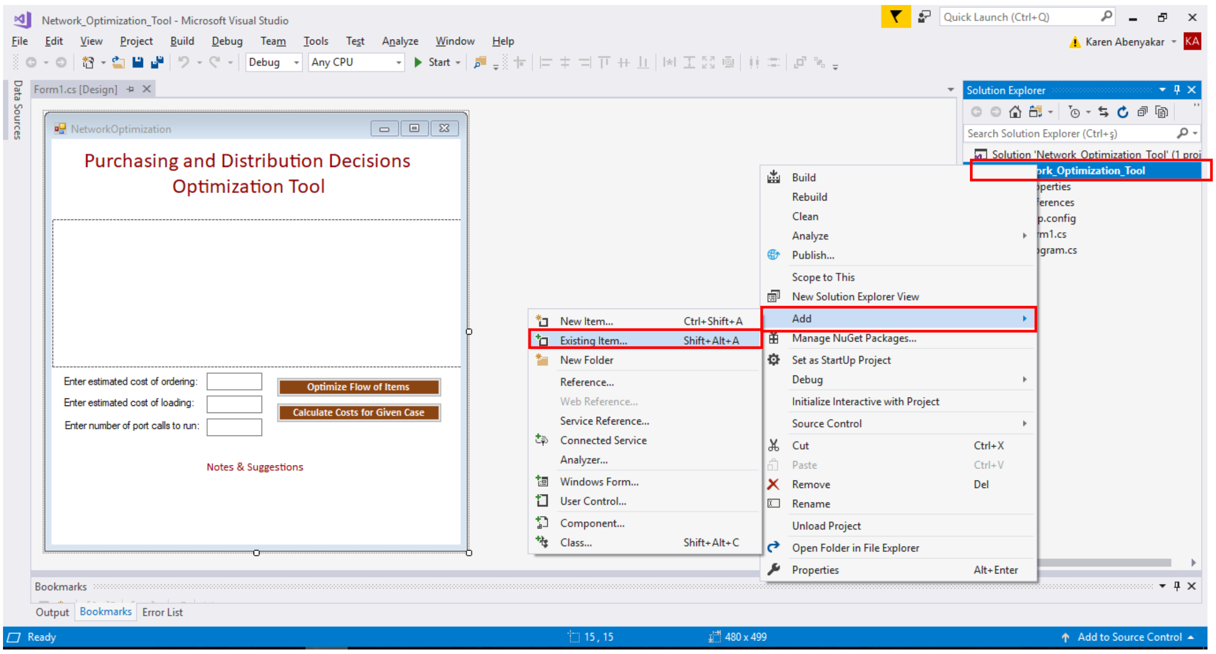
Open the project folder either by directly going to the file directory or right clicking on the project name under Solution Explorer window and opening the file.



1. Delete the ".cs" files (Form1.cs, Form1.Designer.cs, Program.cs). This is required as new files will be added in the following section and this avoids any confusion about the file names that may occur.
2. Copy the files (.cs, .dll, .jpeg) provided within the tool folder to the project folder.

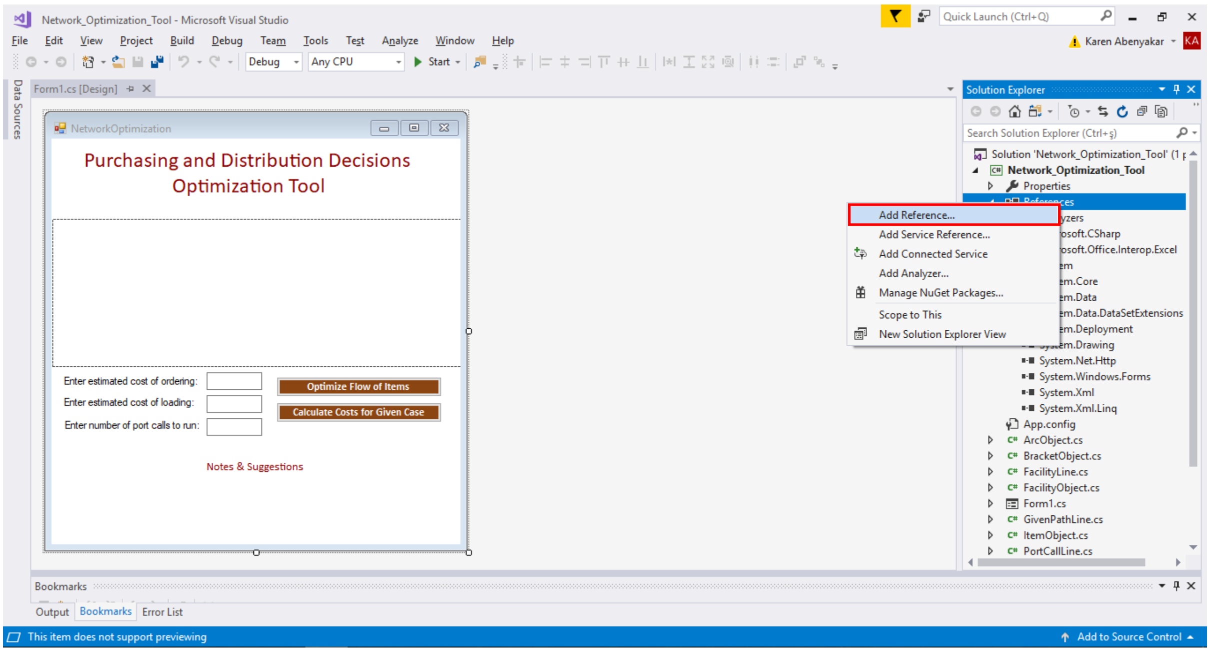



3. Click "Yes to All" if Visual Studio gives the message "This file has been modified outside of the source editor. Do you want to reload it?". Visual Studio may give errors and may not display the interface right away, in the next sections these errors will be cleared.
4. Right clicking on the project name under the Solution Explorer window, add all the .cs files copied into the project folder to the project.



## 2.3 Adding the .dll Files

Click on “References” under the project name in Solution Explorer window, and add the .dll files required for Cplex integration as references. Click on “Browse” and add the .dll files in the project file.



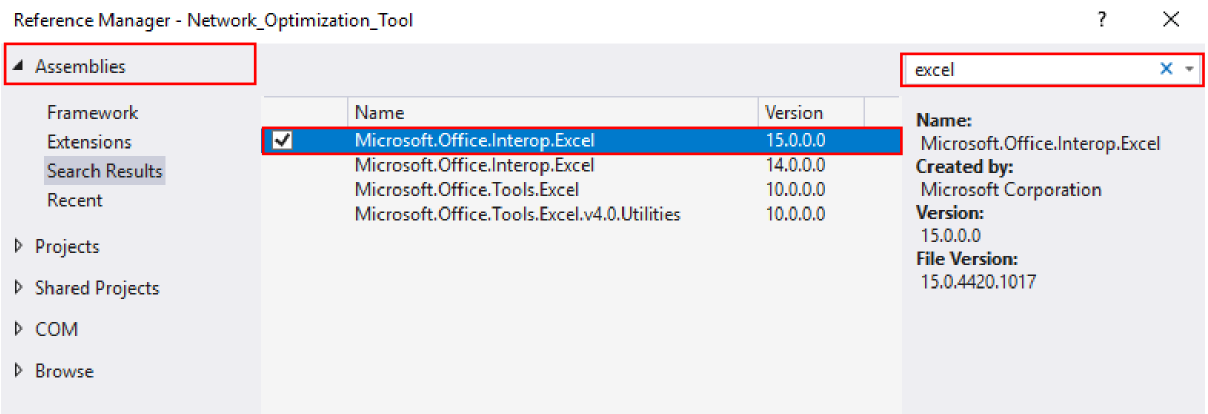

The dll files provided are only compatible with IBM ILOG CPLEX Optimization Studio V12.6.1. For any version .dll files can be obtained from the program file of IBM ILOG CPLEX. File directory examples for different versions are given below:

C:\Program Files\IBM\ILOG\CPLEX_Studio1261\cplex\bin\x64_win64

C:\documents\IBM\ILOG\CPLEX_Studio1262\cplex\examples\x64_windows_vs2013\stat_mda\csbin

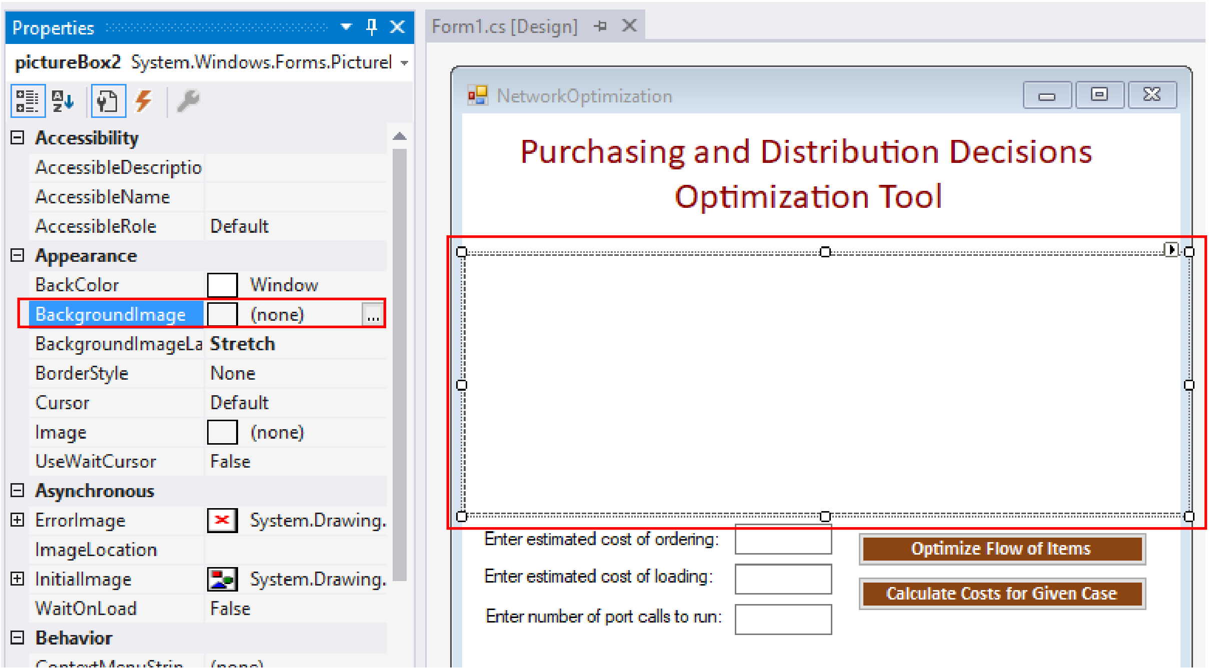
## 2.4. Adding Excel Reference

Click on “References” right clicking the project name in Solution Explorer window, and add the Excel reference under Assemblies, use the search bar if necessary.



## 2.5. Adding the Image

Click on the pictureBox. If the "Properties" window is not visible, right click and select "Properties". Add the image in the tool folder as BackgroundImage.

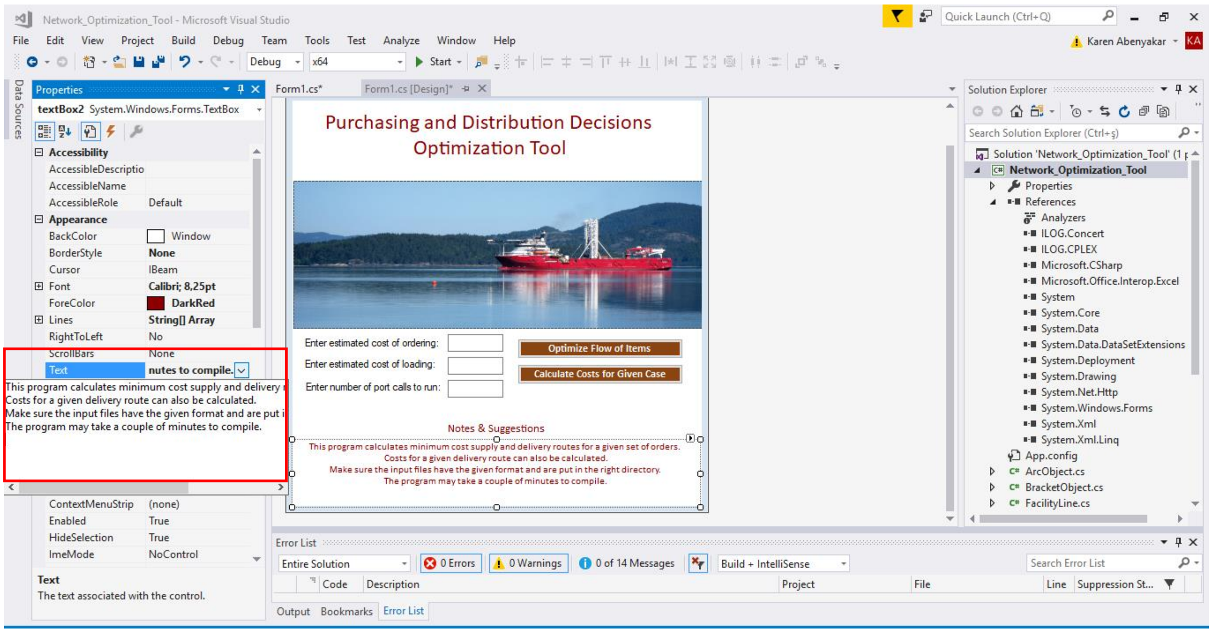



Click on "Import" in the window that opens and select the image file in the project file. If the picture does not cover the whole area or is not the right size, set BackgroundImage Layout property to "Stretch".

## 2.6. Adding Text

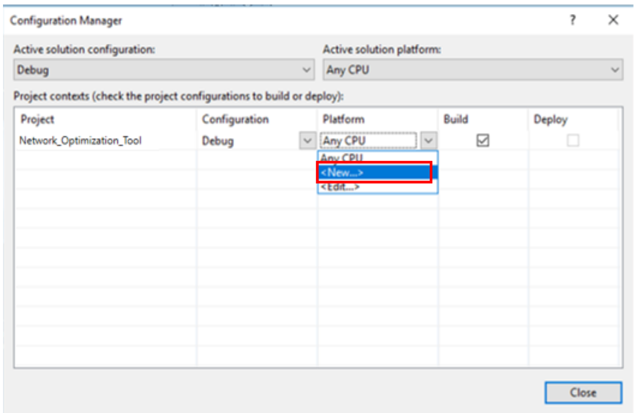
Multiple lines may not appear on textboxes. If the textbox under the "Notes & Suggestions" is empty, below text can be added by copying the given text under the text property section:

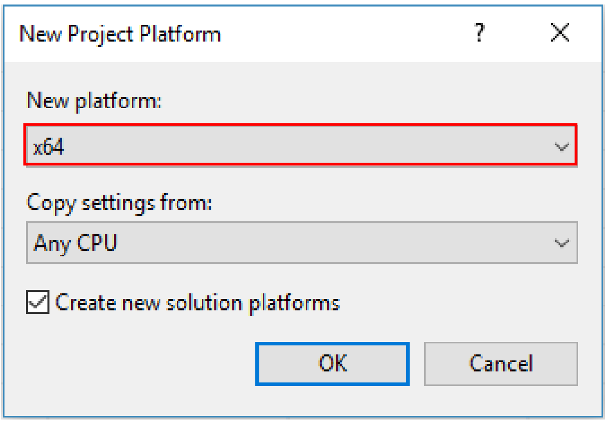
"This program calculates minimum cost supply and delivery routes for a given set of orders.
Costs for a given delivery route can also be calculated.
Make sure the input files have the given format and are put in the right directory.
The program may take a couple of minutes to compile."




## 2.7. Changing the Platform

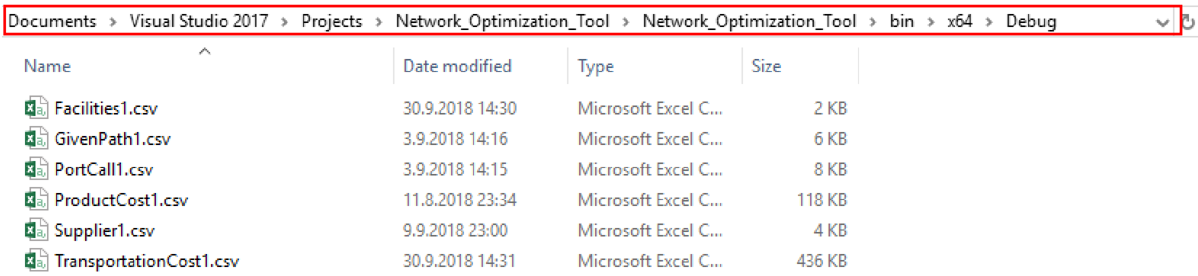
From the above bar select “Build” and then “Configuration Manager”. The target platform should be x64 for Cplex Engine to work. In the window click “New” to change the platform and set new platform to x64.



## 2.8. Adding the Excel (.csv) File

Once the platform is changed, the Debug file for the platform is created. Since Excel files are read from the Debug File, the excel files containing input information can be added to the project file now. Add in the Debug file, the files of the port calls to be run.




Excel (.xlsx) files used for the Thesis are also provided to indicate the data format. Cell values in the provided Excel files can be changed but the title row and the general format of the file should be maintained. Then, by saving the file as csv (Comma delimited) in Excel and adding the .csv file to the directory as specified above the new data can be processed by the program. In the next seciton file formats are explained.

## 3. Format of the Input Files

The input data is read from csv files as use of csv files results in faster data preparation. The set of csv files should be prepared separately per port call. The format of the Excel files should be kept the same for the program to work accurately.

Reducing the input would result in faster run time. For example, using only required facilities and applicable suppliers as input reduces the problem size.

Five csv files are used to read input data for the optimization model:

1. Facilities

   This file includes information on the available facilities in the network. The list of facilities used in the model are defined using this file.
   A dummy interval with lower and upper bounds both equal to zero is needed to ensure that if the facility is not used, zero costs will be incurred.

| Facility | Region | Fixed Cost | Fixed Cost Airfreight | Lower Bound (kg) | Upper Bound (kg) | Total Cost |
|---|---|---|---|---|---|---|
| Warehouse1 | Europe | 70 | 89,5 | 0 | 0 | 0 |
| Warehouse1 | Europe | 70 | 89,5 | 0,01 | 5 | 2,5 |
| Warehouse1 | Europe | 70 | 89,5 | 5,01 | 25 | 11,5 |
| Warehouse1 | Europe | 70 | 89,5 | 25,01 | 100 | 22,5 |
| Warehouse1 | Europe | 70 | 89,5 | 100,01 | 500 | 34 |
| Warehouse1 | Europe | 70 | 89,5 | 500,01 | 1000 | 57 |
| Warehouse1 | Europe | 70 | 89,5 | 1000,01 | 10000000 | 68 |

Facilities can have different lower bound, upper bound and cost values. However, all facilities must have the **same** number of weight intervals. If a facility has fewer number of intervals compared to others, dummy intervals with zero bounds and zero cost can be used. Moreover, it should be ensured that the difference between upper and lower bounds of consecutive intervals are small enough for all weights to have a corresponding cost.

2. PortCall

This file includes information on the demand for a port call. The required items are listed together with required quantities. Item weights and whether the items should be delivered from the supplier to the vessel directly are also entered. Requirement for direct delivery is indicated by entering "TRUE" in the related column. Similarly, if there is no such requirement it is indicated with "FALSE".

It should be noted that Item IDs should be **unique**; duplicate entries cause the program not to run properly.

| Row Number | Region | Item ID | Item Weight | Order Quantity | Direct Delivery Needed |
|---|---|---|---|---|---|
| 1 | Middle East | Item1 | 11,300 | 1 | FALSE |
| 2 | Middle East | Item2 | 0,498 | 1 | FALSE |
| 3 | Middle East | Item3 | 0,498 | 1 | FALSE |
| 4 | Middle East | Item4 | 0,498 | 1 | FALSE |
| 5 | Middle East | Item5 | 0,850 | 1 | FALSE |

3. Supplier

The list of suppliers used in the model are defined using this file. If the supplier applies a threshold discount policy, the related parameters should be entered.

| Supplier | Percentage Discount | Threshold |
|---|---|---|
| Supplier1 | 0,05 | 6000 |
| Supplier2 | 0,05 | 6000 |
| Supplier3 | 0,05 | 6000 |
| Supplier4 | 0,05 | 6000 |
| Supplier5 | 0,05 | 6000 |

If threshold discounts are not applicable the discount percentage can be set to zero and/or the threshold value can be set to a very large number to ensure the program will not consider applying discounts.

4. ProductCost

This file includes the product cost per item- supplier pairs.

This file can contain additional suppliers compared to the Supplier file or additional items compared to the PortCall file. The program only selects the ones in those files.

| Item ID | Vendor ID | Unit Price EUR |
|---|---|---|
| Item1 | Supplier1 | 197,136 |
| Item2 | Supplier2 | 158,654 |
| Item2 | Supplier3 | 148,090 |
| Item3 | Supplier4 | 123,320 |
| Item4 | Supplier5 | 1,189 |
| Item4 | Supplier6 | 2,600 |

5. TransportationCost

   The links (arcs) between locations are defined reading this file. Therefore, all the connections between the facilities (warehouses, agents), suppliers and the vessel should be provided here.

   It should be noted that the vessel should be entered as “**Vessel**” for the program to recognize the vessel.

| Key | From | To | Lower Bound (kg) | Upper Bound (kg) | Cost per kg |
|---|---|---|---|---|---|
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 0 | 25 | 6,403358 |
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 25,01 | 50 | 6,204667 |
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 50,01 | 100 | 5,657365 |
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 100,01 | 500 | 2,770837 |
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 500,01 | 1000 | 2,414097 |
| Supplier1 - Warehouse1 | Supplier1 | Warehouse1 | 1000,01 | 100000 | 2,5 |

   Arcs can have different lower bound, upper bound and cost values. However, all arcs must have the **same** number of weight intervals. If an arc has fewer number of intervals compared to others, dummy intervals with zero bounds and zero cost can be used. Moreover, it should be ensured that the difference between upper and lower bounds of consecutive intervals are small enough for all weights to have a corresponding cost.

To create the combinations of all origin – destination pairs, the Excel file Arcs.xlsm can be used. This file creates all links as defined in the thesis document:

- Supplier - vessel
- Supplier – agent –vessel
- Supplier – central warehouse – vessel
- Supplier – central warehouse - agent –vessel
- Supplier – local warehouse – vessel
- Supplier – local warehouse - agent –vessel

On the “Input Data” sheet, the cells under the title row should be filled with appropriate data for the port call. When the “Write Arcs” button is clicked, the links are created on the “Arcs” sheet.

| Suppliers | Supplier Country | Central Warehouses | CW Country | Local Warehouses | LW Country | Agents | Agent Country | Vessels | Port Country |
|---|---|---|---|---|---|---|---|---|---|
| Supplier1 | Brazil | Warehouse1 | The Netherlands | Local1 | United Arab Emirates | Agent1 | United Arab Emirates | Vessel | United Arab Emirates |
| Supplier2 | Brazil | Warehouse2 | Singapore | | | | | | |
| Supplier3 | Thailand | | | | | | | | |
| Supplier4 | Singapore | | | | | | | | |
| Supplier5 | Brazil | | | | | | | | |

Write Arcs

This worksheet enables having non or multiple central, local warehouses and agents. Similarly, different number of brackets can also be used. It is assumed that there are one or more suppliers and a single vessel. If certain links are not preferred for a warehouse or a supplier, resulting arcs can be manually deleted. All cost brackets corresponding to those arcs should be deleted.

Below the resulting arcs are displayed. The “Distance” and “Unit Cost” columns are filled using lookup formulas. A similar formulation can be used if the costs are read from different cost tables. The formulas are provided in the Excel file.

| From | From Country | To | To Country | Key | From Type | Distance | Bracket | Lower Bou | Upper Bou | Unit Cost |
|---|---|---|---|---|---|---|---|---|---|---|
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 0 - 25 | 0 | 25 | |
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 25 - 50 | 25 | 50 | |
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 50 - 100 | 50 | 100 | |
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 100 - 500 | 100 | 500 | |
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 500 - 1000 | 500 | 1000 | |
| Supplier 1 | Brazil | Warehouse1 | The Netherlands | Brazil - The Netherlands | Supplier | | 1000+ | 1000 | 100000 | |

Here, the transportation costs are written with respect to distance and weight brackets. The transportation costs are read from a single table, as partly displayed below. The same transport fee structure is used for all arcs. If the costs applied by the suppliers or the facilities are known, the costs should be re-written accordingly. For example, for the thesis, the transportation costs are set to zero for suppliers delivering in their country.

| Distance\ Weight | 0 - 25 | 25 - 50 | 50 - 100 | 100 - 500 | 500 - 1000 | 1000+ |
|---|---|---|---|---|---|---|
| LB | 0 | 25 | 50 | 100 | 500 | 1000 |
| UB | 25 | 50 | 100 | 500 | 1000 | 100000 |
| 0 - 500 | 4,80 | 4,60 | 4,21 | 1,40 | 0,98 | 0,34 |
| 500 - 1000 | 4,88 | 4,69 | 4,29 | 1,47 | 1,05 | 0,45 |
| 1000 - 1500 | 4,97 | 4,77 | 4,36 | 1,54 | 1,13 | 0,57 |
| 1500 - 2000 | 5,05 | 4,85 | 4,44 | 1,62 | 1,21 | 0,68 |

“Input Data” and “Arcs” sheets should be cleared before each use. The cases used for the thesis are provided within the file. Please refer to these as an example.

For using the cost calculator function an additional csv file with entries on supplier and distribution options used is required:

6. GivenPath

   This file is used to define a case with given suppliers and delivery options. The representation used for this file is also used when displaying the optimization output. The program output is described in the next sections. Facilities displayed on the columns must be in the same order as the facilities in the Facilities file.

| ItemID | Supplier | Warehouse1 | Warehouse2 | Local | Agent |
|---|---|---|---|---|---|
| Item1 | Supplier1 | 0 | 0 | 1 | 0 |
| Item2 | Supplier2 | 0 | 0 | 1 | 0 |
| Item3 | Supplier2 | 0 | 0 | 1 | 0 |
| Item4 | Supplier3 | 0 | 0 | 1 | 0 |
| Item5 | Supplier3 | 0 | 0 | 1 | 0 |

The distribution decisions are represented with binary variables. “1” indicates that a facility is visited and “0” indicates otherwise.

These files can be modified easily to update the model. Additional facilities or suppliers can be added following the given format. It should be ensured that the links corresponding to the new facilities or suppliers are also defined. That is, the TransportationCost file should be modified according to the changes in other files.

The naming and the format of the texts should be consistent for all the files. For example, the supplier IDs in Supplier and TransportationCost files should match or the Item IDs in PortCall and ProductCost files should match. It should be noted that the program is **case sensitive.**

### 3.1. The Naming Format

The program enables running multiple port calls sequentially. This holds for both the optimization and the calculator functions.

To ensure this the program refers to the numbers in the file names. A number is added to the above file names. For example, if only one program will be run the naming should be **Facilities1, PortCall1, Supplier1, ProductCost1, TransportationCost1**. If more port calls will be run, the numbering should continue consecutively.

The files used for the experiments in the thesis can be referred to for input and naming formats.

## 4. Running the Program

The program is run choosing either “Start Debugging” or “Start Without Debugging” from the Debug section on the above toolbar.

Next, fill in the required fields and click on the desired option. The ordering cost, loading cost and number of port calls to run should be filled in by the user. As explained above, the files should be placed in the right repository and the file names should be applicable to run the given number of port calls.

When the execution is completed a message box displaying “All port calls are run.” would appear.

## 5. Output of the Program

The output of the program is displayed on an Excel spreadsheet. After the execution of each run (per port call), an Excel window with the solution pops-up.

Similar to the representation of the GivenPath file, the distribution decisions are shown with binary variables. “1” indicates that a facility should be visited and “0” otherwise. Whether multiple facilities can be visited, and the order of the facilities visited depends on the arcs defined in TransportCost file.

The cost breakdown structure of the solution is also provided. Similarly, when choosing the option to calculate the costs for a given case, the cost breakdown structure is displayed.

| ItemID | Supplier | Warehouse1 | Warehouse2 | Local | Agent | | Description | Cost |
|---|---|---|---|---|---|---|---|---|
| Item1 | Supplier1 | 1 | 0 | 0 | 0 | | procurement cost: | 29662,7 |
| Item2 | Supplier1 | 1 | 0 | 0 | 0 | | Discount amount: | 0 |
| Item3 | Supplier1 | 1 | 0 | 0 | 0 | | Ordering cost: | 2400 |
| Item4 | Supplier2 | 1 | 0 | 0 | 0 | | Transportation cost: | 26713,22 |
| Item5 | Supplier3 | 1 | 0 | 0 | 0 | | Fixed facility cost: | 319 |
| Item6 | Supplier3 | 1 | 0 | 0 | 0 | | Handling cost: | 243 |
| Item7 | Supplier3 | 1 | 0 | 0 | 0 | | Loading cost: | 1500 |
| Item8 | Supplier3 | 1 | 0 | 0 | 0 | | Total cost: | 60837,92 |
| Item9 | Supplier3 | 1 | 0 | 0 | 0 | | | |

Note the solver provides a solution with 0.01% mixed integer programming gap. When comparing the numbers instead of equality it is suggested to check if their difference is < 0.0001. For example, even if the suppliers and distribution options are the same, the total cost calculated with the optimization tool and the calculator can differ within this precision limit[4].

[4] https://www.ibm.com/support/knowledgecenter/SSSA5P_12.6.2/ilog.odms.cplex.help/refcppcplex/html/branch.html

**Appendix D.** Algorithm Run Time per Port Call

**Table D.** Number of items allocated and run time (minutes) per port calls

| Port Call | # SKUs | Run time (min) |
|---|---|---|
| 1 | 161 | 4,437 |
| 2 | 41 | 0,016 |
| 3 | 120 | 0,045 |
| 4 | 155 | 0,170 |
| 5 | 41 | 0,019 |
| 6 | 144 | 0,112 |
| 7 | 51 | 0,016 |
| 8 | 42 | 0,024 |
| 9 | 104 | 0,042 |
| 10 | 33 | 0,013 |
| 11 | 61 | 0,018 |
| 12 | 44 | 0,015 |
| 13 | 57 | 0,026 |
| 14 | 46 | 0,014 |
| 15 | 207 | 0,363 |

**Appendix E.** Sensitivity Analysis for Transport Costs

**Table E1.** Optimal supply and delivery decisions for Port Call 15 when transportation costs are increased by 10%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S147 | Singapore | 3 | 3 | 883 | 4 |
| S4 | Singapore | 3 | 4 | 116 | 5 |
| S96 | Singapore | 3 | 9 | 2.058 | 37 |
| S102 | The Netherlands | 3 | 62 | 6.483 | 471 |
| S13 | The Netherlands | 3 | 31 | 1.530 | 37 |
| S131 | The Netherlands | 3 | 14 | 2.259 | 88 |
| S144 | The Netherlands | 3 | 12 | 1.397 | 202 |
| S146 | The Netherlands | 3 | 35 | 12.219 | 243 |
| S183 | The Netherlands | 3 | 3 | 878 | 17 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 6 | 3.170 | 41 |
| S70 | The Netherlands | 1 | 17 | 1.205 | 671 |
| S198 | United Arab Emirates | 3 | 10 | 198 | 29 |

The changes occur in the delivery routes and correspond to 8,21% of the SKUs. The decisions remain the same for other SKUs.

**Table E2.** Optimal supply and delivery decisions for Port Call 15 when transportation costs are increased by 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S147 | Singapore | 3 | 3 | 883 | 4 |
| S4 | Singapore | 3 | 4 | 116 | 5 |
| S96 | Singapore | 3 | 9 | 2.058 | 37 |
| S102 | The Netherlands | 3 | 62 | 6.483 | 471 |
| S13 | The Netherlands | 3 | 31 | 1.530 | 37 |
| S131 | The Netherlands | 3 | 15 | 2.261 | 90 |
| S144 | The Netherlands | 3 | 12 | 1.397 | 202 |
| S146 | The Netherlands | 3 | 35 | 12.219 | 243 |
| S183 | The Netherlands | 3 | 3 | 878 | 17 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 6 | 3.170 | 41 |
| S70 | The Netherlands | 1 | 18 | 1.247 | 692 |
| S198 | United Arab Emirates | 3 | 8 | 155 | 7 |

Suppliers are changed for 0,97% and the delivery options for 8,7% of the SKUs. The decisions remain the same for other SKUs.

**Appendix F.** Sensitivity Analysis for Ordering Cost

**Table F1.** Optimal supply and delivery decisions for Port Call 1 when ordering costs are decreased by 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price (€) | Total Weight (kg) |
|---|---|---|---|---|---|
| S11 | Australia | 5 | 1 | 199 | 3 |
| S46 | Brazil | 3 | 2 | 410 | 2 |
| | | 5 | 2 | 802 | 4 |
| S65 | Germany | 3 | 1 | 166 | 40 |
| S188 | Norway | 1 | 2 | 295 | 2.436 |
| S190 | Norway | 3 | 1 | 339 | 11 |
| S101 | Singapore | 5 | 1 | 6.708 | 3.536 |
| S185 | Singapore | 5 | 4 | 809 | 62 |
| S62 | Singapore | 5 | 4 | 3.671 | 1.326 |
| S117 | The Netherlands | 3 | 1 | 1.169 | 7 |
| S146 | The Netherlands | 3 | 9 | 2.875 | 91 |
| S183 | The Netherlands | 1 | 10 | 2.859 | 9.874 |
| S30 | The Netherlands | 3 | 19 | 1.689 | 13 |
| S85 | The Netherlands | 3 | 3 | 2.817 | 35 |
| S58 | United Arab Emirates | 1 | 101 | 4.854 | 1.128 |

Suppliers are changed for 3,11% and the delivery options for 4,97% of the SKUs. The decisions remain the same for other SKUs.

**Table F2.** Optimal supply and delivery decisions for Port Call 1 when ordering costs are decreased by 10%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S46 | Brazil | 3 | 2 | 410 | 2 |
| | | 5 | 2 | 802 | 4 |
| S65 | Germany | 3 | 1 | 166 | 40 |
| S188 | Norway | 1 | 2 | 295 | 2.436 |
| S190 | Norway | 3 | 1 | 339 | 11 |
| S101 | Singapore | 5 | 1 | 6.708 | 3.536 |
| S185 | Singapore | 5 | 4 | 809 | 62 |
| S62 | Singapore | 5 | 4 | 3.671 | 1.326 |
| S117 | The Netherlands | 3 | 1 | 1.169 | 7 |
| S146 | The Netherlands | 3 | 10 | 3.074 | 94 |
| S183 | The Netherlands | 1 | 10 | 2.859 | 9.874 |
| S30 | The Netherlands | 3 | 19 | 1.689 | 13 |
| S85 | The Netherlands | 3 | 3 | 2.817 | 35 |
| S58 | United Arab Emirates | 1 | 101 | 4.854 | 1.128 |

Suppliers are changed for 2,48% and the delivery options for 4,35% of the SKUs. The decisions remain the same for other SKUs.

**Appendix G.** Sensitivity Analysis for Loading Cost

**Table G1.** Optimal supply and delivery decisions for Port Call 1 when loading costs are decreased by 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S46 | Brazil | 3 | 4 | 1.608 | 7 |
| S65 | Germany | 3 | 1 | 850 | 40 |
| S188 | Norway | 1 | 2 | 382 | 2.436 |
| S190 | Norway | 3 | 1 | 339 | 11 |
| S101 | Singapore | 1 | 1 | 8.705 | 3.536 |
| S62 | Singapore | 1 | 4 | 3.671 | 1.326 |
| S117 | The Netherlands | 3 | 1 | 1.169 | 7 |
| S146 | The Netherlands | 3 | 10 | 3.074 | 94 |
| S183 | The Netherlands | 1 | 13 | 4.404 | 9.935 |
| S30 | The Netherlands | 3 | 19 | 2.191 | 13 |
| S85 | The Netherlands | 3 | 3 | 2.817 | 35 |
| S58 | United Arab Emirates | 1 | 102 | 4.936 | 1.129 |

The changes occur in the delivery routes and correspond to 4,97% of the SKUs. The decisions remain the same for other SKUs.

**Table G2.** Optimal supply and delivery decisions for Port Call 8 when loading costs are decreased by 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S29 | Denmark | 1 | 1 | 6.447 | 1.451 |
| S132 | Norway | 3 | 1 | 3.300 | 69 |
| S166 | Norway | 3 | 1 | 3.200 | 2 |
| S102 | The Netherlands | 3 | 12 | 343 | 32 |
| S20 | The Netherlands | 3 | 2 | 878 | 7 |
| S39 | The Netherlands | 3 | 1 | 49 | 0 |
| S6 | The Netherlands | 3 | 12 | 266 | 2 |
| S91 | The Netherlands | 3 | 3 | 656 | 1.677 |
| S162 | United Kingdom | 1 | 9 | 336 | 61 |

Suppliers are changed for 4,76% and the delivery options for 21,43% of the SKUs. The decisions remain the same for other SKUs.

**Table G3.** Optimal supply and delivery decisions for Port Call 15 when loading costs are decreased by 10% or 20%

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S147 | Singapore | 3 | 3 | 883 | 4 |
| S4 | Singapore | 3 | 4 | 116 | 5 |
| S96 | Singapore | 3 | 9 | 2.058 | 37 |
| S102 | The Netherlands | 3 | 62 | 6.483 | 471 |
| S13 | The Netherlands | 3 | 31 | 1.530 | 37 |
| S131 | The Netherlands | 3 | 14 | 2.259 | 88 |
| S144 | The Netherlands | 3 | 12 | 1.397 | 202 |
| S146 | The Netherlands | 3 | 35 | 12.219 | 243 |
| S183 | The Netherlands | 3 | 3 | 878 | 17 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 6 | 3.170 | 41 |
| S70 | The Netherlands | 1 | 17 | 1.205 | 671 |
| S198 | United Arab Emirates | 3 | 10 | 198 | 29 |

The changes occur in the delivery routes and correspond to 8,21% of the SKUs. The decisions remain the same for other SKUs.

**Appendix H.** Analysis for Discount Policies

**Table H1.** Optimal supply and delivery decisions for Port Call 9 when 10% discount is applied by suppliers when total product price exceeds 1000€

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S186 | Brazil | 3 | 1 | 36 | 6 |
| S46 | Brazil | 3 | 3 | 255 | 4 |
| S199 | Singapore | 3 | 3 | 124 | 3 |
| S100 | The Netherlands | 3 | 28 | 1.638 | 144 |
| S102 | The Netherlands | 3 | 6 | 427 | 4 |
| S128 | The Netherlands | 3 | 29 | 1.211 | 100 |
| S142 | The Netherlands | 3 | 3 | 744 | 43 |
| S146 | The Netherlands | 3 | 16 | 3.458 | 81 |
| S31 | The Netherlands | 3 | 2 | 164 | 1 |
| S74 | The Netherlands | 3 | 7 | 190 | 10 |
| S92 | The Netherlands | 3 | 6 | 1.174 | 10 |

The changes occur in the supplier choices and correspond to 8,65% of the SKUs. The decisions remain the same for other SKUs.

**Table H2.** Optimal supply and delivery decisions for Port Call 11 when 10% discount is applied by suppliers when total product price exceeds 1000€, 2000€ or 3000€

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S45 | Singapore | 3 | 2 | 103 | 1 |
| S102 | The Netherlands | 3 | 21 | 1.370 | 100 |
| S128 | The Netherlands | 3 | 5 | 105 | 5 |
| S142 | The Netherlands | 3 | 1 | 383 | 13 |
| S144 | The Netherlands | 3 | 1 | 391 | 2.000 |
| S146 | The Netherlands | 3 | 30 | 4.374 | 95 |
| S69 | United Kingdom | 3 | 1 | 30 | 1 |

The changes occur in the supplier choices and correspond to 9,84% of the SKUs. The decisions remain the same for other SKUs.

**Table H3.** Optimal supply and delivery decisions for Port Call 15 when 10% discount is applied by suppliers when total product price exceeds 3000€.

| Supplier | Supplier Country | Delivery Option | # SKUs | Total Price(€) | Total Weight(kg) |
|---|---|---|---|---|---|
| S96 | Singapore | 3 | 2 | 428 | 19 |
| S102 | The Netherlands | 3 | 66 | 8.161 | 473 |
| S13 | The Netherlands | 3 | 31 | 1.530 | 37 |
| S131 | The Netherlands | 3 | 23 | 3.013 | 116 |
| S144 | The Netherlands | 3 | 12 | 1.451 | 200 |
| S146 | The Netherlands | 3 | 38 | 13.403 | 247 |
| S183 | The Netherlands | 3 | 3 | 878 | 17 |
| S192 | The Netherlands | 3 | 1 | 945 | 32 |
| S35 | The Netherlands | 3 | 6 | 3.170 | 41 |
| S70 | The Netherlands | 3 | 16 | 1.126 | 668 |
| S198 | United Arab Emirates | 3 | 9 | 197 | 28 |

The changes occur in the supplier choices and correspond to 9,66% of the SKUs. The decisions remain the same for other SKUs.