Strategic and Tactical Planning of the Downstream Petroleum Supply Chain

Carolina Diniz Melo

Thesis to obtain the Master of Science Degree in

Petroleum Engineering

Supervisors: Doctor Ana Paula Ferreira Dias Barbosa Póvoa

Doctor Susana Isabel Carvalho Relvas

Examination Committee

Chairperson: Doctor Maria João Correia Colunas Pereira

Supervisor: Doctor Susana Isabel Carvalho Relvas

Members of the Committee: Doctor Leão José Fernandes

July 2019

Dedicatory

To all women in science.

Our path is harder but we can change the world.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

ABSTRACT

Petroleum Supply Chain (PSC) is divided into three main segments: upstream, midstream and downstream. Considering these three segments, there are still some research gaps in the downstream supply chain considering the strategic-tactical decision levels. Therefore, the aim of this thesis is to develop a Mixed Integer Linear Programming (MILP) mathematical model that will support the definition of a distribution strategy for supplying markets that may span over more than one country.

The model is based on that developed by Kazemi & Szmerekovsky (2015), which addresses strategic and tactical decisions (such as determining optimal location and capacities for distribution centers, selection of transportation modes, determining flow allocation, etc.) considering multiple products while minimize the fixed and distributing costs. The model proposed in this work extends the previous work and adds terms in objective function and constraints related to imports and exports between countries, not yet considered.

In order to test and validate the model developed, an illustrative case study was considered and to show the applicability of the model, a real case comprising the Portuguese oil supply chain and its operation in Iberia was used considering one of the market players present in both countries. The model was implemented in GAMS programming language and solved using the solver CPLEX.

The results analyzed not only consider the current network and how it can be optimized in terms of resource usage, but also foresee which network adjustments would be more advantageous in the case study selected.

Keywords: downstream petroleum supply chain, optimization, mathematical programming, mixed integer linear programming, strategic and tactical planning.

RESUMO

A cadeia de abastecimento do petróleo é dividida em três segmentos: *upstream*, *midstream* e *downstream*. Considerando estes três segmentos, ainda há oportunidade de pesquisa na cadeia *downstream* compreendendo os níveis estratégico e tático. Sendo assim, o objetivo dessa dissertação de mestrado é desenvolver um modelo de programação matemática linear inteira-mista, que fundamentará a definição de uma estratégia de distribuição para abastecer mercados em mais de um país.

O modelo desenvolvido é baseado em Kazemi & Szmerekovsky (2015), o qual determina decisões estratégicas e táticas (tais quais a determinação da localização e capacidades ótimas para centros de distribuição, seleção de modos de transporte, determinação do fluxo de materiais, etc.) considerando múltiplos produtos enquanto minimiza os custos fixos e de distribuição. O modelo proposto neste trabalho expande o trabalho anterior e adiciona termos na função objetivo e restrições relacionadas a importação e exportação entre países, aspectos ainda não considerados.

Para testar e validar o modelo desenvolvido, um caso ilustrativo foi considerado e para mostrar a aplicabilidade do modelo, um caso de estudo real considerando a cadeia de abastecimento do petróleo em Portugal e a sua operação na península Ibérica foi utilizado considerando um dos *players* do mercado presente em ambos os países. O modelo foi implementado na linguagem de programação GAMS e resolvido utilizando o solver CPLEX.

Os resultados analisados não só consideram a presente rede e como esta pode ser otimizada em termos de utilização de recursos, mas também prevê quais ajustes seriam mais vantajosos considerando o caso de estudo selecionado.

Palavras-chave: cadeia de abastecimento do petróleo *downstream*, otimização, programação matemática, programação linear inteira-mista, planejamento estratégico e tático.

Acknowledgments

First, I want to thank God for blessing me with an amazing family. I could not have been born in a better place.

I want to thank my family for being always supportive in my decisions (even the craziest ones), being there for me in the toughest moments and visiting me in Portugal. A special thanks to my parents, who have been always encouraging me, to my grandmother, who is always by my side and took a plane for the first time (a 10-hour flight) just to visit me and to my godmother, who always listens to me. You are awesome and I love you all!

I want to thank Polytechnic School of University of São Paulo for making possible the opportunity of studying these two years abroad at Instituto Superior Técnico in the Double Degree program and Banco Santander for awarding me with the scholarship.

A special thanks to my supervisors Professor Ana Póvoa and Professor Susana Relvas for supervising this Master thesis and bringing amazing contributions to this work. Thank you for the patience and guidance, for providing me an office at Taguspark and for presenting me the colleagues of Center for Management Studies (CEG-IST), who helped me with GAMS and many other issues.

I want to thank Professor Elsa Vásquez Alvarez from Polytechnic School of University of São Paulo for supervising my first scientific researches and for presenting me the amazing field of study of operations research.

Last but not least, to all my friends, thank you for being supportive, listening to me and never letting me give up. Thanks to my friends that came to Portugal to visit me. Thanks to my friends who invited me to visit them in Italy and Ireland. Thanks to my friends since childhood who still talk to me and are there for me no matter how far we are. Thanks to my friends that could not come here but were always present. Thanks to my friends that I lived with and together we could share many moments of happiness.

Table of Contents

List of Figures

List of Tables

Acronyms

A1 – Jet Fuel

ARIMA – Autoregressive Integrated Moving Average

B5 – Diesel

BIP – Binary Integer Programming

C3 – Propane

C4 – Butane

CLC – Companhia Logística de Combustíveis

CORES – Corporación de reservas estratégicas de productos petrolíferos

CVaR – Conditional Value-at-Risk

DC – Distribution Center

DSS – Decision Support System

ENPV – Expected Net Present Value

ENSE – Entidade Nacional para o Setor Energético

EUR – Euro

FU – Fuel Oil

GAMS – General Algebraic Modeling System

GO – Gas Oil

IP – Integer Programming

IRP – Integrated Refinery-Planning

LP – Linear Programming

LPG – Liquefied Petroleum Gases

MILFP – Mixed Integer Linear Fractional Programming

MILP – Mixed Integer Linear Programming

MINLP – Mixed Integer Nonlinear Programming

MIP – Mixed Integer Programming

NLP – Nonlinear Programming

NPV – Net Present Value

OR – Operations Research

OSC – Oil Supply Chain

PSC – Petroleum Supply Chain

SAA – Sample Average Approximation

U5 – Gasoline 95

U8 – Gasoline 98

US – United States

USD – US Dollar

Chapter 1 – Introduction

This chapter aims to introduce the topic of this Master's thesis, the objectives and the methodology. This chapter is structured as follows: Section 1.1 briefly introduces the motivation and context of the topic of the thesis; Section 1.2 comprises the objectives to be achieved in the thesis; Section 1.3 explains the methodology followed to develop the thesis; Section 1.4 shows how the thesis is structured.

1.1. Motivation and Context

Until the middle of the eighteenth century, the world economy relied on the manual manufacture of products. However, the need of increasing production in order to attend market demands implied a reinvention of the production methods from hands to machine production powered by steam. This was the begin of a new era in the world history, better known as First Industrial Revolution, which took place in England and used coal as a major source of energy (Hobsbawm, 2000).

In spite of coal is still used today, mainly in China, it is not the main source of energy anymore because it generates a lot of pollution and other more powerful sources of energy were discovered (BP - British Petroleum, 2018). Thus, during the Second Industrial Revolution in the end of nineteenth century, the exploration of oil has begun. In Pennsylvania, Edwin Drake successfully drilled the first modern oil well and the first refineries were built to extract kerosene from crude oil in order to use it as a lighting and heating fuel. In the early twentieth century, the advent of automotive industry required another oil product (that was an unwanted product from crude oil at first) to be extracted: gasoline (Yergin, 1991).

Today the oil and gas industry supplies more than 50% of the whole world energy. Other energy sources such as renewables are increasing their share but they still far from overcome oil and natural gas. Oil is also a source of raw material to petrochemical industry, which uses it to produce plastics, rubber, solvents, etc. Therefore, it is expected that the world will still depend on oil and gas industry for a few decades to supply its energy needs (BP - British Petroleum, 2018). Since this industry is the world's major supplier of energy today and there are enough proven reserves, there are many research opportunities for studies regarding the oil industry as a constant need of improvement exists.

One important field of study regarding the oil industry is the planning and management of its supply chain. Petroleum Supply Chain (PSC) is a complex and dynamic system, which involves high revenues and high costs. It is divided into three main sectors: upstream, which comprises oil exploration and production; midstream, responsible for refining operations; and downstream, considering oil products distribution (Lima, et al., 2018).

As the upstream sector has been well researched, there is a great opportunity to explore the downstream sector in research terms (Fernandes, et al., 2014). As this segment deals with several products' distribution it includes a set of diverse facilities such as storage depots, wholesale and retail market that are linked to two types of distribution: primary and secondary. The distribution includes several transportation modes, which may even be combinable with each other (Lima, et al., 2016). Therefore, the complexity of the downstream segment is huge since it deals with a multi-product distribution between several storages in wholesale and retail market that can be performed using several types of transportation modes including a combination of more than one mode.

The activities of such systems are costly and in order to seek for minimum costs or maximum profit, without compromising safety and quality of the operations there is a need of decision supporting tools to aid the decision-making process (Lima, et al., 2018). This work explores this need and aims to develop a mathematical model for the downstream supply chain to support the associated planning process.

1.2. Objectives

The main purpose of this Master's thesis is to develop a strategy for optimizing the distribution of oil derivatives in markets that may span over more than one country and to develop a Mixed Integer Linear Programming (MILP) mathematical model in order to do it. A secondary goal is to apply a real case of Portuguese PSC and its operation in Iberia to the model in order to demonstrate its potential.

In order to achieve the main purpose of the thesis, intermediate objectives are to be accomplished: i) to understand the Petroleum Supply Chain and each of the three segments that composes it: upstream, midstream and downstream; ii) to explore further the downstream segment; iii) to define the planning levels and how operations research can be used to develop decision support tools; iv) to build up a literature review on the topic; v) to understand the main sources of literature that may help the problem resolution; vi) to define and characterize the problem approached in the model; vii) to develop a MILP model in order to solve the problem and validate it using a illustrative case study; and viii) to apply the real case of Portuguese PSC to the model developed.

1.3. Methodology

The methodology followed in order to develop the thesis includes six steps, which are presented in Figure 1, which schematizes the methodology followed.

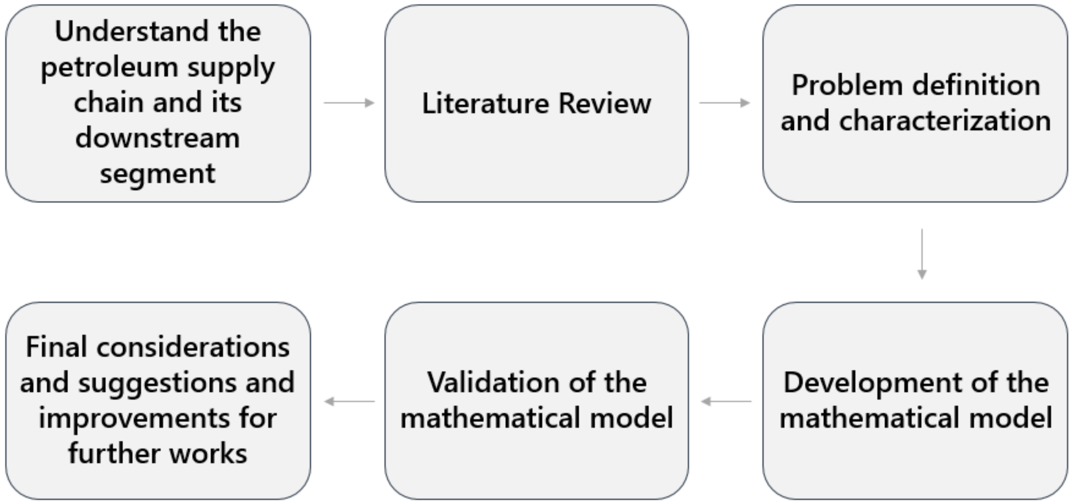

Figure 1. Methodology followed.

The first step is to understand the petroleum supply chain and, mainly, its downstream segment, which still needs some research attention.

The second step is to identify important papers that developed research regarding optimization applying mathematical programming tools in the downstream segment of the petroleum supply chain. This step is fundamental to the next one, since these papers will help to come up with ideas to define the problem and to solve it.

The third step is the problem definition and characterization based on the gaps identified in the literature review.

The fourth step is the development of the mathematical model to solve the problem defined.

The fifth step comprises the validation of the model developed with an illustrative case study and the application of a real case to the model to demonstrate the potential of the model.

The sixth step includes final considerations regarding the model developed, applications in real life and suggestions in order to improve it in further works.

1.4. Structure of the thesis

This thesis is structured into 6 chapters. Figure 2 schematizes the structure of the thesis.

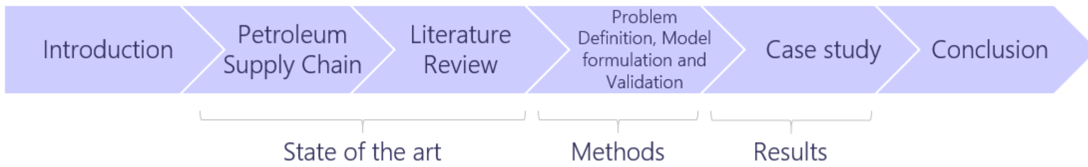

Figure 2. Structure of the thesis.

The first chapter presents an introduction, the objectives to be reached and the methodology to be followed in order to accomplish the established objectives.

The second chapter and third chapter together comprise the state of the art. The second chapter describes the Petroleum Supply Chain (PSC) focusing mainly in the downstream segment, highlighting the importance of using operations research techniques in the PSC and the third chapter includes the literature review. This part is essential to support the development of the problem definition.

The fourth chapter comprises the methods. It defines and characterizes the problem to be solved, describes the mathematical model developed to solve the problem and presents the model validation using an illustrative case study.

The fifth chapter comprises the results and discussion. It describes the real case study applied to the mathematical model in order to demonstrate its potential. Furthermore, the fifth chapter presents and discusses the solution proposed for the real case by the mathematical model developed and makes suggestions for further works.

The sixth chapter concludes the thesis.

Chapter 2 – Petroleum Supply Chain

This chapter aims to explain the structure of the petroleum supply chain and the importance of applying operations research techniques in PSC. This chapter is structured as follows: Section 2.1 discusses the concept of supply chain and the structure of the petroleum supply chain; Section 2.2 highlights the downstream segment of the PSC; Section 2.3 gives a brief history of operations research; Section 2.4 explains the elements that composes a mathematical model and some of the categories used to classify a model; Section 2.5 comprises the planning levels that classifies the decision process in PSC; Section 2.6 shows the importance of using operations research techniques in PSC.

2.1. The Petroleum Supply Chain

The Petroleum Supply Chain (PSC), also called Oil Supply Chain (OSC), is divided into three segments: upstream, midstream and downstream (see Figure 2). The upstream involves oil exploration and production, which includes the search for areas that may contain hydrocarbons, drilling operations and production, which means to bring the hydrocarbons to the surface, and crude oil transportation. Some authors consider the crude oil transportation as an upstream segment activity (Lima, et al., 2018) and others consider as a midstream activity (Leiras, et al., 2011). Despite these disagreements, the midstream regards refining operations. The downstream refers to storage and refined products distribution and marketing (Lima, et al., 2018). Some authors divide the PSC into only two segments: upstream and downstream. In this case, the downstream segment includes the refining operations (Lima, et al., 2016).

PSC begins in upstream segment with oil exploration and production (Sahebi, et al., 2014). After exploration, oil terminals receive crude oil that is transported by tankers. Moreover, crude oil can be also imported. Then, pipelines transport crude oil from oil terminals to refineries (Neiro & Pinto, 2004). After that, the midstream segment comprises refineries and petrochemicals to transform crude oil and produce oil products (Sahebi, et al., 2014). Crude oil is a mixture of hydrocarbons, so each of its fractions must be separated in different products. At refineries, crude is heated and put on a distillation column, where the products are recovered at different temperatures. Some refineries, that are more complex, reprocess the heavier fractions in order to obtain more of the lighter products such as liquid petroleum gases (LPG), gasoline and naphtha (EIA - U.S. Energy Information Administration, 2012). Refineries can be connected to each other and take advantage of the degree of complexity of each one (Neiro & Pinto, 2004). Finally, the downstream segment is responsible for transporting oil products to distribution centers (DC) in wholesale segment and then transporting from wholesale to retail segment (Neiro & Pinto, 2004).

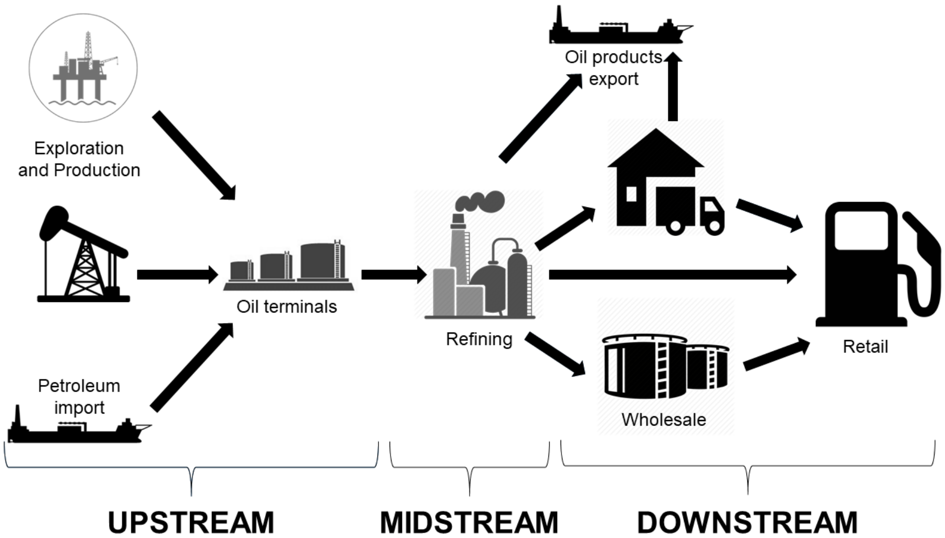

Figure 3. The petroleum supply chain.

According to Fernandes, et al. (2014) the downstream sector of PSC has not been researched fairly well in comparison to the other segments, which implies that there is a great opportunity in exploring this field of study. Thus, the next section explains the downstream segment of PSC.

2.2. The downstream segment of the Petroleum Supply Chain

A set of installations and transports connecting them composes the downstream sector infrastructure (see Figure 3). The major facilities are storage depots, wholesale and retail market. Power plants, petrochemicals and big fuel consumers comprise the wholesale segment and small fuel consumers comprise the retail segment. In wholesale, oil products are sold to industry, aviation, marine, transportation sub-segments and retailers such as warehouses, supermarkets and gas stations. In retail, service stations sell oil products to be used in transportation and domestic heating (Lima, et al., 2016).

The transport among the downstream facilities is divided into two types of distribution: the primary and the secondary distribution. The primary originates in refinery and it is responsible for distributing oil products among refineries, petrochemicals and depots in wholesale segment. The transportation modes and their respective resources (in parenthesis) in primary distribution are pipeline (pipelines), maritime (ships), railroad (train wagons) and road (tank trucks) (Lima, et al., 2016). The secondary transportation originates in storage depots and it transfers the oil products from local, regional and international refineries and petrochemicals to the final customers in retail segment or export them abroad. The transportation resources most used in secondary distribution are tank trucks and sometimes train wagons. However, pipelines are used in particular situations such as the distribution of jet fuel to airports (Lima, et al., 2016).

The transport through pipelines requires high capital investment but it is the most economic and reliable mode of transporting over long distances a large amount of oil products. It is possible to deliver high volumes of distinct refined products with low product contamination using pipelines. Where there are no pipelines available, but it is still possible to transport large amounts of products through sea, the marine transportation is the most economical mode. The safest and most economical onshore transportation mode is by train wagons. However, when these three transportation modes are not available or the demand in final destination does not require large amounts of products, trucks transport the oil derivatives. Another characteristic regarding transportation modes is the product flow that is continuous only in pipelines and discrete in ships, wagons and trucks (MirHassani, 2008).

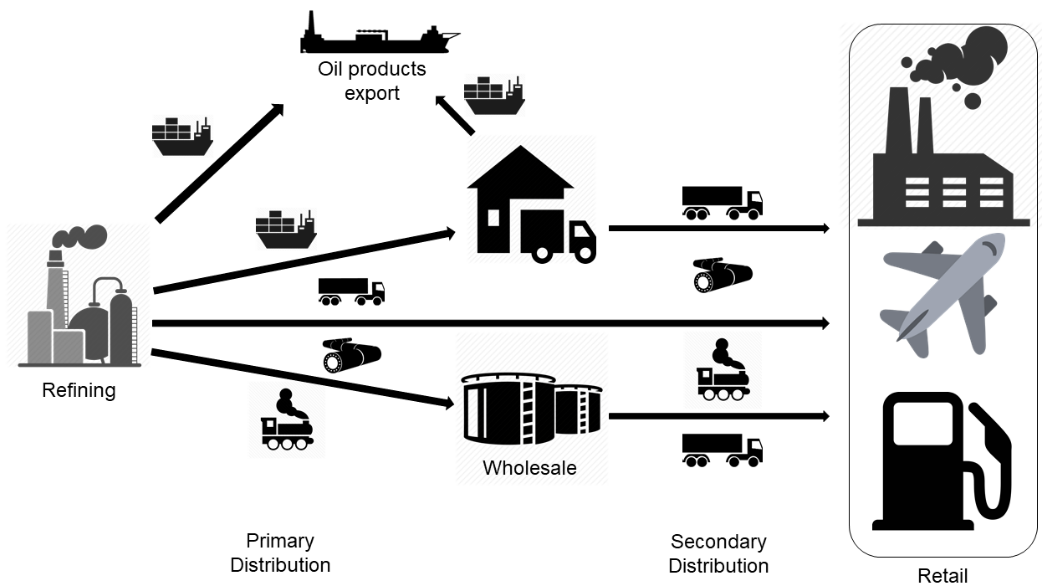

Figure 4. The downstream petroleum supply chain.

Furthermore, the downstream segment has some peculiarities that may increase or decrease its complexity when planning the supply chain. First, petroleum (and, consequently, its products) is considered a commodity, fungible and it has no expiration deadline, thus many buy and sell transactions can occur before its consumption. Another important feature that also increases complexity is that oil products are non-discrete, this is, they cannot be identified individually and they are not packaged. However, there are also other features that decrease complexity. First, the demand is considerably stable for specific markets, it is possible to foresee the future demand using historical data and consumer tastes or products modernization do not affect it. Moreover, there are less products to track in comparison to other industries and the mixture of products is static and stable (Lima, et al., 2016).

As common within the planning process also when planning the downstream petroleum supply chain, three decision-planning levels must be considered: strategic, tactical and operational. The next section explains each of these levels.

2.3. Decision-Planning Levels

According to Lima et al. (2016), the decision process is classified into three planning levels: strategic, tactical or operational. Each of these levels diverge on the type of decisions and time planning horizon (Lima, et al., 2018). There is a hierarchy among these levels: the strategic imposes limit to the tactical and the tactical imposes limit to the operational (Lima, et al., 2016). Moreover, the decision planning can be vertically integrated, combining two planning levels of decision, for example, strategic-tactical, strategic-operational or tactical-operational (Misni & Lee, 2017).

The strategic planning level deals with long-term decisions, in an annual scale (Lima, et al., 2018). The decisions within the strategic level are related to identify the facilities best locations to be structured, to determine their capacities and to select the technologies to be applied at each facility. Facility relocation problems, outsourcing and investment planning are also considered as strategic decisions (Sahebi, et al., 2014). The strategic level decisions are the most complex ones because as they comprise the definition of the structure of the supply chain, the set-up costs for implementation are high (Lima, et al., 2016).

The decisions in tactical planning have medium-term implications, in a monthly scale and they are restrained by the configurations established in the strategic planning. In this planning level, the decisions are related to the establishment of the best material flow across the chain (Lima, et al., 2016), and to the production planning and inventory management (Misni & Lee, 2017).

The operational planning level deals with short-term decisions, in a weekly scale. These decisions are restrained by the operating policies established in the tactical level (Lima, et al., 2018). The decisions in this level concern to vehicle routing and scheduling of products and activities (Misni & Lee, 2017).

Being the planning process related to future events, uncertainty needs to be accounted for. Its presence in each stage depends on the decision horizon. The higher the decision horizon, the higher the uncertainties are. That is, there are more uncertainties in strategical planning than in tactical and there are more in tactical than in operational (Lima, et al., 2016).

As the PSC involves high costs and high revenues, it is important to make the optimal decisions in each planning level. In order to find optimal solutions to a certain planning situation, operations research models and methodologies can be very helpful. The next section presents how operations research's tools can be used in PSC.

2.4. Operations research in PSC

2.4.1. A brief history of operations research and some currently applications

Operations or Operational (in British) Research (OR) is a field of study, which involves a set of techniques to assist in the decision-making process in problems that involve how to lead and coordinate operations in an organization. The decision-making process initiates with the problem characterization and definition. Then, a mathematical model is developed in order to solve the problem as it may optimize the performance by reducing costs or increasing profit, for example. After that, an OR software solves the model and the solutions obtained go to the model validation step, which tests if they are valid for the real problem (Hillier & Lieberman, 2005).

However, OR techniques have not always been dependent of computers since it has begun during the World War II, when the resources to military operations were scarce and, therefore, they had to be allocated in the most effective manner. Then, scientists were hired by the British and U.S. military management to solve this and other strategic and tactical issues. These scientists developed very effective techniques that enabled the victory of the Allies in some battles during the war (Hillier & Lieberman, 2005).

After the war, it was possible to see that organizations in business, industry and government were facing problems that were very close to those faced by the militaries. Therefore, the OR techniques were spread to other fields beyond the military (Hillier & Lieberman, 2005). Currently, the applications of OR in companies includes logistics, supply chain management, scheduling of production and many other areas that have much information to be processed and a decision to be taken.

In the 1980s, the computer revolution boosted OR techniques and applications since the computers provide solution in seconds of complex problems that could be almost impossible to do by hand. Nowadays, there are many software and algorithms to solve OR problems (Hillier & Lieberman, 2005). The General Algebraic Modeling System (GAMS) is an example of software that is used to solve OR problems.

2.4.2. The models in operations research

As the OR techniques were improved, the problems were categorized according to the type of the model developed and many methods of solution were created. A model simplifies the real system through mathematical expressions. As a model is simply a representation of the reality, it does not contain all the elements that composes the real problems but the most important ones.

The following elements composes a typical mathematical model: the decision variables (and sometimes parameters), the objective function and the constraints. The mathematical model consists in maximize or minimize an objective function subject to a series of constraints that may be equalities or inequalities in order to find an optimal solution. It is important to emphasize that there may be multiple best solutions, and this is the reason why the model tries to find “an” optimal solution (Hillier & Lieberman, 2005). The objective function commonly represents the profit to be maximized or the cost to be minimized.

There are many categories to classify a mathematical model and some of the most important ones are explained below.

In Linear Programming (LP), also known as linear optimization, the objective function and the constraints must be linear functions and the type of decision variable is continuous.

In Integer Programming (IP), the objective function and the constraints are linear functions and the decision variables may be all integer or integer and continuous. If all the decision variables are integer, this is a Pure Integer Programming. If these integer decision variables are discrete and restricted to 0 or 1, this is a Binary Integer Programming (BIP) problem. The binary variables have an enormous importance in a situation to make a yes-or-no decision. However, if only some decision variables are integer, this is a Mixed Integer Programming (MIP) problem, also called Mixed Integer Linear Programming (MILP). Another characteristic of Integer Programming is that it is NP-complete.

In Nonlinear Programming (NLP), the objective function or at least one of the constraints is a nonlinear function and the decision variables can be all continuous or integer and continuous. If some of the decision variables are integer, the problem is a Mixed Integer Nonlinear Programming (MINLP).

Some problems that are modeled using LP, MILP, NLP, etc. are extremely complex, causing an issue that can be overcome applying decomposition strategies such as Benders decomposition, Lagrangean decomposition and bilevel decomposition (Andersen, et al., 2013)

The mathematical models can also be deterministic or stochastic. The deterministic models produce the same output when the initial conditions and the parameters are the same. However, there is a randomness present in the stochastic models. That is, the same set of initial conditions but with uncertainty in a part or the whole set of parameters will produce different outputs. Variables will obtain different values when uncertainty is realized.

Furthermore, when a problem considers uncertainty, there are several approaches to deal with them such as stochastic programming, robust optimization and fuzzy programming. If the acquired data has a particular distribution, the stochastic programming is commonly used. However, if there is no particular distribution regarding the data, fuzzy programming can be applicable but it must be possible to determine membership functions and boundaries (Azadeh, et al., 2017).

2.4.3. Why use operations research techniques in petroleum supply chain

The oil and gas industry has a huge impact worldwide due to the world energy supply that this industry provides (Ghaithan, et al., 2017). Since 1990, petroleum represents over 30% of the world's energy demand (Saad, et al., 2018) and natural gas represents over 20% currently, therefore, together these fuels supply more than 50% of the world's energy (BP - British Petroleum, 2018). The applications of oil and gas industry are not limited only to powering vehicles but to production of plastics, detergents, rubber, textiles, etc. and also to electricity generation (Saad, et al., 2018).

Although this industry is very profitable, their costs are huge. These costs involve rigs, equipment, maintenance, crew, etc. For example, in offshore hydrocarbon reserves, (that represents more than one third of global reserves), the cost of exploration and well development represents a large share of the total costs and the rigs represent a major part in these costs (Skjerpen, et al., 2018). According to Bassi et al. (2012), rigs can cost up to US$600,000 daily.

In addition to the large costs, the investments are also huge in the oil industry. The investments must be high because the facilities for exploration and production offshore need to operate over the entire life span of the project (around 10 to 30 years) besides their expensive cost. If the investments are not planned carefully and if the wrong decisions were made, this would affect the entire project's profitability (Goel & Grossmann, 2004).

Within this setting is very important to plan carefully in the oil industry namely on the supply chain area. To do so is important to account for this system characteristics and to that consider the presence of uncertainty. So the variations in the production level, the unpredictable oil market prices and the unforeseeable demands are important sources of uncertainty in the Oil Supply Chain (OSC) (Lima, et al., 2018). The demand for oil products is always changing and some markets begin to stand out (Lima, et al., 2016). From 2007 to 2017, while oil consumption in U.S. and Europe decreased by 5% and 10% respectively, in Asia Pacific it has increased by almost 33% and it now represents almost twice of U.S. oil consumption. In the same period, oil consumption increased by 32% in Africa, 27% in Middle East, 16% in South and Central America and 9% in CIS. In 2007, the oil consumption in these four regions represented 97% of U.S. consumption but in 2017 these four regions consumption represented 125% of U.S.'s (BP - British Petroleum, 2018).

Moreover, the oil industry is inserted in an unstable context with many geopolitical issues that reinforces all of these uncertainties, risks, high costs and investments (Lima, et al., 2016).

Therefore, professionals in this field are challenged constantly to take the best decisions in order to spend the less but earn the most. These professionals' objective is to plan a secure and resilient supply chain that considers the uncertainties and responds to unforeseeable events in a fast and cost effective manner. If Operations Research's tools are used, the decision-making process can improve, costs can reduce and revenues can increase (Lima, et al., 2016). Moreover, the Operations Research's tools can be applied in the three segments of the PSC. The models referring to the upstream sector usually select the oil wells to be drilled and the operations decisions associated are crude oil transportation, scheduling and platform production. In midstream segment, the models include planning and scheduling of refinery production. The decisions in downstream sector refer to the network design and the material flow, which include products distribution, optimization in transports from refinery to storage depots and storage (Kazemi & Szmerekovsky, 2015). Because of this, it is possible to have plenty of applications of Operations Research in many fields of oil and gas industry. This will be detailed in the next chapter.

2.5. Conclusion

In this chapter the structure of the Petroleum Supply Chain was described, highlighting its downstream segment, which has not been sufficiently researched. Furthermore, this chapter presented the decision levels used when planning and managing the PSC. Finally, it was explained the importance of applying operations research's techniques in PSC.

The downstream segment of PSC is inserted in a scenario full of uncertainties and many mathematical models can be developed based on it. The activities included in this sector are mainly distribution and storage of oil products. The OR models in downstream PSC try to find an optimal solution for profit maximization or cost minimization by making decisions regarding many activities such as the planning of the transportation modes to be used, the amounts of each product is to be transported by each mode and the location and capacity of the storages.

Thus, after understanding the PSC, the next step will be devoted to produce a literature review on optimization in downstream segment of PSC. This is presented in the next chapter.

Chapter 3 – Literature Review

The objective of this chapter is to present a literature review in downstream PSC optimization. The papers selected were classified in five different categories based on their decision-planning level (or the integration of more than one level). A set of several keywords such as “downstream”, “oil and gas”, “petroleum supply chain”, “optimization” and “operations research” and their combination were used to search for papers in platforms as Google Scholar, Science Direct and Web of Knowledge. The search resulted in 39 papers but only the most relevant and recent ones were analysed. The discarded papers presented models in the upstream and midstream segments of the PSC and, therefore, they were not considered relevant as this work will focus on the downstream supply chain. It is true that some of the 24 selected papers are more focused in refining operations than in the downstream segment itself but these papers also consider the products distribution to the customers and so they were analysed. The majority of papers reviewed were published in the last 10 years, despite that the time frame of the collected papers covers the last 20 years. Still, the older papers are still relevant in the field.

The chapter is structured in six sections: Section 3.1 presents the models developed considering strategic planning; Section 3.2 presents the models that considered tactical planning; Section 3.3 presents the models that considered operational planning; Section 3.4 integrates the models with strategic and tactical planning; Section 3.5 integrates the models with tactical and operational planning; and Section 3.6 concludes the chapter, summarizing all the papers analyzed.

3.1. Strategic planning

Strategic planning comprises long-term decisions such as the network design (number, location and capacity of the facilities) (Barbosa-Póvoa, 2014). This problem has been treated by several authors but five main papers were considered relevant and are analysed below. This can be divided in two main groups: the papers that addressed the problem as deterministic and the papers that considered the presence of uncertainty. In the latter a single paper was identified.

3.1.1. Strategic planning – Deterministic approaches

Fernandes et al. (2013) developed a deterministic MILP model coded in GAMS with strategic planning, considering a multi-entity, multi-product, multi-echelon and multi-transportation downstream PSC. The objective was to maximize the total network profits considering six terms: the refinery margin (the difference between ex-refinery price and refining costs, multiplied by the refined volume, minus the crude oil supply costs and the result is multiplied by the capital percentage per entity) plus the retail segment margin, minus the exportation and importation costs and transportation and storage depots tariffs. The model determines the optimal storage depot locations (consists of installation of new ones or closure of the existents), storage capacities, allocation of volumes for crude oil, transportation modes and routes, refinery production and network affectations for long term planning.

Finally, a real-case involving a Portuguese PSC network was used to test the model (Fernandes, et al., 2013).

Andersen, et al. (2013) developed two deterministic MILP models (aggregated and detailed) and both models considered strategic planning. The number of discrete variables in detailed model was 53,660 compared to 1,400 in aggregated model. Because of this, the computational model required to solve the detailed model was quite large and, therefore, a bilevel decomposition was proposed to achieve a computational saving of 40%. The problem comprises the integration of ethanol and gasoline supply chains. Ethanol is one of the most promising alternatives to fossil fuels for the next decades, since it is produced from biomass. The problem considered two types of biomass (wood residues and switchgrass) that, after harvesting and drying, are transported to biorefineries, where ethanol and a blend of 85% ethanol and 15% gasoline called E85 are produced. Gasoline is produced at refineries and a part of it feeds ethanol plants and the other part is sent to gasoline distribution centers. The E85 blend is also sent to gasoline distribution centers and the blending of ethanol and gasoline (to produce E10 or E30) can happen in the retail center or at the distribution centers (Andersen, et al., 2013).

The difference between the models developed by Andersen, et al. (2013) is at the retail centers: the first model (aggregated) comprises the fuel demand per region without details of gas stations and the second (detailed) comprises the amount of gas stations per region. The transportation modes considered were truck, railway and pipeline. The objective function of both models was minimize the costs and it consisted in five terms: investment cost, processing and maintenance cost, transportation cost, storage cost and purchase cost of gasoline (in order to perform the blending). The results concluded that the aggregated model is an approximation of the detailed one, since the aggregated did not consider all the gas stations considered in detailed model. Therefore, the detailed model comprised the costs of these gas stations, making an increase of 18% in total cost (Andersen, et al., 2013).

Saad, et al. (2018) developed a deterministic and a simulation model. The deterministic LP model was developed at the strategic planning level in downstream segment with a one year planning horizon, while the simulation model was proposed at operational level, combining continous and discrete simulation techniques and it was focused in crude oil separation and distillation unit (midstrream segment). In the deterministic model, the objective function consisted in minimize the cost, considering the sum of the following costs: production and transportation of crude oil, production and transportation of the final product, storage and penalty for shortage or exceed of product, minus sales revenue. The constraints considered were transportation and storage constraints, material and demand balance and production yield (Saad, et al., 2018).

3.1.2. Strategic planning – Stochastic problem

A single paper was identified addressing the strategic problem at the PSC considering uncertainty. This is the paper by MirHassani & Noori (2011) that developed a two stage stochastic MILP with strategic planning considering a 12-month planning horizon. The decisions in first stage comprise the planning of capacity installments and they must be taken before determining the uncertainty. The decisions in second stage considers routes planning and they must be taken after considering the oil demand. The objective is to study the capacity expansion of an oil products distribution network in an uncertain environment and minimize the total cost over the planning horizon. The uncertainty considered was the product demand (MirHassani & Noori, 2011).

3.2. Tactical planning

Tactical planning comprises medium-term decisions such as inventory policies definition, material flows, transportation strategies and resources planning (Barbosa-Póvoa, 2014). In this area two papers were identified as relevant. Again as in the previous section also two groups of papers are here considered. The ones that addressed the problem as deterministic and the ones that considered the presence of uncertainty.

3.2.1. Tactical planning – Deterministic approaches

Ghaithan, et al. (2017) developed a multi-dimensional and multi-objective model in downstream segment of PSC. The model considered a medium-term planning horizon of 6 months. The tactical planning decisions that the model determines are flow volume of crude oil, oil products and gas products between each node, optimal processing plans, import and export volumes and allocation of local customers to bulk plants. The three objective function were cost minimization, revenue maximization and service level maximization. The model did not consider uncertainties and it was solved using the Improved Augmented ε-Constraint algorithm. Finally, a case study from Saudi Arabia was used to test and validate the model (Ghaithan, et al., 2017).

Furthermore, as OPEC countries are questioning about if reducing their oil production quotas would help to increase crude oil and petroleum products sales price, the sensitivity analysis is a matter of major importance. The results of model showed that if OPEC quota or oil production decreases and if price increases simultaneously, a higher total revenue would be obtained compared to a case with high OPEC quota and low price. Therefore, the model shows that in case of a decrease in oil price, the best strategy would imply in increasing the price to get higher returns. The sensitivity analysis was also performed regarding the domestic demand in Saudi Arabia and resulted in increase the local selling price, that, hence, would decrease the domestic demand and high revenue would be achieved. As Saudi Arabia has enough reserves and resources, the model also verifies that it is able to fulfill most of oil products demand with high value of service. Finally, it is suggested to expand the model by integrating upstream and downstream sectors or adding uncertainties such as oil price and oil demand (Ghaithan, et al., 2017).

3.2.2. Tactical planning – Stochastic approaches

Lima, et al. (2018) developed a multistage stochastic linear programming model in order to make decisions regarding refinery production planning, inventory management and distribution planning with a tactical planning. The decisions include transportation modes, material flows and import & export management in a discrete time scale. The model considered two sources of uncertainty: oil price and oil demand. The methodology autoregressive integrated moving average (ARIMA) that forecasts the uncertainty based on past data was used to deal effectively with the uncertainties. The objective function was to maximize the profit. Finally, the model was tested using a real case study of a multi-echelon, multi-transportation, multi-product and uni-entity Portuguese downstream oil supply chain.

3.3. Operational planning

Operational planning deals with decisions that have short-lasting effect, such as allocation of human resources, truck loading, scheduling and routing (Barbosa-Póvoa, 2014). In this area, three papers were identified as relevant and all of them addressed the problem as deterministic.

3.3.1. Operational planning – Deterministic approaches

Pinto et al. (2000) developed deterministic MILP and MINLP models with operational planning. The planning horizon was 3 days discretizes in 2-hours intervals. The first model was a non-convex mixed integer non-linear programming (MINLP) and, hence, there was no global solution ensured by conventional MINLP algorithms. Thus, a MILP model was derived from the first in order to be solved optimally. The objective function of the models was to maximize the profit and the objective was to show planning and scheduling applications for refinery operations, which are problems that can be efficiently represented by large-scale MIP optimization models. The model was validated using a real case from Brazilian PSC (Pinto, et al., 2000).

Neiro & Pinto (2004) developed a deterministic large-scale MINLP model that integrates the three segments of oil supply chain with operational planning. The problem considers a set of crude oil suppliers, refineries and distribution centers. The model should decide which oil types to select and their transportation plan, production levels and how to distribute the products and to manage the inventory along the planning horizon. The objective function is to maximize the profit by subtracting costs related to raw material, transportation, inventory and operation from product sales. The constraints are based on three classes of elements: processing units, storage tanks and pipelines. In this problem, pipelines distribute crude oil from petroleum terminals to refineries and oil products from refineries to intermediate terminals or directly to distribution centers. It is possible to apply this model to real problems and, therefore, it was validated using a case study from Petrobras in Brazilian PSC (Neiro & Pinto, 2004).

Ye et al. (2017) developed two MILP models in order to deal with the refined-oil shipping problem based on a real case from an oil company in China. The first model uses a time-slot concept under a continuous-time representation and the second uses a discrete-time representation and together these models unite their advantages: the continuous-time reduces binary variables and the discrete-time is a modelling approach that can fit in other scheduling problems with more complex operating rules. Moreover, no uncertainties were considered in these models. In this problem two types of refined-oil are considered: diesel and gasoline and 12 subtypes. It is considered only one starting place and 40 destination portals and the transportation mode includes only a fleet of ships of different sizes. At the beginning of each month, the demand for each oil subtype is announced by each of the portals and the time horizon to deliver the demanded oil subtype is one month. Each combinations of a destination portal with a demanded oil subtype is referred as a task. Therefore, in order to optimize the vessel scheduling, the objective was to minimize the shipping cost by combining tasks and dividing them into vessels of different sizes (Ye, et al., 2017).

3.4. Strategic and tactical planning

Models developed integrating strategic and tactical planning consider long and medium-term decisions, such as the structure of the supply chain and material flows, respectively (Barbosa-Póvoa, 2014). Several authors approached this problem but only ten main papers were considered relevant and were analysed below. This section can be divided in two main groups: the papers that addressed the problem as deterministic and the papers that considered the presence of uncertainty. In the first four papers were identified and in the latter six papers were identified.

3.4.1. Strategic and tactical planning – Deterministic approaches

Kim, et al. (2008) developed an integrated model of supply network and production planning for oil products with strategic and tactical planning. The decisions that the deterministic MILP model developed considered relocation of distribution centers and reduction of the distribution costs. Moreover, a MINLP model was developed by joining the MILP model with a non-linear production model. The objective function of both models was to maximize the profit. The model was validated using a real world example from South Korea including three refineries with four products. Three case studies were considered to test the model: separate planning of individual refineries, collaborative network planning by all the refineries and network integration among all the refineries. The results demonstrated that there were potential benefits in collaborative planning for production and distribution of oil products (in both single refinery and multiple refinery models). Moreover, results showed the importance of separately planning the supply network and production for each oil product in order to obtain the most efficient routes from the sources to the markets (Kim, et al., 2008).

Fernandes, et al. (2014) developed a deterministic MILP model with strategic and tactical planning. The model considers multiple companies, products, echelons, refineries and transportation modes. The decisions involve to determine the optimal network including: installation, closure and operation of storage depot locations, definition of storage capacity, individual costs and tariffs, planning of transporation modes and routes, allocation of volumes for crude oil, import, export, refinery production and depot transfers and customer fulfillment. The restrictions considered were satisfy customer demands and production, storage depot and transportation capacity. The objective function was to maximize the profit by subtracting costs of refinery margin, exportation, importation, inventory (crude, refinery, depot and retail), unsatisfied demand and transportation and storage depot tariffs from the sum of oil companies revenues, oil companies shared revenues in participated infrastructures, retail margin and entities participation in transportation operator margin and storage depot operator margin (Fernandes, et al., 2014).

Fernandes, et al. (2014) verified its model using a real-case of downstream PSC in Portugal. This model obtained higher profits compared to the model developed by Fernandes, et al. (2013), which considered individualistic operation. In large countries (such as Spain), there are single-entity PSC networks and in smaller countries (such as Portugal), there are multientity networks and the petroleum entities compete for the smaller market. The study concluded that although logistics costs and tariffs in multientity networks with individualistic strategies are higher than those in single-entity network, in a collaborative strategies environment the results are close to the more efficient single-entity (Fernandes, et al., 2014).

Kazemi & Szmerekovsky (2015) developed a deterministic MILP model coded in GAMS with strategical and tactical planning of the downstream Petroleum Supply Chain (PSC). Their objective was to minimize the fixed and distributing costs along refineries, distribution centers, transportation modes and demand nodes and to determine the optimal locations and capacities for the distribution centers, transportation mode selection (pipeline, waterway carriers, rail and truck), product allocation and transfer volumes. The strategic part concerns in determining distribution centers' locations and capacities and the tactical part in flow allocation and transportation modes. This research focused in the following fuel products: gasoline, diesel and jet fuel. Finally, a case study with real data from U.S. oil industry and transportation networks was presented (Kazemi & Szmerekovsky, 2015).

Another essential characteristic of the model developed by Kazemi & Szmerekovsky (2015) is that there was a comparison between the use in strategic planning of a multimodal transportation or a single-mode (pipeline), which is a specific case of the multimode model that considers only pipeline transportation. The analysis resulted in a cost increase of 2% using the pipeline-based planning and, therefore, it was concluded that it is critical to use multi-modal transportation to take cost-effective decisions in strategic planning (Kazemi & Szmerekovsky, 2015).

Fiorencio et al. (2015) developed a Decision Support System (DSS) in order to aid investment decisions and to optimize the distribution of the oil products. The DSS was based on a deterministic MILP model with strategic and tactical planning and two case studies were use in order to evaluate the model using real data from Brazilian PSC. The first case study compares two projects, which the first analyses the increase in the capacity of vessels and the second analyses the increase in the capacity of a pipeline between a maritime terminal and a distribution base. The second case study analyses an expansion project for a pipeline that supplies several distribution bases. The objective was to minimize costs considering the sum of five terms (investments, freight, holding, operation and demurrage costs) minus national commercialization income and international commercialization profit. The strategic planning manages investments to be made in logistics infrastructure such as storage and product-handling capacities for terminals and tactical planning manage issues such as modes of transportation and flow allocation. The authors also performed a sensitivity analysis of the Net Present Value (NPV) that accounts for investment costs in both case studies in order to aid the decision-making process. The first case study showed that the expansion of the vessels capacity together with the pipeline expansion resulted in an increase of NPV. Hence, both investments work well together. The second case study showed that if pipeline capacity was expanded, it would reduce transportation costs because it would require less transporation by trucks. However, NPV sensitivity analysis showed that each pipeline section has a different investment cost (Fiorencio, et al., 2015).

3.4.2. Strategic and tactical planning – Stochastic approaches

MirHassani (2008) developed a stochastic MILP model considering oil demand as an uncertainty and comprising strategic and tactical planning. The model considers pipelines, ships, railway and trucks as transportation modes for oil products. The objective function is to minimize the costs related to transferring oil products by each transportation mode, penalties for shortage and exceed and inventory cost. Moreover, the model should also calculate the minimum and maximum amount of each oil derivative that could be imported and exported and take care of the worst case regarding shortage. The model was solved using a real-life problem and the conclusion was that this model could be efficiently solved for realistic large-scale problems (MirHassani, 2008).

Oliveira & Hamacher (2012) developed a two-stage stochastic MILP in order to optimize the investment planning process of a logistics infrastructure of oil products distribution considering the demand levels as an uncertainty. The model considers issues of tactical planning to evaluate decisions of strategic nature and it uses the Sample Average Approximation (SAA) methodology in order to produce approximations of the optimal solution, since there are lots of possible scenarios. The objective function is to minimize the costs of investment, inventory, freight, operations, demurrage in marine terminals, commercialization and backlog. The model was validated using a real case of northern Brazil (Oliveira & Hamacher, 2012).

Tong, et al. (2014) developed a MILP model in order to deal with hydrocarbon biofuel supply chain design and production planning and used robust optimization to deal with the uncertainties considered, which were fuel demand (gasoline, diesel and jet fuel) and biomass availability. Both models resulted in a single Mixed-Integer Linear Fractional Programming (MILFP) model with strategic and tactical planning. The objective function was to minimize the functional-unit-based economic performance by dividing the annual cost by total biofuel sold to the customers. The supply chain design decisions involve location, size, number and technology selection of preconversion facilities and the planning decisions involve harvesting, production and distribution decisions. The model was tested using a real case considering the state of Illinois (US) (Tong, et al., 2014).

Oliveira, et al. (2014) developed a two-stage stochastic MILP model in order to deal with the investment planning problem based on stochastic Benders decomposition, considering the oil products demand as the source of uncertainty. The model involves strategic and tactical decisions, which the first regard the location of facilities such as terminals and distribution bases, capacities of storage and product-handling and construction or expansion of the transportation modes and the latter consists in flow allocation. The model's first stage determines the projects to implement and when and the second determines the best flow of products and inventory and supply levels. The objective function in both stages is to minimize the investment and logistics cost (Oliveira, et al., 2014).

Fernandes, et al. (2015) developed a stochastic MILP in order to design and plan the downstream PSC under uncertainty and considering strategic and tactical planning. The uncertainty considered is the products demand, the strategic decisions regard installation, sizing and operation of facilities, tariffs and the fair price strategic cost and the tactical decisions rergard inventory levels, products routing and periodic depot. The model is biobjective and its two objective functions are to maximize the Expected Net Present Value (ENPV) and to minimize the Conditional Value-at-Risk (CVaR). The model was validated using a real case of Portuguese PSC (Fernandes, et al., 2015).

Although Azadeh, et al. (2017) focused their work in upstream and midstream segments, it was also proposed to consider downstream segment in a single model, since the dual complication of distribution. Azadeh, et al. (2017) developed a multi-objective MINLP model with strategic and tactical planning. Long-term and mid-term decisions were integrated considering a planning horizon of 15 years discretized into 6-month periods. The two objective functions in the model were to maximize the profit using the net present value method (that is, divide net earning minus total depreciable capital by the interest during the period under analysis) and to minimize environmental threats using Eco indicator 99. The model consisted of making some decisions such as facilities location (wells, platforms, refineries, depots and external markets), establishment planning (this is, to determine, for example, when facilities will be established) and production, transportation and distributing planning. This model also considers upstream and midstream segments via green aspects. Fuzzy programming was used to deal with the following uncertainties: cost and production capacity of refined products and consumption rate of oil products. As the problem was so large, a unique meta-heuristics approach based on MOEA-D was developed to solve the problem, decomposing it into several sub problems. Finally, the model was verified using a real case in Persian Gulf (Azadeh, et al., 2017).

3.5. Tactical and operational planning

Tactical and operational planning combine these two levels of planning and involve a medium to short planning horizon, addressing activities such as transportation strategies and scheduling, respectively (Barbosa-Póvoa, 2014). In this section, five main papers were identified as relevant and were analyzed below. Three of them addressed the problem as deterministic and two as stochastic.

3.5.1. Tactical and operational planning – Deterministic approaches

Kuo & Chang (2008) developed a deterministic MILP model considering integration of two activities hierarchically linked: production planning and scheduling schemes for the refinery segment of PSC. The model involved both tactical and operational decisions. The tactical ones are considered higher-level decisions such as the amounts of crude oil to be acquired and production and inventory levels of several oil products, according to the market demands, which are planned over a medium-term horizon (months). The operational decisions are considered lower-level scheduling tasks, which includes determining the specific time that each unit must be operated to achieve the production goals. These decisions are planned over a short-term horizon (weeks). The objective function was profit maximization over a specified planning horizon given by the total revenue minus the total costs that includes raw materials, operation, transportation and inventory. The transportation modes considered were pipelines to transport process materials from one unit to another, tankers to import raw materials and intermediates and pipelines or trucks to deliver products and byproducts to domestic customers (Kuo & Chang, 2008).

Alabi & Castro (2009) developed a deterministic large primal three-blocks-angular LP model considering a planning horizon from 2 to 300 days, this is, both tactical and operational planning. The problem approached was the integrated refinery-planning (IRP) that can be divided into three sub-problems: crude oil supply, refining and product distribution. In order to simplify the model, energy balance was not considered (only mass balance). The objective function is to maximize the profit. However, the function was described as the minimization of a seven terms sum (cost of all crude consumed, refining operations, purchased materials, transportation and inventory of blending, product and storage tanks) minus total revenue. As the problem was too large to be solved, interior-point algorithms together with two decomposition techniques (Dantzig-Wolfe and block coordinate-descent) effectively approached it. The most effective approach for optimal and approximate feasible solutions was interior-points with block coordinate-descent (Alabi & Castro, 2009).

Guyonnet, et al. (2009) integrates oil procuring, refinery planning and product distribution in an integrated deterministic MINLP model with tactical and operational planning. Three models composes the integrated model, namely: crude oil unloading model, production planning model and distribution model. The objective function in each model was to maximize the profit. The crude oil unloading model considered the perceived revenue of crude sent to refinery, purchase cost of crude and safety stock penalties in its objective function. The production planning model considered total revenue minus costs (crude oil, intermediate commodities, storage and unsatisfied demands). The distribution model considered total amount of sales minus the transportation cost, the penalties incurred by a stock below the safety stock, and the unsatisfied demand. This paper concluded that it is possible to reach better results if the different parts of the refinery supply chain are integrated than if considers each part alone. The integrated model can ensure that the profit is optimize in the entire system and not only in subparts (Guyonnet, et al., 2009).

3.5.2. Tactical and operational planning – Stochastic approaches

Tong, et al. (2012) developed a two-stage stochastic MILP with tactical and operational planning approaching an optimal refinery planning problem under uncertainties, which were products demand and yield. The model uses the Conditional Value-at-Risk theory in order to deal with the uncertainties and risks (customer dissatisfaction and inventory violation). Moreover, the model used Markov Chains to perform the distribution of product yield uncertainty, which has achieved better results when compared with uniform distribution. The objective function was to minimize the costs regarding transporation, inventory, purchase, holding, changeover and penalty with customer dissatisfaction and inventory violation (Tong, et al., 2012).

Leiras, et al. (2013) developed two two-stage stochastic MILP models in order to plan a multisite refineries network considering different planning levels in each model (tactical and operational). The uncertainties considered in tactical planning are the oil price and products demand and in operational planning are oil supply and process unit capacity. The objective function in both models is to maximize the profit. The decisions in tactical planning comprise allocation of oil quantities to each refinery and production targets of products to each refinery. The decisions in the operational model comprise the material amount that should be processed at each time interval in each unit at each refinery. The models were validated using a real case of Brazilian industry (Leiras, et al., 2013).

3.6. Conclusion

This chapter main goal was to identify relevant papers that addressed the planning process in the PSC using optimization approaches. Within this, deterministic and stochastic approaches were considered. Twenty-four papers were considered as relevant and these were analyzed with some detail and their main characteristics summarized in Table 1.

From the performed analysis it is possible to conclude that there are some research gaps regarding the downstream segment of PSC that are still to be addressed. Namely it is important to look into the strategic and tactical planning considering the presence of uncertainties, where the treatment of real cases should be explored, as this allows the validation of the developed models.

Table 1. Summary of papers used in Literature Review.

Paper	Planning Level			Model	Objective function			Deterministic	Uncertainty	
	Strategic	Tactical	Operational		min Cost	max Profit	Other		Oil price	Oil demand
(Pinto, et al., 2000)			X	MILP and MINLP		X		X		
(Neiro & Pinto, 2004)			X	MINLP		X		X		
(MirHassani, 2008)	X	X		Stochastic MILP	X					X
(Kuo & Chang, 2008)		X	X	MILP		X		X		
(Kim, et al., 2008)	X	X		MILP and MINLP		X		X		
(Alabi & Castro, 2009)		X	X	MILP		X		X		
(Guyonnet, et al., 2009)		X	X	MINLP		X		X		
(MirHassani & Noori, 2011)	X			Two-stage stochastic MILP	X					X
(Oliveira & Hamacher, 2012)	X	X		Two-stage stochastic MILP	X					X
(Tong, et al., 2012)		X	X	Two-stage stochastic MILP	X					X
(Fernandes, et al., 2013)	X			MILP		X		X		
(Andersen, et al., 2013)	X			2 MILP models	X			X		
(Leiras, et al., 2013)		X	X	2 Two-stage stochastic MILP		X			X	X
(Fernandes, et al., 2014)	X	X		MILP		X		X		
(Tong, et al., 2014)	X	X		MILFP	X					X
(Oliveira, et al., 2014)	X	X		Two-stage stochastic MILP	X					X
(Kazemi & Szmerekovsky, 2015)	X	X		MILP	X			X		
(Fiorencio, et al., 2015)	X	X		MILP	X			X		
(Fernandes, et al., 2015)	X	X		Stochastic MILP			X		X	X
(Azadeh, et al., 2017)	X	X		Multi-objective MINLP		X	X		X	X
(Ye, et al., 2017)			X	Two MILP models	X			X		
(Ghaithan, et al., 2017)		X		Multi-objective model	X		X	X		
(Lima, et al., 2018)		X		Multistage stochastic LP model		X			X	X
(Saad, et al., 2018)	X			LP	X			X		

Chapter 4 – Problem Definition, Model Formulation and Validation

The aim of this chapter is to characterize the problem studied in this Master thesis, to present the mathematical model developed and to validate the model. The chapter is divided into six sections: Section 4.1 is responsible for defining and characterizing the problem to be developed; Section 4.2 describes the mathematical model developed; Section 4.3 brings the main contributions of the model developed in comparison with the base model; Section 4.4 describes the illustrative case study; Section 4.5 analyses the results obtained after validating the model using the illustrative case study; and Section 4.6 concludes the chapter.

4.1. Problem Definition

As identified in the previous chapter there are some space for research in the downstream supply chain considered the strategic-tactical decision levels. This is the focus of this Master thesis, where the aim was to develop a MILP mathematical model that supports the definition of a distribution strategy for supplying markets that may span over more than one country. This later feature is important since in different countries, different public policies may apply to the distribution operation and these must be accounted when managing the supply chain.

Knowing that strategic decisions comprise the determination of locations and capacities of storage, terminals and distribution bases and planning of transportation modes; and that tactical decisions look into aspects such as the planning of transportation modes, flows' allocation and evaluation of the need to import products or the opportunity to export them, the problem addressed can be generically described as follows:

Given a downstream PSC, in which one company fully manages a set of oil products from a set of refineries to supply a set of locations according to their demands through a set of depots using possible and available transportation modes.

Determine the design and planning of the supply chain, which consists on the installation and and/or closure of facilities while considering its required capacity and how these are going to be operated at a planning level – which transportation modes and routes to use, what are the material flows, refinery productions and import or export of materials.

Subject to customer demands, oil products yield, material balance and storage and transportation capacity constraints.

So as to minimize the costs regarding opening new distribution centers and distribution, which are mainly related to transportation, inventory, import and export.

In order to solve the problem defined, a mathematical model was developed and it will be approached in the next sections.

4.2. Mathematical model

After defining the problem, the following step was to formulate a mathematical model in order to solve it. The model was based on that developed by Kazemi & Szmerekovsky (2015), which addresses strategic and tactical decisions (such as determining optimal location and capacities for distribution centers, selection of transportation modes, determining flow allocation, etc.) considering multiple products while minimize the fixed and distributing costs.

In order to formulate the MILP mathematical model, we consider two countries A and B, that are commercial partners, and the model was developed under country A's perspective. This is, the objective of the problem is to design and plan the downstream petroleum supply chain minimizing country A's costs. It is also possible to consider more than two countries, this is a more generic model considering a country of origin A and a set B of countries, and all data regarding the other countries considered would replace country B's.

The case study in Iberia illustrates well the problem proposed, in which Portugal is represented as country A and Spain as country B, because the country that Portugal imports and exports the largest amount of oil derivatives is from/to Spain (Autoridade da Concorrência, 2018).

4.2.1. Sets, subsets and parameters

It was considered a set I of refineries i with capacities S_i, subdivided in subset A of refineries a located in country A and in subset B of refineries b located in country B; and a set J of distribution centers (storage depots) j, subdivided in subset N of possible new depots n to be opened in country A and in subset H of existent depots h in country A. Each of the possible new depots n are associated with a fixed cost f_n to open each of them and a cost per unit of capacity β_n.

The model also includes a set P of oil products p; a set U of customer nodes u with annual demands $D_{p,u}$ for each product p, subdivided in subset K of customer nodes k located in country A and in subset W of customer nodes w in country B; and a set R of transportation modes r, which transport products p with cost per unit of product, $C_{p,a,j,r}$, from refineries a to depots j, transport products p with cost per unit of product, $T_{p,j,k,r}$, from depots j to customer nodes k and transport imported products p from refineries b to refineries a with cost per unit of product, $TIMP_{p,b,a,r}$. In this study, four transportation modes are considered: pipelines, barge, rail and truck.

Other parameters considered were: the price per unit of product p, $PIMP_{p,b,a,r}$, transported by transportation mode r, that refinery a must pay to import product p from refinery b; the price per unit of product p, $PEXP_{p,a,b}$, that refinery a charges to export product p to refinery b; the fraction $\alpha_{b,p}$ of refinery b capacity used to produce product p; and the annual maximum capacity of transportation: from refinery a to depot j using transportation mode r, $QRD_{a,j,r}$, from depot j to customer node k using transportation mode r, $QDC_{j,k,r}$, and from refinery b to refinery a using transportation mode r, $QRR_{a,b,r}$.

Table 2 summarizes all the sets, subsets and parameters used in the mathematical model developed. $QRD_{a,j,r}$, $QDC_{j,k,r}$ and $QRR_{a,b,r}$ are defined as 0 if a pipeline or rail are not installed in the route considered or if the route is not able to consider maritime transportation.

Table 2. Sets, subsets and parameters used in the mathematical model

Sets	
$i \in I$	Set of refineries, i = 1, 2, ..., I
$j \in J$	Set of depots, j = 1, 2, …, J
$p \in P$	Set of products, p = 1, 2, …, P
$r \in R$	Set of transportation modes, r = truck, barge, rail, pipeline
$u \in U$	Set of customer demand nodes, u = 1, 2, …, U
Subsets	
$a \in A \subseteq I$	Set of refineries a in country A
$b \in B \subseteq I$	Set of refineries b in country B
$n \in N \subseteq J$	Set of possible new depots locations n in country A
$h \in H \subseteq J$	Set of depots h in country A
$k \in K \subseteq U$	Set of customer demand nodes k in country A
$w \in W \subseteq U$	Set of customer demand nodes w in country B
Parameters	
$C_{p,a,j,r}$	Transportation cost per unit of product p from refinery a to depot j via transportation mode r
$D_{p,u}$	Annual demand for product p at customer node u
f_n	Fixed cost of opening the distribution center n
M	A large number (10^9) used as an upper limit for variable V_n
$PEXP_{p,a,b}$	Price per unit of product p sold by refinery a to refinery b
$PIMP_{p,b,a,r}$	Price per unit of product p sold by refinery b to refinery a transported by transportation mode r
$QDC_{j,k,r}$	Annual maximum capacity of transportation from depot j to demand point k using transportation mode r
$QRD_{a,j,r}$	Annual maximum capacity of transportation from refinery a to depot j using transportation mode r
$QRR_{b,a,r}$	Annual maximum capacity of transportation from refinery b to refinery a using transportation mode r
S_i	Capacity of refinery i (tons of products per year)
$T_{p,j,k,r}$	Transportation cost per unit of product p from depot j to demand point k via transportation mode r
$TIMP_{p,b,a,r}$	Transportation cost per unit of product p from refinery b to refinery a via transportation mode r
$\alpha_{b,p}$	Refinery b capacity utilization per product p
β_n	Cost per unit of capacity at distribution center n
$\Psi_{p,a}$	Maximum fraction of product p that is reasonable to be produced by each refinery a

4.2.2. Variables

As the model developed is a MILP, two types of decision variables are considered: binary and continuous.

Binary is an integer type of variable that can assume only two values: 0 or 1. The binary variable considered is X_n, which assumes the value of 1 if the depot *n* is opened or 0, otherwise.

The continuous variables here can be real or positive. Real is a continuous type of variable that can assume any real number as its value. Therefore, the objective variable *z*, that represents the total costs to be minimized, is the real variable considered in this model.

If a continuous variable can only assume any value higher than or equal to 0 is here defined as non-negative variable. Six non-negative variables were defined in this model: the fraction $\gamma_{a,p}$ of refinery *a* capacity that should be used to produce product *p*; the ideal capacity V_n of depot *n*; the amounts of product *p* transported with mode *r*: shipped from refinery *a* to depot *j*, $Y_{p,a,j,r}$, shipped from depot *j* to customer node *k*, $Z_{p,j,k,r}$, imported from refinery *b* to refinery *a*, $IMP_{p,b,a,r}$, and exported from refinery *a* to refinery *b*, $EXP_{p,a,b}$, independent of transportation mode *r* used, as the importing country (in this case, country B) is responsible for transportation. These variables are defined as non-negative instead of real in order to satisfy non-negativity constraints and the reason why all these six variables must not be negative is that it would be meaningless since they represent fractions, capacities or amounts. Table 3 summarizes the variables considered in the mathematical model developed.

Table 3. Variables used in the mathematical model

Binary variable	
X_n	1, if the depot n is opened; 0, otherwise
Continuous variables	
z	Objective variable: total costs
$\gamma_{a,p}$	Refinery a capacity utilization per product p
V_n	Capacity of distribution center n (tons per year)
$Y_{p,a,j,r}$	Amount of product p shipped from refinery a to depot j with mode r
$Z_{p,j,k,r}$	Amount of product p shipped from depot j to demand point k with mode r
$IMP_{p,b,a,r}$	Amount of product p imported from refinery b to refinery a with mode r
$EXP_{p,a,b}$	Amount of product p exported by refinery a to refinery b

4.2.3. Objective function

The objective function (1) minimizes the total cost for country A of opening distribution centers, shipping products from its refineries to the demand nodes, import products from country B and export to country B.

$$
\begin{aligned}
z = \min \sum_{n \in N} f_n X_n + \sum_{n \in N} V_n \beta_n + \sum_{p \in P} \sum_{a \in A} \sum_{j \in J} \sum_{r \in R} C_{pajr} Y_{pajr} + \sum_{p \in P} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} T_{pjkr} Z_{pjkr} \\
+ \sum_{p \in P} \sum_{b \in B} \sum_{a \in A} \sum_{r \in R} TIMP_{pbar} IMP_{pbar} + \sum_{p \in P} \sum_{b \in B} \sum_{a \in A} \sum_{r \in R} PIMP_{pbar} IMP_{pbar} \\
- \sum_{p \in P} \sum_{a \in A} \sum_{b \in B} PEXP_{pab} EXP_{pab}
\end{aligned}
\quad (1)
$$

The first term represents the total fixed cost of opening distribution centers and the second term is the total variable cost of opening distribution centers, associated with its capacity. The third term indicates the cost of transporting products from refineries in country A to depots and the fourth represents the cost of transporting products from depots to customer nodes. The fifth term states the cost of transporting imported products from country B to country A. The sixth term comprises the price paid by country A to country B for the products imported and the seventh term consists on the price paid by country B to country A for the products exported by country A. As the seventh term represents a revenue of country A, it is negative.

Therefore, the mathematical model decisions determined in order to minimize country A's costs are:

- To open or not a distribution center in country A;
- The optimum amount of each product that each refinery in country A should produce;
- The amount of each product that should be transported by each mode from each refinery in country A to each distribution center in country A;
- The amount of each product hat should be transported by each mode from each distribution center in country A to each customer node in country A;
- The amount of each imported product that should be transported by each mode from each refinery in country B to each refinery in country A;
- The amount of each product that each refinery in country A should import from each refinery in country B;
- The amount of each product that each refinery in country A should export to each refinery in country B.

4.2.4. Constraints

The model developed is subjected to a set of constraints that translate the problem characteristics.

$$
\sum_{j \in J} \sum_{r \in R} Z_{pjkr} = D_{pk} \quad \forall p \in P, \forall k \in K \quad (2)
$$

$$V_n \leq MX_n \; \forall n \in N \tag{3}$$

$$\sum_{b\in B} S_b\alpha_{bp} + \sum_{a\in A}\sum_{b\in B} EXP_{pab} - \sum_{b\in B}\sum_{a\in A}\sum_{r\in R} IMP_{pbar} \;\; \geq \;\; \sum_{w\in W} D_{pw} \; \forall p \in P \tag{4}$$

$$1.10\sum_{p\in P}\sum_{k\in K}\sum_{r\in R} Z_{pnkr} \;\; \leq V_n \;\; \forall n \in N \tag{5}$$

$$\sum_{a\in A}\sum_{r\in R} Y_{pajr} - \sum_{k\in K}\sum_{r\in R} Z_{pjkr} \;\; = 0 \;\; \forall j \in J, \forall p \in P \tag{6}$$

$$\sum_{j\in J}\sum_{r\in R} Y_{pajr} \leq S_a\gamma_{ap} + \sum_{b\in B}\sum_{r\in R} IMP_{pbar} \;\; - \sum_{b\in B} EXP_{pab} \; \forall p \in P, \forall a \in A \tag{7}$$

$$S_b\alpha_{bp} \;\; \geq \sum_{a\in A}\sum_{r\in R} IMP_{pbar} \;\; \forall p \in P, \forall b \in B \tag{8}$$

$$S_a\gamma_{ap} \;\; \geq \sum_{b\in B} EXP_{pab} \;\; \forall p \in P, \forall a \in A \tag{9}$$

$$\sum_{p\in P}\sum_{a\in A}\sum_{j\in J} Y_{pajr} \;\; \leq \sum_{a\in A}\sum_{j\in J} QRD_{ajr} \; \forall r \in R \tag{10}$$

$$\sum_{p\in P}\sum_{j\in J}\sum_{k\in K} Z_{pjkr} \;\; \leq \sum_{j\in J}\sum_{k\in K} QDC_{jkr} \; \forall r \in R \tag{11}$$

$$\sum_{p\in P}\sum_{b\in B}\sum_{a\in A} IMP_{pbar} \;\; \leq \sum_{b\in B}\sum_{a\in A} QRR_{bar} \; \forall r \in R \tag{12}$$

$$\sum_{p\in P} \gamma_{ap} \leq 1 \; \forall a \in A \tag{13}$$

$$\gamma_{ap} \leq \psi_{pa} \; \forall a \in A, \forall p \in P \tag{14}$$

Constraint (2) guarantees that the demand for each product in each customer node in country A is satisfied by the amount of products that arrives to final customers in country A from the distribution centers.

Constraint (3) aims to limit the capacity of each distribution center that is opened and to ensure that no capacity is going to be assigned to a distribution center that will not be opened.

Constraint (4) states that the amount of each product produced by country B's refineries, plus the amount of each product that country B import from country A, minus the amount of each product that country B exports to country A, must satisfy (which means that it must be greater than) country B's demand for each product.

Constraint (5) ensures that the capacity of each new depot must be higher than the amount of products that flows through this depot. The factor 1.10 that multiplies the left side of the equation aims to guarantee that the depot can handle up to a 10% increase in the demand.

Constraint (6) is a mass balance constraint. It states that all of the amount that arrive in a depot from a refinery will be transported from this depot to each customer node.

Constraint (7) ensures that the amount of each product produced and imported by refineries in country A, minus the amount of each product exported by country A, must satisfy the amount that is transported to refineries to depots.

Constraint (8) indicates that the amount of each product that a refinery in country B can produce must be higher than the amount of the same product that it exports.

Constraint (9) indicates that the amount of each product that a refinery in country A can produce must be higher than the amount of the same product that it exports.

Constraint (10) ensures that the total amount of products transported by each mode from refinery *a* to depot *j* does not exceed the mode's maximum capacity.

Constraint (11) ensures that the total amount of products transported by each mode from depot *j* to customer node *k* does not exceed the mode's maximum capacity.

Constraint (12) ensures that the total amount of imported products transported by each mode from refinery *b* to refinery *a* does not exceed the mode's maximum capacity.

Constraint (13) states that in each refinery the sum of refinery capacity utilization per product must be equal or less than 1, as $\gamma_{a,p}$ represents the percentage of total refinery capacity used to produce a product.

Constraint (14) states the maximum reasonable fraction of product p that should be produced by each refinery a.

4.3. Main contributions of the present developed model

As the model developed was based on Kazemi & Szmerekovsky (2015) – base model, it is important to analyse both models and emphasize the main contributions of the model developed in comparison with the base one.

Firstly, the model developed creates a distribution strategy that spans over more than one country, while Kazemi & Szmerekovsky (2015) considered the distribution in a single country. Therefore, this model incorporates costs regarding import and export that were not considered in the previous model.

Another point is that Kazemi & Szmerekovsky (2015) did not limit the transportation mode selection. However, this model establishes the annual maximum capacity of each transportation mode represented by the parameters $QRD_{a,j,r}$, $QDC_{j,k,r}$ and $QRR_{b,a,r}$. Moreover, these parameters are declared 0 when a route is infeasible, limiting the selection of a pipeline when it is not built or the selection of barge if a port is not available in the location.

Furthermore, the model developed can define the optimal fractions of each product that each refinery should produce. In order to better fit the model to the reality, the parameter $\Psi_{p,a}$ was established to limit to a reasonable value the maximum fraction of each product to be produced. Unfortunately, it is not possible to convert 100% of the crude oil in gasoline.

Regarding to the distribution centers, Kazemi & Szmerekovsky (2015) only analyses potential new depots and therefore, does not consider the depots that are already opened in its network. On the other hand, the model developed considers the existent distribution center and also makes the decision of opening or not a distribution center in a determined location.

Finally, another important feature of the model is versatility. It is possible to analyse the decision of building a pipeline between two nodes in a simple manner. In order to do this, a new depot should be supposed in the same location of the depot that the new pipeline starts or ends. The fixed cost of this new depot is actually the total cost of the pipeline in question and the variable cost is null. Then, the pipeline distance between the depot and the refinery or customer node is defined. After that, the model will decide to open or not this fictional new depot and only if it is decided to be opened, the pipeline will be considered.

An important observation about the situation of deciding or not to build a pipeline in an existent depot is that all the possible and available routes through this depot must also be assigned to the fictional depot, resulting in two equal routes with the same annual maximum capacity. Therefore, a constraint must be created to define that the sum of two equal routes must be less than the annual maximum capacity assigned to the original route.

4.4. Illustrative case study

Before applying a real case to the model, it is important to validate it using an illustrative case. The reason why an illustrative case was used in first place is that it is very smaller than the real case and, therefore, it was easier to check for mistakes and if the model was working properly.

The illustrative case study comprises two countries called Country A and Country B. Country A has two refineries i1 and i2 and Country B has only refinery i3. Country A has one distribution center j1 and it is evaluating to build a distribution center j2 or/and j3. There are three customer demand nodes (u1, u2 and u3) and one airport (uair1) in Country A. There is only one customer demand node (u4) and one airport (uair2) in Country B. The illustrative case is represented in a map below (see Figure 5).

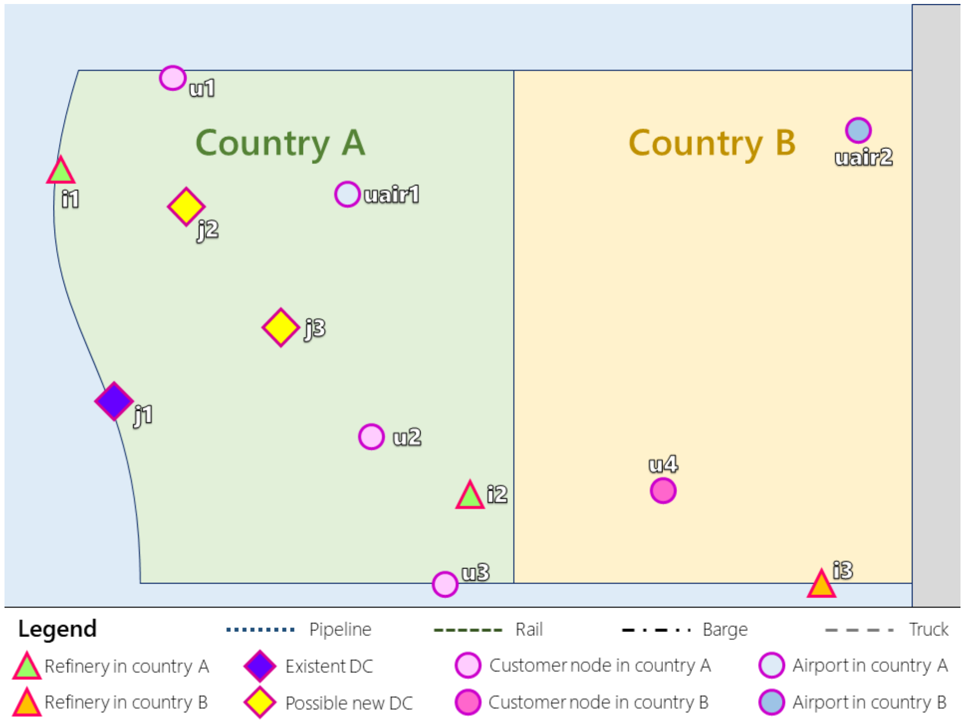

Figure 5. Map of the illustrative case.

After that, the routes were defined considering available transportation modes between: refineries in country A and distribution centers; distribution centers and customer nodes; and refineries in country A and country B. The illustrative case considers four transportation modes: pipeline, barge, rail and truck. Figure 6 show the available routes in the map of the illustrative case.

Figure 6. Available routes in illustrative case.

Moreover, besides deciding to open or not the distribution centers j2 and j3, the mathematical model also decides, if one of these distribution centers is opened, to build a pipeline between distribution center j2 and refinery i2 or between distribution center j3 and refinery i1 (see Figure 7).

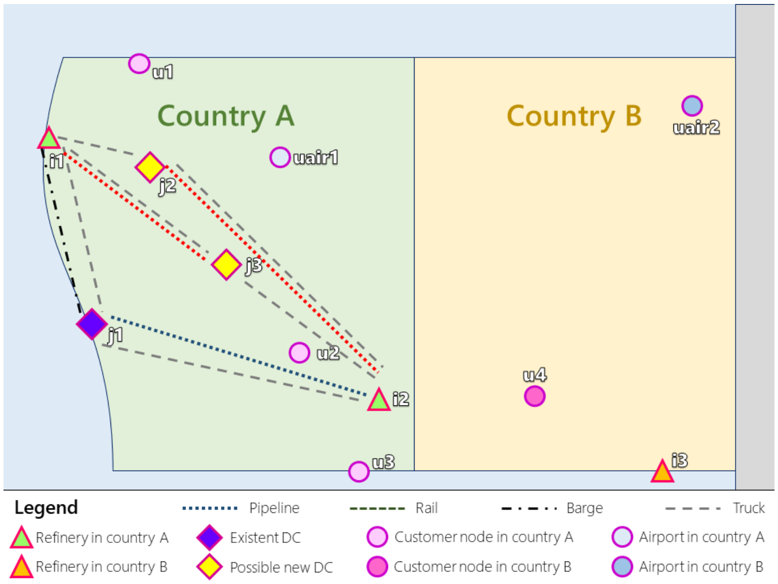

Figure 7. Pipelines (in red) to be built or not.

After defining the routes of each transportation mode between two nodes, values were assigned to these routes and to the annual maximum capacity when rail or pipeline was an available transportation mode. The data regarding the distances by each transportation mode is available at Table 4, Table 6 and Table 8 and each transportation mode annual maximum capacities are available at Table 5, Table 7 and Table 9.

The illustrative case considers that the three refineries considered produce three products: gasoline, diesel and jet fuel. Table 10 shows the capacity of each refinery and Table 11 shows the fraction of its total capacity that is used to produce each of the three products. It is important to say that Table 11 only presents data regarding the refinery in Country B because the mathematical model determines this data regarding the refineries in Country A. Table 12 shows the maximum fraction of the total capacity of a refinery in Country A that can be used to produce a product p. Table 13 presents the annual demand in each customer node for each oil product.

Finally, all the costs were established in the illustrative case. The transportation costs considered were the same of Kazemi & Szmerekovsky (2015) and they are available at Table 14. As the transportation costs were presented in Kazemi & Szmerekovsky (2015) in USD/ton-mile, the same units were considered in the illustrative case study. The price to import one m^3 of any product was considered as US$1,200 and the price to export one m^3 of any product was considered as US$1,000. The fixed cost of opening depot j2 was US$10,000,000 and depot j3 was US$7,000,000. The variable costs of opening depot j2 was considered as US$1,000 per m^3 of capacity and depot j3 as US$10.

Table 4. Distance in miles between refineries and depots in Country A

Distance refineries country A and depots (miles)									
	via truck			via pipeline				via barge	
	j1	j2	j3		j1	j2	j3		j1
i1	150	50	150	i1			90	i1	140
i2	200	200	150	i2	160	150			

Table 5. Annual maximum transportation capacity between refineries and depots in Country A

QRD Annual maximum capacity (m^3/year)							
Truck				barge			
	j1	j2	j3		j1	j2	j3
i1	-	-	-	i1	-	0	0
i2	-	-	-	i2	0	0	0
Pipeline				rail			
	j1	j2	j3		j1	j2	j3
i1	0	0	4000000	i1	0	0	0
i2	4000000	4000000	0	i2	0	0	0

Table 6. Distance in miles between depots and customer nodes in Country A

Distance depots and customer nodes in country A (miles)									
	via truck				via barge			via rail	
	u1	u2	u3	uair1		u1	u3		u2
j1	180	150	180	170	j1	230	250	j1	135
j2	50	160	250	70					
j3	150	50	150	60					

Table 7. Annual maximum transportation capacity between depots and customer nodes in Country A

QDC Annual maximum capacity (m^3/year)									
truck					barge				
	u1	u2	u3	uair1		u1	u2	u3	uair1
j1	-	-	-	-	j1	-	0	-	0
j2	-	-	-	-	j2	0	0	0	0
j3	-	-	-	-	j3	0	0	0	0
pipeline					rail				
	u1	u2	u3	uair1		u1	u2	u3	uair1
j1	0	0	0	0	j1	0	4000000	0	0
j2	0	0	0	0	j2	0	0	0	0
j3	0	0	0	0	j3	0	0	0	0

Table 8. Distance in miles between refineries in Country A and refineries in Country B

Distance refineries in country A and refineries in country B (miles)		
	via truck	via barge
	i3	i3
i1	500	750
i2	200	

Table 9. Annual maximum transportation capacity between refineries in Country A and refineries in Country B

QRR Annual maximum capacity (m^3/year)				
	truck	barge	pipeline	rail
	i3	i3	i3	i3
i1	-	-	0	0
i2	-	0	0	0

Table 10. Annual refining capacity of each refinery i

Capacity of refineries i (m^3/year)	
	S_i
i1	20000000
i2	8000000
i3	70000000

Table 11. Fraction of total refinery capacity used to produce each product p

$\alpha_{b,p}$				
	gasoline	diesel	jetfuel	other
i3	0.2	0.4	0.3	0.1

Table 12. Maximum fraction of product p that is reasonable to be produced by each refinery in Country A

Maximum reasonable amount ($\psi_{a,p}$)			
	gasoline	diesel	jetfuel
i1	0.25	0.5	0.2
i2	0.25	0.5	0.2

Table 13. Annual demand for each product p at demand nodes u

Annual demand for product p at demand node u (m^3/year)			
	Gasoline	Diesel	Jet fuel
u1	3000000	6000000	0
u2	2000000	3000000	0
u3	2500000	4000000	0
u4	10000000	17000000	0
uair1	0	0	9000000
uair2	0	0	14000000

Table 14. Transportation costs considered in illustrative case study

Transportation costs (USD/ton-mile)	
	C,T,TIMP
pipeline	0.0049
barge	0.01
rail	0.07
truck	0.18

After assigning all the data, the illustrative case was tested on GAMS and the results obtained are available in next section.

4.5. Illustrative case results

The model considering the illustrative case study (Illustrative Model 1) was implemented in GAMS programming language and solved using the solver CPLEX in a personal computer Intel® Core i3-4030U with 1.90GHz and 4 GB RAM memory. The model has 64 equations and 257 single variables, of which 2 are discrete. The execution time was 0.031 CPU seconds.

The solution obtained by the model (variable *z*) was a total minimum annual cost of US$4,077,935,800 for Country A. In order to obtain this minimum cost, the strategic decisions made by the model was that Country A should open the distribution center j3 with a total capacity of 5,940,000 m^3 and build the pipeline between the refinery i1 and the DC j3.

The tactical decisions made by the model comprises the variables γ, Y, Z, IMP and EXP. The variable γ, which is the fraction of each product p that each refinery in Country A should produce, achieved the maximum reasonable value ψ established for all refineries and products (see Table 12). Variable Y is the amount of each product p that should be transported by transportation mode r from refinery a to distribution center j and the values obtained are available at Table 15. Variable Z is the amount of each product p that should be transported by transportation mode r from distribution center j to customer nodes k and the values obtained are available at Table 16. The values obtained to variable IMP were that refinery i1 in Country A should import via barge 500,000 m^3 of gasoline and

3,400,000 m^3 of jet fuel from refinery i3 in Country B annualy. Furthermore, the refinery i2 in Country A should export to refinery i3 in Country B 1,000,000 m^3 of diesel annualy (variable EXP).

Table 15. Illustrative case study results for variable Y

Variable Y (m^3/year)									
gasoline			Diesel			jet fuel			
	pipeline	barge		pipeline	barge		pipeline		barge
	j1	j1		j1	j1		j1	j3	j1
i1		5500000	i1		10000000	i1		5400000	2000000
i2	2000000		i2	3000000		i2	1600000		

Table 16. Illustrative case study results for variable Z

Variable Z (m^3/year)										
Gasoline					diesel				jet fuel	
	truck	rail	Barge			rail	barge			truck
	u2	u2	u1	u3		u2	u1	u3		uair1
j1	1000000	1000000	3000000	2500000	j1	3000000	6000000	4000000	j1	3600000
j3					j3				j3	5400000

In order to attest the efficiency of the model, the illustrative case was tested without considering the possibility of opening DCs j2 and j3 and building the pipelines (Illustrative Model 2). It means that the decisions made by this second model were only the tactical ones. The solution obtained by this second model (variable *z*) was a total minimum annual cost of US$4,123,018,400 for Country A, this is 1.1% higher than the previous model that integrates strategical and tactical decisions. The values obtained for the other variables are available at Appendix A.

Although an increase of 1.1% in total cost may seem irrelevant, the costs in oil industry are very high, as said before. Hence, it means that considering only the tactical decisions, it would result in an increase of 45 million USD, what numerically attest that integrating decision-planning levels can achieve better solutions.

Furthermore, in a long-term planning horizon the results can be more expressive. In order to make this analysis, the refining capacities of each refinery, the annual demands and the maximum capacity of each transportation mode were multiplied by 5 and 10 and the Illustrative Models 1 and 2 were implemented with these new values. When the values above mentioned are multiplied by 5, a 5-year planning horizon is considered and when they are multiplied by ten, a 10-year planning horizon is considered. The results obtained by the objective function in these models are available below at Table 17 and the comparison of the statistics of both models in all planning horizons analyzed (1, 5 and 10 years) are available at Table 18.

Table 17. Analysis in a long-term planning horizon

Long-term planning horizon analysis			
	Planning Horizon		
	1 year	5 years	10 years
	z	*z*	*z*
Illustrative Model 1	4,077,935,800.00	20,361,700,000.00	40,716,400,000.00
Illustrative Model 2	4,123,018,400.00	20,615,100,000.00	41,230,200,000.00
Percentage increase	1.11%	1.24%	1.26%
Absolute increase	45 million	253 million	513 million

Table 18. Performance results for Illustrative case study

		Equations	Single Variables	Discrete Variables	Objective (USD)	CPU (s)
Illustrative Model 1	1 year	64	257	2	4.077×10^{9}	0.031
	5 years	64	257	2	2.036×10^{10}	0.031
	10 years	64	257	2	4.072×10^{10}	0.031
Illustrative Model 2	1 year	64	257	2	4.123×10^{9}	0.031
	5 years	64	257	2	2.062×10^{10}	0.015
	10 years	64	257	2	4.123×10^{10}	0.032

The values in Table 17 helps to express the importance of strategic planning. Without investing in opening depot j3 and building the pipeline between refinery i1 and depot j3, it would cost 45 million extra to Country A in a year, 253 million in 5 years and 513 million in 10 years. Furthermore, even considering a 10-year planning horizon, the model does not recommend opening the depot j2 and building the pipeline between refinery i2 and depot j2. It is important to say that the model proposed does not correspond to the reality, it only represents it and suggest a decision to be made through an economic point of view and according to the given parameters.

Another observation regarding the model is that it considers that after the investment to open a depot and/or build a pipeline is made, the depot and/or the pipeline is/are already there available to be used. Therefore, a suggestion is to implement the work-time to build these facilities in future models.

Analysing the results obtained, it is possible to see that the model achieved the objectives proposed. The model integrates the strategic and tactical decision-planning levels and make the optimal decisions in order to minimize the costs. The strategic decisions comprise opening or not a depot and installing or not a pipeline. On the other hand, the tactical decisions comprise the assignment of the optimum material flow through each transportation mode, the optimum amount to import (and the transportation mode to carry the imports) and the optimum amount to export. Furthermore, it was possible to state that better solutions are obtained when the planning levels are integrated, in this case, investing in the structure and changing it (strategical level), brings new possibilities for material flow in tactical level and saves money in the long term planning horizon.

However, an important observation is that the model does not prioritize a product to the detriment of others when considering a determined transportation mode. This is an essential matter when dealing with jet fuel, as it can be easily contaminated and, therefore, it should be primarily transported by pipelines and train wagons.

Therefore, a suggestion for further works is to incorporate a feature that prioritizes the transportation of jet fuel in pipelines and train wagons, in order to avoid contamination.

4.6. Conclusion

This chapter aimed at defining and charaterizing the problem to be solved, describing the mathematical model developed, which is to create a distribution strategy for supplying markets that may span over more than one country, and providing the validation of the model. The model is based on Kazemi & Szmerekovsky (2015) and minimizes the cost while it makes decisions regarding opening new distribution centers, the optimum amount of product that each refinery should produce and distribution of these products (which comprises transportation, import and export costs).

Furthermore, this chapter emphasizes the features added in the model developed and the main contributions that they bring in comparison with the previous model.

After developing the mathematical model, it was important to validate it using an illustrative case in order to check for mistakes. The validation is essential to assess the efficiency of the model developed. (Kazemi & Szmerekovsky, 2015). It is important to say that all data presented regarding the illustrative case study (except for the transportation costs) was made up and has no commitment to the reality. After validation, a real case of Portuguese PSC was applied to the model, in order to demonstrate the potential of the model, which is described in next chapter.

Chapter 5 – Case study

These chapter goals are to present the real case study that was applied to the model developed in order to demonstrate its potential and to analyze the results obtained. Section 5.1 describes the real case and it is developed in two subsections, as the real case considers two countries; Subsection 5.1.1 presents the Portuguese downstream oil supply chain, which is the first part of case study to be used in order to validate the mathematical model; Subsection 5.1.2 presents the Iberian market, which is the second part of the case study; Section 5.2 presents the Iberia database and its sources; Section 5.3 analyses the results obtained after applying the real case to the model; Section 5.4 presents suggestions for improvement for further works; and Section 5.5 concludes the chapter.

5.1. Real case study

In order to show the model applicability, this is now applied to a real case that aims to develop a distribution strategy for supplying Iberia with oil products produced by a single company in Portugal while minimizing the costs for Portugal.

5.1.1. Portuguese downstream oil supply chain

As mentioned the case study that was used in the thesis considers the Iberian market with oil products produced in Portuguese refineries. The oil products to be considered are gasoline 95, gasoline 98, gas oil (diesel) and jet fuel. At first, the model will not consider uncertainties.

In Portugal there are two oil refineries (Matosinhos and Sines) managed by a single company and 278 local markets (Portuguese cities) in Portuguese network. In the model, the local markets were simplified to 18, considering only the capital city of each Portuguese district as a demand node. The transportation modes used in Portuguese PSC are pipelines, maritime, railway and road. Sines and Matosinhos produce eight different oil products: jet fuel (A1), biodiesel (B5), propane (C3), butane (C4), fuel oil (FU), gas oil (GO), gasoline 95 (U5) and gasoline 98 (U8). (Lima, 2018). There are thirteen storage depots in Portugal. (Autoridade da Concorrência, 2018). However, the single company considered in the model owns only six depots and these are the ones that were considered in the case study. Figure 8 shows the location of refineries, storages, pipeline and terminals in Portugal.

Figure 8. The Portuguese PSC. (Adapted from Autoridade da Concorrência, 2018).

The refining capacity of Sines and Matosinhos refineries together is 330 thousand barrels per day and Sines is responsible for 70% of this total capacity (around 220 kbbl/day). Therefore, Portugal owns 20% of total refining capacity at Iberian Peninsula. (GALP, s.d.).

Matosinhos refinery began operations in 1969 and it is a hydroskimming refinery, this is, a refinery that executes primarily distillation. Sines began operations in 1978, it was improved in 2013 and it is a complex refinery today that owns a unit of hydrocracking and fluid catalytic cracking. (GALP, s.d.). Hence, as Sines is more modern, it receives fuel oil loadings from Matosinhos through maritime transportation. The objective is to produce products that are more valuable such as gas oil. (Mota, 2012).

It is possible to deliver oil products indirectly (through one of the six distribution centers) or directly to the 18 capital city of Portuguese districts but the model always considers primary and secondary distribution. However, if a direct distribution is recommended, the model will indicate the primary distribution starting at the refinery and finishing at its own depot. Pipelines, rail, maritime and road transportation modes are used for primary distribution (origin in refineries), while only roads are used for secondary distribution (origin in distribution centers). Maritime transportation is used to import crude oil and to export and import refined products. There are two pipelines in Portuguese PSC: one multiproduct from Sines refinery to CLC and a jet fuel pipeline between Matosinhos and Porto airport. (Lima, 2018).

Jet fuel is an oil product that can be easily contaminated and, therefore, it is important to deal with its logistics apart from the other products. These refineries are responsible for supplying jet fuel through trucks to the following airports: Lisbon (all the time), Porto and Faro (only in case of eventuality). Lisbon airport is supplied by Companhia Logística de Combustíveis (CLC) through trucks, Porto airport is supplied by Matosinhos refinery through pipelines and Faro airport is supplied by Cepsa refinery in Huelva (Spain) through trucks and by Sines refinery using train wagons. (Mota, 2012).

5.1.2. The Iberian market

The case study considered the distribution of oil products produced in Portugal to the Iberian Peninsula (see Figure 5) and, therefore, the Azores, Madeira, Balearic Islands and Canary Islands were not considered. 45 provinces in Spain and 18 districts in Portugal compose the Iberian market. The two Portuguese refineries can supply the Spanish market using trucks and ships. Moreover, Portugal can import oil products from the eight refineries in Spain and trucks and ships can transport the imports.

Figure 9. The refineries, storages and supply bases in Iberia. (DGEG - Direção-Geral de Energia e Geologia, s.d.).

The route of the primary distribution of oil products to be considered in the case study will start at refineries and finish at storage depots. The route of the secondary distribution will start at the storage depots and finish at the capital city of each province or district according to their demand for each product.

5.2. Real case database

In order to validate the model, a database regarding the Portuguese downstream PSC and the Iberian market was created. This section presents which data was acquired and its source. The whole database is available at Appendix B.

Firstly, the model is composed by two countries and it is developed through the point of view of one of these countries, which is Portugal in the real case. Moreover, the model considers a network that is fully managed by one company and therefore, as Galp manages both Portuguese refineries (Sines and Matosinhos), great part of the database comes from Galp's website (GALP, s.d.).

As Galp is the company that fully manages the supply chain, data regarding the depots that belongs to Galp was acquired. Thus, the Portuguese distribution centers that are considered are Leixões, Boa Nova, Aveiras de Cima (CLC), Tanquisado, Sines (maritime terminal) and Sines storage. (Autoridade da Concorrência, 2018).

After that, the distances via truck and barge (if available) between the refineries (Sines and Matosinhos) and the distribution centers and between the distribution centers and the capital city of each Portuguese district were computed using Google Maps and Google Earth. Pipeline and rail distances were acquired in CLC website (CLC - Companhia Logística de Combustíveis, s.d.) and Fernandes, et al. (2013).

In addition to this, the annual maximum capacities database was created. Regarding trucks and barges (when available) there is no maximum capacity assigned. The maximum capacity of the pipeline between Sines and Aveiras de Cima was collected in CLC website. However, only few information was found regarding the pipelines between Matosinhos refinery and Leixões maritime terminal and between Matosinhos and Porto airport. Therefore, no maximum capacity of these pipelines was established. The maximum capacity of the pipelines that the model decides to build or not are also assumed to be the same as the CLC pipeline. In order to assign the maximum capacity via rail, the total capacity of Portuguese tank wagons (Instituto Nacional de Estatística, 2010) was multiplied by 365, considering that all the available tank wagons use the rail route established only once a day. If a route is not available via barge, pipeline or rail, the annual maximum capacity value is assigned as 0.

Then, information regarding the Iberian market was acquired. Firstly, data regarding the annual demand for gasoline 95, gasoline 98, jet fuel and diesel in Spain were acquired at CORES - Corporación de reservas estratégicas de productos petrolíferos (2018). The data obtained covers from 2013 to 2017. Thus, it was made an estimation of the demand in Spain using linear regression. The annual demand in 2018 for the four products in Portugal was acquired at ENSE (ENSE - Entidade Nacional para o Setor Energético , s.d.). However, as the data acquired was the total for the whole country, each product total demand was divided by Portugal population and then multiplied by each district population, in order to estimate the district demand for each product. This estimation procedure was used in Kazemi & Szmerekovsky (2015).

After that, as in this model it is considered that the refineries are resposible for import and export oil derivatives, all refineries in Iberia were considered in this model, except for Asesa because this is an atypical refinery, that distillates heavy and extra heavy crude oil to obtain mainly bitumen (Asesa, s.d.). Thus, the maximum refining capacity and the fraction of this capacity that was used to produce each product were obtained for refineries Petronor, Cartagena, La Coruña, Puertollano and Tarragona at Repsol's Integrated Management Report (Repsol, 2017), for refineries La Rabida and San Roque at Cepsa's Annual and Corporate Responsibility Report (Cepsa, 2018) and for Castellón at BP's website (BP - British Petroleum, s.d.). The maximum refining capacity of Portuguese refineries and the fractions of each product produced in 2018 were obtained at Galp's website (GALP, s.d.). The fractions were used to estimate the parameter ψ (2018 data added by 0.02), the maximum reasonable amount that a refinery in Portugal should produce. An important observation is that no information was found regarding the fractions of gasoline 95 and gasoline 98 that were produced in Spain, only about both types of gasoline. Therefore, the percentage produced of each type was estimated based on the demand in Spain.

Then, the distances via truck and barge (if available) between Portuguese and Spanish refineries were computed in Google Maps and Google Earth. Alongside with, the annual maximum capacity for the routes that are infeasible via barge were defined as 0.

In order to evaluate the decisions of opening a distribution center or not and building a pipeline or not, the costs considered were based on the values used for the construction of Aveiras de Cima depot and the pipeline between this depot and Sines refinery. The total amount invest in the whole project (depot and pipeline) were 215,000,000 EUR, of which 65% corresponded to the depot (139,750,000 EUR) and 35% to the 147 km pipeline (75,250,000 EUR). However, the model consider fixed and variable costs in order to open a depot or not. Therefore, it was arbitrarily considered that 62% of the cost of opening the depot corresponded to the fixed cost (87,250,000 EUR) and 38% corresponded to the variable cost related to the DC capacity. As the capacity of Aveiras de Cima depot is 350,000 m^3, the variable cost β_n per m^3 of storage capacity was considered as 150 EUR/m^3. Thus, the parameter f_n was considered as 87,250,000 EUR when n is a possible new depot. These values were obtained at CLC website. (CLC - Companhia Logística de Combustíveis, s.d.).

Furthermore, in order to assign values to the parameters PIMP and PEXP, the ex-refinery prices in Portugal and Spain for diesel and gasoline were obtained at FuelsEurope Statistical Report (FuelsEurope, 2017). As only gasoline was stated in the report, the same ex-refinery prices were assigned to gasoline 95 and gasoline 98. As no information was acquired regarding jet fuel, the 2013 ex-refinery price available at Fernandes, et al. (2013) was considered for both countries. The 2013 price was chosen because it was the most recent data in Fernandes, et al. (2013) and because the prices regarding gasoline and diesel were very close to 2017 values found at FuelsEurope (2017).

Regarding transportation costs, only a few information regarding Iberia was available. Therefore, the transportation costs available in Kazemi & Szmerekovsky (2015) were considered, after converted from USD per ton-mile to EUR per ton-km. These transportation costs are the parameters $C_{p,a,j,r}$, $T_{p,j,k,r}$ and $TIMP_{p,b,a,r}$.

After acquiring the data regarding the Portuguese PSC and the Iberian market, the location for a possible new depot and two possible new pipelines were decided (see Figure 10). The location of the possible new depot was chosen at Portalegre district because the capital city (Portalegre) is almost equally distant of both refineries and it is located in the middle of the country, what can lead to a better distribution in this area. The first pipeline was chosen to connect Lisbon and Aveiras de Cima (CLC) depot mainly because the largest airport in Portugal is located in Lisbon and it is supplied only through trucks. The problems of supplying only through trucks the country's largest airport includes jet fuel contamination and vulnerability for unforseeable events such as strikes. As the length of the pipeline between Lisbon and Aveiras de Cima would be 50 km, approximately a third of pipeline between Aveiras de Cima and Sines refinery, the parameter f_n was considered as 25,000,000 EUR. The second pipeline was chosen to connect the storage in Sines refinery to Faro, where is located another airport. Faro airport is supplied through train wagons from Sines refinery and through trucks from refinery La Rabida in Spain. As the length of this pipeline would be 130 km, approximately the same as the pipeline between Aveiras de Cima and Sines refinery, the parameter f_n was considered as 75,250,000 EUR.

Figure 10. Location of possible new distribution center and pipelines

5.3. Real case results

The real case was analyzed considering a one-year planning horizon and in a long-term planning horizon (5, 7 and 10 years). The analysis considering a one-year planning horizon is presented in subsection 5.3.1 and regarding long-term is presented in subsection 5.3.2. Furthermore, Appendix C presents the results for the decision variables.

5.3.1. General analysis

The model considering the real case study was implemented in GAMS programming language and was solved using the solver CPLEX in a computer Intel® Xeon® CPU X5680 @

3.33GHz 3.33GHz (2 processors) and 24 GB RAM memory. The model has 194 equations and 3,359 single variables, of which 3 are discrete. The execution time was 0.047 CPU seconds.

The solution obtained by the model considering the real case (variable *z*) was -4.4828×10^9. At first the value obtained seems weird as the objective function is the total cost but analysing the objective function, it is possible to see that there is a negative term, which is the total amount earned by exporting products. Therefore, if the amount exported is high, this term in the objective function equation can overlap the other terms. Analysing the results obtained and considering that both Portuguese refineries are operating in maximum capacity, that is exactly what happened. All the results obtained are available at Appendix C.

As Portugal has an annual refining capacity installed of approximately 19.2 million m^3 (of which almost 14.8 million m^3 are used to produce gasoline 95, gasoline 98, jet fuel and diesel, if the refineries are operating at maximum capacity) and the total demand for gasoline 95, gasoline 98, jet fuel and diesel is approximately 7.5 million tonnes, which is less than half of the total refining capacity, Portugal can export around 7 million tonnes of these fuels annualy. The results show that exporting this extra production, the amount earned counterbalances all the transportation costs and still remains a revenue of EUR 4.4828×10^9. However, it is important to remember that the refineries in Portugal are not operating currently at maximum capacity (according to Galp's website, 100 MMboe are refined annualy in Portugal, what corresponds to approximately 82% of the maximum refining capacity installed) and the costs of refining and importing crude oil are not considered in this model. Therefore, the decision of operating in maximum capacity may not be the wisest from an economic point of view, although the model shows an enoumous revenue as result.

Another result proposed by the model is that there is no need for Portugal to import oil derivatives. However, in order to be self sufficient in terms of oil derivatives, crude oil must be imported and there are also refining costs, which were not considered in this model. Therefore, a suggestion for further works is to incorporate these costs in order to better analyse this decision.

Furthermore, an analysis was performed in order to find out what is the lowest capacity that refineries in Portugal can work (considering that refineries in Spain are working at maximum capacity) in order to fully supply Iberia along with Spanish refineries. This analysis was made by reducing the refining capacity of Sines and Matosinhos and running the model until the software finds no solution because if the production in Portugal is below a certain number, the demand will not be satisfied and the model will not find any solution. The result was that if Spanish refineries are working at maximum capacity, Portuguese refineries must be working at 69% of their capacities so all these refineries together can fully supply Iberia. In this scenario, Sines and Matosinhos together are able to supply entirely Portugal and export 2,181,940 m^3 of gasoline 95,455,686 m^3 of gasoline 98,672,823 m^3 of diesel and 223,293 m^3 of jet fuel to Spain.

Another analysis was performed in order to find out what is the lowest capacity that refineries in Portugal can work at without needing to import oil derivatives. This analysis was made by reducing the refining capacity of Sines and Matosinhos and running the model until the solution indicates an amount to import. Also, the refining capacity of Spanish refineries was increased, supposing that they are importing derivatives, because as shown in previous analysis, when Portuguese refineries are working at 69% of their capacity they have to export to Spain to fully supply the Spanish market along with Spanish refineries. The result was that only if Portuguese refineries are working at 60% of their capacity that they would not be able to fully supply Portugal and diesel must be imported, while the amount produced of gasoline 95, gasoline 98 and jet fuel are enough to supply Portugal and even to be exported.

Considering a one-year planning horizon, the model suggested that the possible new depot in Portalegre should not be opened and both pipelines should not be built. However, as the investment is high, it is important to analyse these decisions in a long-term planning horizon. Therefore, subsection 5.3.2 analyses the results obtained considering a 5, 7 and 10-year planning horizon.

Regarding the material flow, two important observations must be made about the results obtained. The first is that the model did not consider the transportation through rail from Sines storage to Faro. The reason that it happened is that the model chose the maritime route through Tanquisado depot, as maritime transportation is cheaper than via rail. However, as jet fuel can be easily contaminated and Faro demands jet, at least jet fuel should be transported via rail.

The second observation is that the supply in Lisbon is occurring only through the depot of Tanquisado using maritime transportation. However, the problem is that Lisbon airport demands a high amount of jet fuel and, as jet fuel can be easily contaminated, it would be better to transport the jet from Sines refinery to Aveiras de Cima depot through pipelines and after that through trucks to Lisbon airport, which is the route used today.

Therefore, it is important to consider in further works that jet fuel should be transported through pipeline and rail preferably and the shorter distance as possible through barge and trucks.

5.3.2. Long-term analysis

As the model proposed considering a 1-year planning horizon decided that the possible new depot in Portalegre should not be opened and both pipelines should not be built, a long-term analysis was performed, considering a time frame of 5, 7 and 10 years. It is important to perform a long-term analysis because the decisions of opening a new depot and building a new pipeline are strategical decisions and, sometimes, as the investment is high, the results appear in a longer planning horizon.

In order to do this analysis, the annual demands and the maximum capacity of each transportation mode were multiplied by the horizon and these values were replaced in the original model. The refining capacity of Portuguese refineries was considered as 82% of the maximum capacity in order to better fit the reality. After running these models in GAMS, the strategic decisions suggested by each of them are available at Table 19 and the comparison of the statistics of the models in all planning horizons analyzed (1, 7, 5 and 10 years) are available at Table 20. The results obtained for variables Y, Z and EXP are available at Appendix C.

Table 19. Strategic decisions in long-term analysis

		Strategic decisions		
		Installing pipeline between Aveiras de Cima and Lisbon	Installing pipeline between Sines storage and Faro	Opening a depot at Portalegre
Planning Horizon	1 year	-	-	-
	5 years	-	-	-
	7 years	-	Yes	-
	10 years	Yes	Yes	-

Table 20. Performance results for real case study

	Equations	Single Variables	Discrete Variables	Objective (EUR)	CPU (s)
1 year	194	3,359	3	-4.483×10^{9}	0.047
5 years	194	3,359	3	-1.491×10^{10}	0.109
7 years	194	3,359	3	-2.081×10^{10}	0.047
10 years	194	3,359	3	-2.973×10^{10}	0.047

Analysing the results of the models considering different planning horizons, it is possible to see that even though installing a pipeline between Sines storage and Faro would require a higher investment than the pipeline between Aveiras de Cima and Lisbon, it would be recommended to so if a 7-year planning horizon analysis is performed. However, if a 10-year planning horizon analysis is performed, the model recommends to invest in both pipelines. Figure 11 illustrates the decisions over the time horizons analysed.

The decision of not opening the depot at Portalegre can be understood because this new depot would require a high investment and it would be accessible only through trucks, which is the most expensive transportation mode. Another reason is that Portugal is a small country and its depots are already strategically located.

Again, it is important to emphasize that the model made the decisions under an economic point of view. Considering a 7-year planning horizon, the model decided to install a pipeline between Sines storage and Faro and not to install a pipeline between Aveiras de Cima and Lisbon. However, other non-economic factors should be analyzed in order to make this decision, such as jet fuel contamination. For example, Lisbon airport, which is the one that most demands jet fuel in Portugal, is only supplied through trucks and supplying only through trucks is subject to unforeseeable conditions such as delays in the deliver and strikes. Moreover, Sines storage and Faro are already connected through rail and although transportation is more expensive than through pipelines, the issue about jet fuel possible contamination is solved. Therefore, the decision of installing a pipeline between Aveiras de Cima and Lisbon is more crucial and urgent than installing a pipeline between Sines storage and Faro, as it seemed in the model results.

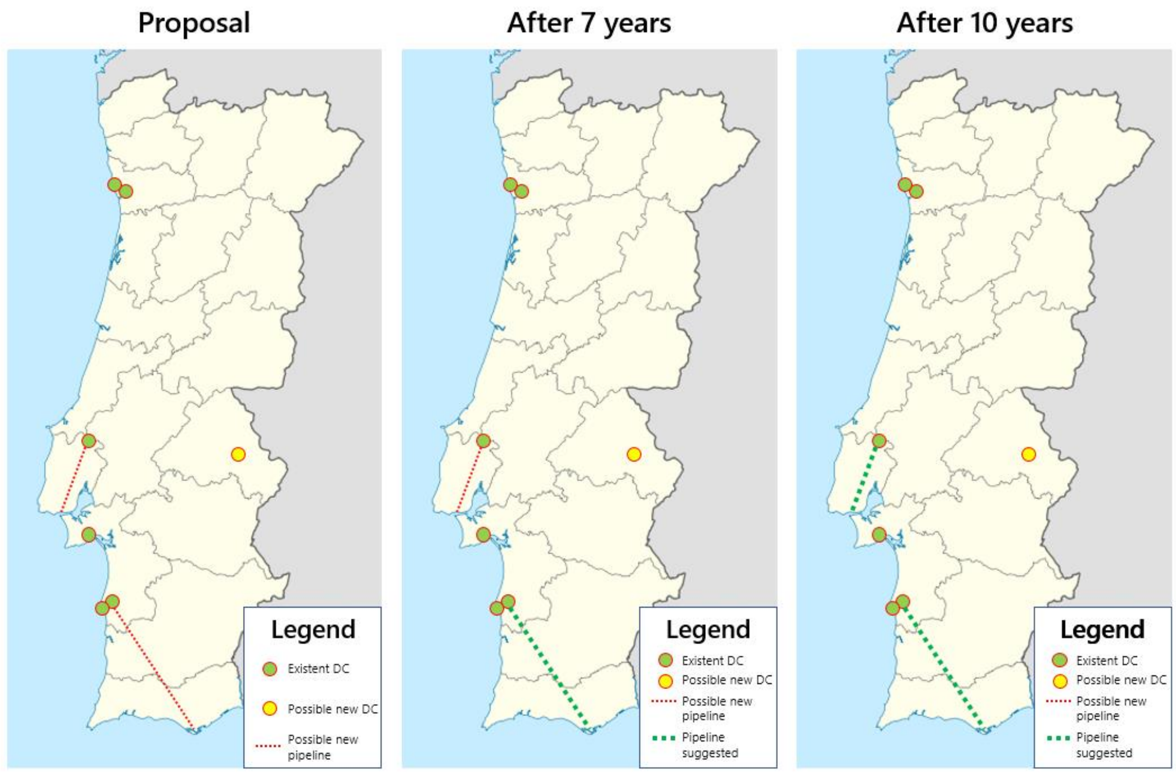

Figure 11. Strategic decisions in long-term

5.4. Suggestions for further works

Although the model succeded well within its goals, it still has a lot to improve in order to better represent the reality.

As stated in Lima (2018), in Portugal transportation by trucks is used only in distances lower than 250 km. Therefore, it is important to limit the transportation by trucks to distances lower than 250 km in order to fit best the reality in Portugal. Moreover, it can be considered in further works the distribution directly to the cities and not through the district capitals.

The jet fuel contamination is a topic that the model did not approach and it is very important to do so. The model does not prioritize jet fuel transportation through pipelines and rail than barge and trucks, being transported through the latter only the minimum possible distance, as it can be easily contaminated.

Another suggestion is to integrate the model with upstream and midstream segments. It would be interesting including the cost of importing crude and transporting it to the refineries and the costs related to refining operations. Considering these costs, would be possible to analyze what would be the optimum fraction of its refining capacity that each refinery should work at because depending on these costs, importing oil derivatives may be an advantage.

Integrating biofuels to the products considered in the model would be an interesting suggestion for further works because Spain and Portugal have different agreements regarding the amount of biofuels that they should incorporate.

As many uncertainties affect the petroleum supply chain, another important observation is that these uncertainties should be considered and the problem should be approached stochastically.

Finally, another suggestion would be to integrate the whole distribution in Iberia, in a way that the costs for all companies would be optimized.

5.5. Conclusion

These chapter goals were to present the real case used to show the applicability of the mathematical model developed and to analyze the results obtained. Firstly, the real case considering the Portuguese PSC and the Iberian market was presented and data was acquired regarding it. Furthermore, all data presented is public information and, therefore, it is not classified. The main sources of information to the real case consisted in the websites of the oil companies that operate in Iberia (Galp, Repsol, Cepsa and BP Oil España) and Fernandes, et al. (2013).

The analysis presented regarding the validation with the illustrative case study of the mathematical model in Chapter 4 and the application of a real case to the model developed in Chapter 5 shows that it achieved the goals proposed and it is able to make strategic and tactical decisions. The strategic decisions comprise:

- Opening or not a new distribution center and determining its capacity;
- Installing or not a new pipeline between two nodes.

On the other hand, the tactical decisions consisted in:

- Choosing the best material flow in each route between two nodes via each transportation mode;
- Choosing the amount that should be imported and exported.

Moreover, according to the literature, decision planning can vertically integrate more than one decision-planning level (Misni & Lee, 2017), which is a strategy that may help to improve the outcomes (Lima, et al., 2016). Thus, it is worth noting that the analysis performed regarding the illustrative case study verified what was stated in literature: the results were better when strategic and tactical planning were integrated.

Analyzing the real case study in the long-term, the model shows that it would be a good strategic decision to install two pipelines in Portugal: from Sines storage to Faro and from Aveiras de Cima to Lisbon. These decisions are important, as airports must be supplied with jet fuel in both capital cities, Faro and Lisbon, and it is a fuel that can be easily contaminated. Moreover, the decision is even more crucial regarding the pipeline between Aveiras de Cima and Lisbon because Lisbon airport is the largest in Portugal and it is supplied only through trucks, what exposes it to unforeseeable risks that go beyond jet fuel contamination, such as delays and strikes.

However, a mathematical model is not an exact representation of the reality; it only simplifies it through mathematical equations. Hence, it has some features to improve in order to fit it best to the reality and give better results. Therefore, some suggestions for further works were presented in this chapter:

- Limit the transportation by trucks to distances lower than 250 km in order to fit best the reality in Portugal;
- Prioritize jet fuel transportation through pipeline and rail rather than through barge and trucks due to the fact that jet fuel can be easily contaminated;
- Integrate the model with features of upstream and midstream segments such as cost of importing and transporting crude oil and refining cost;
- Consider also biofuels because Spain and Portugal have different agreements regarding the amount of biofuels that they should incorporate;
- Approach the problem stochastically due to the many uncertainties that affect the PSC;
- Integrate the whole distribution in Iberia, minimizing the cost for all companies that operate in Iberia in a cooperative manner.

Chapter 6 – Conclusion

The Master's thesis in Petroleum Engineering aimed at developing a mathematical model that solved a problem regarding the downstream petroleum supply chain. To do so, several steps were developed:

Firstly, the Petroleum Supply Chain and its downstream segment were understood in Chapter 2. Moreover, it was highlighted the importance of using Operations Research tools in PSC. This chapter also explained the decision-planning levels when planning and managing the PSC and the structure of a mathematical model.

Then, Chapter 3 provided the literature review where a set of relevant papers exploring mathematical models regarding the downstream PSC were analyzed. These papers were categorized according to their planning level or the combination of two levels.

After that, the problem was defined and the mathematical model developed was presented in Chapter 4. The objective was to develop a deterministic mathematical model in order to define a strategy for supplying markets that may span over more than one country considering strategic and tactical planning. This chapter has also emphasized the main contributions of the model developed when compared with Kazemi & Szmerekovsky (2015):

- More than one country is considered and, therefore, costs related to import and export were incorporated;
- The model limits the capacity of a transportation mode and it does not establish flow in an unfeasible route;
- The model decides the fraction of total refinery capacity should be used to produce each product considered;
- Already existent distribution centers are considered along with the decision of opening or not a new distribution center;
- The model is versatile and it can determine if a distribution center should be opened or not, if a pipeline should be built or not or both features together.

After developing the model, it was important to validate it in order to attest the efficiency of the model. To do so, an illustrative case study was considered and presented in Chapter 4. The model developed was validated and it was verified that it achieved the objectives proposed of making strategic and tactical decisions. The strategic decisions involve opening or not a distribution center and installing or not a pipeline, while the tactical decisions comprise deciding the best material flow in each route through possible and available transportation modes and the amount that should be imported and/or exported.

The analysis performed regarding the illustrative case study verified that the results were better when strategic and tactical planning were integrated, what was stated in literature (Lima, et al., 2016).

Then, Chapter 5 presented and discussed the results obtained from applying the real case study to the model. The real case objective consisted in a distribution strategy for supplying the Iberian market with oil products produced in Portuguese refineries managed by a single company.

It is worth noting that the model made important strategic decisions regarding the real case study. The model decided when analyzing in the long-term that a pipeline between Sines storage and Faro and a pipeline between Aveiras de Cima and Lisbon should be installed. These decisions are very important, mainly regarding the second pipeline because Lisbon airport is the largest airport in Portugal and it is supplied only through trucks. Supplying the largest airport only through trucks involves risks such as jet fuel contamination and lack of supply due to strikes.

Furthermore, the model made the tactical decision that, before installing these pipelines, Faro and Lisbon airports should be supplied through barge. However, Faro airport is supplied through rail from Sines storage and through trucks from refinery La Rabida in Spain due to the ease of jet fuel contamination and Lisbon airport is supplied through the routes Sines refinery to Aveiras de Cima via pipeline and from Aveiras de Cima to the airport via trucks due to the same reason. Therefore, it is important to incorporate features in the model that would prioritize jet fuel transportation through pipelines and rail.

Other suggestions proposed for further works comprise limiting the transportation by trucks to distances lower than 250 km, integrating the model with features of upstream and midstream segments, considering also biofuels, approaching the problem stochastically and integrating the whole distribution in Iberia, considering a multi-company cooperative model.

References

Alabi, A. & Castro, J., 2009. Dantzig-Wolfe and block coordinate-descent decomposition in large-scale integrated refinery-planning. *Computers & Operations Research,* Volume 36, pp. 2472-2483.

Andersen, F. E., Díaz, M. S. & Grossmann, I. E., 2013. Multiscale strategic planning model for the design of integrated ethanol and gasoline supply chain. *AIChE J,* 59(12), pp. 4655-4672.

Asesa, s.d. *Refino de Petróleo.* [Online] Available at: http://www.asesa.es/oil-refining-xcid [Acedido em 23 05 2019].

Autoridade da Concorrência, 2018. *Análise ao Setor dos Combustíveis Líquidos Rodoviários em Portugal Continental,* s.l.: s.n.

Azadeh, A. et al., 2017. Evolutionary multi-objective optimization of environmental indicators of integrated crude oil supply chain under uncertainty. *Journal of Cleaner Production,* Volume 152, pp. 295-311.

Barbosa-Póvoa, A. P., 2014. Process supply chains management - where are we? Where to go next?. *Process and Energy Systems Engineering,* pp. 2-23.

Bassi, H. V., Filho, V. J. M. F. & Bahiense, L., 2012. Planning and scheduling a fleet of rigs using simulation–optimization. *Computers & Industrial Engineering,* Volume 63, pp. 1074-1088.

BP - British Petroleum, 2018. *BP Statistical Review of World Energy,* s.l.: s.n.

BP - British Petroleum, s.d. *BP España.* [Online] Available at: https://www.bp.com/es_es/spain.html [Acedido em 23 05 2019].

Cepsa, 2018. *2018 Annual and Corporate Responsibility Report,* s.l.: s.n.

CLC - Companhia Logística de Combustíveis, s.d. *CLC - Companhia Logística de Combustíveis, S. A..* [Online] Available at: http://www.clc.pt/ [Acedido em 23 05 2019].

CORES - Corporación de reservas estratégicas de productos petrolíferos, 2018. *Informe estadístico anual 2017,* s.l.: s.n.

DGEG - Direção-Geral de Energia e Geologia, s.d. *Oleodutos.* [Online] Available at: http://www.dgeg.gov.pt/
[Acedido em 11 12 2018].

EIA - U.S. Energy Information Administration, 2012. *Crude oil distillation and the definition of refinery capacity.* [Online] Available at: https://www.eia.gov/todayinenergy/detail.php?id=6970#
[Acedido em 6 December 2018].

ENSE - Entidade Nacional para o Setor Energético , s.d. *Introduções ao Consumo.* [Online] Available at: http://www.ense-epe.pt/introducoes-consumo/
[Acedido em 23 05 2019].

Fernandes, L. J., Relvas, S. & Barbosa-Póvoa, A. P., 2013. Strategic network design of downstream petroleum supply chains: Single versus multi-entity participation. *Chemical Engineering Research and Design,* Volume 91, pp. 1557-1587.

Fernandes, L. J., Relvas, S. & Barbosa-Póvoa, A. P., 2014. Collaborative Design and Tactical Planning of Downstream Petroleum Supply Chains. *Ind. Eng. Chem. Res.,* 53(44), pp. 17155-17181.

Fernandes, L. J., Relvas, S. & Barbosa-Póvoa, A. P., 2015. Downstream Petroleum Supply Chain Planning under Uncertainty. *Computer Aided Chemical Engineering,* Volume 37, pp. 1889-1894.

Fiorencio, L., Oliveira, F., Nunes, P. & Hamacher, S., 2015. Investment planning in the petroleum downstream infrastructure. *International Transactions in Operational Research,* 22(2), pp. 339-362.

FuelsEurope, 2017. *Statistical Report,* s.l.: s.n.

GALP, s.d. *Aprovisionamento, refinação e logística.* [Online] Available at: https://www.galp.com/corp/pt/sobre-nos/o-que-fazemos/refinacao-distribuicao/aprovisionamento-refinacao-e-logistica
[Acedido em 11 12 2018].

Ghaithan, A. M., Attia, A. & Duffuaa, S. O., 2017. Multi-objective optimization model for a downstream oil and gas supply chain. *Applied Mathematical Modelling,* Volume 52, p. 689–708.

Goel, V. & Grossmann, I. E., 2004. A stochastic programming approach to planning of offshore gas field developments under uncertainty in reserves. *Computers and Chemical Engineering ,* Volume 28, pp. 1409-1429.

Guyonnet, P., Grant, F. H. & Bagajewicz, M. J., 2009. Integrated Model for Refinery Planning, Oil Procuring, and Product Distribution. *Ind. Eng. Chem. Res.,* Volume 48, pp. 463-482.

Hillier, F. S. & Lieberman, G. J., 2005. *Introduction to Operations Research.* 8th ed. s.l.:McGraw-Hill .

Hobsbawm, E. J., 2000. *Da Revolução Industrial Inglesa ao Imperialismo.* 5 ed. Rio de Janeiro: Forense Universitária.

Instituto Nacional de Estatística, 2010. *Estatísticas dos Transportes 2009,* s.l.: s.n.

Kazemi, Y. & Szmerekovsky, J., 2015. Modeling downstream petroleum supply chain: The importance of multi-mode transportation to strategic planning. *Transportation Research Part E ,* Volume 83, pp. 111-125.

Kim, Y. et al., 2008. An integrated model of supply network and production planning for multiple fuel products of multi-site refineries. *Computers and Chemical Engineering,* Volume 32, pp. 2529-2535.

Kuo, T.-H. & Chang, C.-T., 2008. Application of a Mathematic Programming Model for Integrated Planning and Scheduling of Petroleum Supply Networks. *Ind. Eng. Chem. Res.,* Volume 47, pp. 1935-1954.

Leiras, A., Ribas, G. & Hamacher, S., 2013. Tactical and Operational Planning of Multirefinery Networks under Uncertainty: An Iterative Integration Approach. *Ind. Eng. Chem. Res.,* Volume 52, pp. 8507-8517.

Leiras, A., Ribas, G., Hamacher, S. & Elkamel, A., 2011. Literature review of oil refineries planning under uncertainty. *Int. J. Oil, Gas and Coal Technology,* 4(2), p. 156–173.

Lima, C. G., 2018. *Tactical and Operational planning of the Downstream Oil Supply Chain under uncertainty,* Lisboa: s.n.

Lima, C., Relvas, S. & Barbosa-Póvoa, A., 2018. Stochastic programming approach for the optimal tactical planning of the downstream oil supply chain. *Computers and Chemical Engineering,* Volume 108, pp. 314-336.

Lima, C., Relvas, S. & Barbosa-Póvoa, A. P. F. D., 2016. Downstream oil supply chain management: A critical review and future directions. *Computers and Chemical Engineering,* Volume 92, pp. 78-92.

MirHassani, S. A., 2008. An operational planning model for petroleum products logistics under uncertainty. *Applied Mathematics and Computation,* Volume 196, pp. 744-751.

MirHassani, S. A. & Noori, R., 2011. Implications of capacity expansion under uncertainty in oil industry. *Journal of Petroleum Science and Engineering,* Volume 77, pp. 194-199.

Misni, F. & Lee, L. S., 2017. A Review on Strategic, Tactical and Operational Decision Planning in Reverse Logistics of Green Supply Chain Network Design. *Journal of Computer and Communications,* Volume 5, pp. 83-104.

Mota, N. M. M. d. A. d. C., 2012. *Análise de cenários para definição de planos de contingência na distribuição secundária de produtos petrolíferos,* Lisboa: s.n.

Neiro, S. M. S. & Pinto, J. M., 2004. A general modeling framework for the operational planning of petroleum supply chains. *Computers and Chemical Engineering,* Volume 28, pp. 871-896.

Oliveira, F., Grossmann, I. E. & Hamacher, S., 2014. Accelerating Benders stochastic decomposition for the optimization under uncertainty of the petroleum product supply chain. *Computers & Operations Research,* Volume 49, pp. 47-58.

Oliveira, F. & Hamacher, S., 2012. Optimization of the Petroleum Product Supply Chain under Uncertainty: A Case Study in Northern Brazil. *Ind. Eng. Chem. Res.,* Volume 51, pp. 4279-4287.

Pinto, J. M., Joly, M. & Moro, L. F. L., 2000. Planning and scheduling models for refinery operations. *Computers and Chemical Engineering,* Volume 24, pp. 2259-2276.

Repsol, 2017. *Integrated Management Report,* s.l.: s.n.

Saad, S. M., Elsaghier, E. H. & Ezaga, D., 2018. Planning and optimising petroleum supply chain. *Procedia Manufacturing,* Volume 17, pp. 803-810.

Sahebi, H., Nickel, S. & Ashayeri, J., 2014. Strategic and tactical mathematical programming models within the crude oil supply chain context—A review. *Computers and Chemical Engineering,* Volume 68, pp. 56-77.

Skjerpen, T., Storrøsten, H. B., Rosendahl, K. E. & Osmundsen, P., 2018. Modelling and forecasting rig rates on the Norwegian Continental Shelf. *Resource and Energy Economics,* Volume 53, pp. 220-239.

Tong, K., Feng, Y. & Rong, G., 2012. Planning under Demand and Yield Uncertainties in an Oil Supply Chain. *Ind. Eng. Chem. Res.,* Volume 51, pp. 814-834.

Tong, K., You, F. & Rong, G., 2014. Robust design and operations of hydrocarbon biofuel supply chain integrating with existing petroleum refineries considering unit cost objective. *Computers and Chemical Engineering,* Volume 68, pp. 128-139.

Yergin, D., 1991. *The Prize: The Epic Quest for Oil, Money & Power.* New York: Simon & Schuster .

Ye, Y., Liang, S. & Zhu, Y., 2017. A mixed-integer linear programming-based scheduling model for refined-oil shipping. *Computers and Chemical Engineering,* Volume 99, pp. 106-116.

Appendix A – Supplementary results for the illustrative case study

This Appendix provides the extra results obtained with the Illustrative Model 2.

Table 21. Illustrative Model 2 results for variable Y.

Variable Y (m^3/year)								
gasoline			diesel			jet fuel		
	pipeline	barge		pipeline	barge		pipeline	barge
	j1	j1		j1	j1		j1	j1
i1		5500000	i1		9000000	i1		7400000
i2	2000000		i2	4000000		i2	1600000	

Table 22. Illustrative Model 2 results for variable Z.

Variable Z (m^3/year)										
gasoline				diesel					jet fuel	
	rail	barge			truck	rail	barge			truck
	u2	u1	u3		u2	u2	u1	u3		uair1
j1	2,000,000	3,000,000	2,500,000	j1	1,000,000	2,000,000	6,000,000	4,000,000	j1	9,000,000

Table 23. Illustrative Model 2 results for variable IMP.

Variable IMP (m^3/year)		
	i1 via barge	
	gasoline	jet fuel
i3	500,000	3,400,000

Table 24. Illustrative Model 2 results for variable EXP.

Variable EXP (m^3/year)	
	i3 - diesel
i2	1,000,000

Table 25. Illustrative Model 2 results for variable γ.

Variable γ			
	gasoline	diesel	jet fuel
i1	0.25	0.5	0.2
i2	0.25	0.5	0.2

Appendix B – Portuguese PSC and Iberian market database

The Appendix B provides the database regarding the Portuguese PSC and the Iberian market that was used to validate the mathematical model. Table 26 presents the distance in km between the refineries in Portugal and the depots via truck, barge, pipeline and rail. If a transportation mode is not available between a refinery and a depot, it is signed with a -.

Table 26. Distance in km between refineries in Portugal and depots.

Distance refineries in Portugal and depots (km)				
	via truck		via barge	
Depots - Portugal	Matosinhos	Sines	Matosinhos	Sines
Leixões	5,3	438	-	401
Boa Nova	1	441	-	-
CLC - Aveiras de Cima	261	178	-	-
Tanquisado	358	129	383	66
Sines - Terminal	447	10	401	-
Sines - Storage	441	2	-	-
	via pipeline		via rail	
Depots - Portugal	Matosinhos	Sines	Matosinhos	Sines
Leixões	2	-	-	-
Boa Nova	-	-	-	-
CLC - Aveiras de Cima	-	147	-	-
Tanquisado	-	-	-	-
Sines - Terminal	-	-	--	-
Sines - Storage	-	-	-	-

Then, the maximum capacity through each transportation mode between refineries and depots was determined as: no maximum capacity through trucks, no maximum capacity for available routes through barge, 0 for unavailable routes through barge, rail and pipeline, 4,000,000 m^3 annualy through pipeline between Sines refinery and CLC – Aveiras de Cima depot and no maximum capacity was established for the pipeline between Matosinhos refinery and Leixões depot, as no information was available.

Table 27 presents the distance between depots and customer nodes in Portugal in km through trucks. No maximum capacity through trucks was established.

Table 27. Distance in km between depots and customer nodes in Portugal through trucks.

Distance depots and customer nodes in Portugal via trucks (km)						
	Depots - Portugal					
Customer Nodes - Portugal	Leixões	Boa Nova	CLC - Aveiras de Cima	Tanquisado	Sines - Terminal	Sines - Storage
Aveiro	81	84,3	205	309	378	372
Beja	460	463	200	142	100	94
Braga	58,4	59,8	313	400	487	481
Bragança	210	213	435	522	609	603
Castelo Branco	264	268	175	261	316	310
Coimbra	128	131	154	259	328	322
Évora	416	419	156	106	134	128
Faro	559	563	300	251	171	185
Guarda	206	209	266	336	408	418
Leiria	188	195	73	207	257	267
Lisbon	319	322	59	101	201	195
Portalegre	299	302	174	197	266	271
Porto	7	10	263	350	437	431
Santarém	253	256	27	119	190	194
Setubal	350	353	90	10	128	122
Viana do Castelo	71	68	336	423	510	504
Vila Real	98	101	347	433	504	498
Viseu	133	136	240	326	414	408
Porto Airport	12,6	6	276	362	450	444

Table 28 presents the distance between depots and customer nodes in Portugal in km through barge. The routes assigned with “-“ are not available through barge and the maximum capacity of them was established as 0. No maximum annual capacity was established to the routes available through barge.

Table 28. Distance in km between depots and customer nodes in Portugal through barge.

Distance depots and customer nodes in Portugal via barge (km)						
	Depots - Portugal					
Customer Nodes - Portugal	Leixões	Boa Nova	CLC - Aveiras de Cima	Tanquisado	Sines - Terminal	Sines - Storage
Aveiro	70	-	-	333	353	-
Beja	-	-	-	-	-	-
Braga	-	-	-	-	-	-
Bragança	-	-	-	-	-	-
Castelo Branco	-	-	-	-	-	-
Coimbra	-	-	-	-	-	-
Évora	-	-	-	-	-	-
Faro	605	-	-	292	214	-
Guarda	-	-	-	-	-	-
Leiria	-	-	-	-	-	-
Lisbon	335	-	-	83	135	-
Portalegre	-	-	-	-	-	-
Porto	-	-	-	379	500	-
Santarém	-	-	-	-	-	-
Setubal	383	-	-	-	66	-
Viana do Castelo	116	-	-	529	596	-
Vila Real	-	-	-	-	-	-
Viseu	-	-	-	-	-	-
Porto Airport	-	-	-	-	-	-

Table 29 presents the distance between depots and customer nodes in Portugal in km through pipeline. The only pipeline in Portugal considered between depots and customer nodes connects the Boa Nova depot and Porto Airport. The length of this pipeline and the maximum capacity could not be obtained and therefore, the length was estimated in Google Maps and no maximum capacity was established. There is no other pipeline available in the other routes considered between depots and customer nodes and, therefore, the maximum capacity for all of them was established as 0.

Table 29. Distance in km between depots and customer nodes in Portugal through pipeline.

Distance depots and customer nodes in Portugal via pipeline	
	Depots - Portugal
Customer Nodes - Portugal	Boa Nova
Porto Airport	4

Table 30 presents the distance between depots and customer nodes in Portugal in km through rail. The only rail in Portugal considered between depots and customer nodes connects the Sines storage depot and Faro. The maximum capacity of this transportation could not be obtained and therefore, it was estimated based on Instituto Nacional de Estatística (2010) as 301,490 m^3 per year. There is no other rail available in the other routes considered between depots and customer nodes and, therefore, the maximum capacity for all of them was established as 0.

Table 30. Distance in km between depots and customer nodes in Portugal through rail.

Distance depots and customer nodes in Portugal via rail (km)	
	Depots - Portugal
Customer Nodes - Portugal	Sines - Storage
Faro	155

The transportation between Portugal and Spain (import and export) was considered only through truck and barge and hence, the annual maximum capacity through pipeline and rail was established as 0 to all routes. Table 31 presents the distance in km between Portuguese and Spanish refineries through truck and barge. No maximum capacity was established for the routes through trucks and for the available routes through barge. The maximum capacity for unavailable routes was considered as 0.

Table 31. Distance in km between Portuguese and Spanish refineries through trucks and barge.

Distance refineries Portugal and Spain (km)				
	Refineries - Portugal			
	via truck		via barge	
Refineries - Spain	Matosinhos	Sines	Matosinhos	Sines
Petronor - Vizcaya - Spain - Repsol	715	964	796	1279
Cartagena - Spain - Repsol	1017	861	1279	1033
A Coruña - Spain - Repsol	304	727	337	855
Puertollano - Spain - Repsol	679	572	-	-
Tarragona - Spain - Repsol	1050	1170	1731	1540
Castellón - Spain - BP	983	979	1600	1370
La Rabida - Spain - Cepsa	682	250	711	309
San Roque - Spain - Cepsa	775	496	848	546

Table 32 presents the maximum refining capacity of all refineries considered in the model in bbl/day and m^3/year.

Table 32. Maximum refining capacity of Portuguese and Spanish refineries in bbl/day and m^3/year.

Refineries	Max Capacity - S_i - (bbl/day)	m^3 per year
Matosinhos	110,000	6,424,000
Sines	220,000	12,848,000
Petronor - Vizcaya - Spain - Repsol	220,000	12,848,000
Cartagena - Spain - Repsol	220,000	12,848,000
A Coruña - Spain - Repsol	120,000	7,008,000
Puertollano - Spain - Repsol	150,000	8,760,000
Tarragona - Spain - Repsol	186,000	10,862,400
Castellón - Spain - BP	110,000	6,424,000
La Rabida - Spain - Cepsa	190,000	11,096,000
San Roque - Spain - Cepsa	240,000	14,016,000

Table 33 presents the fraction of total amount refined by each refinery in Spain that is used to produce product p. It is important to say that no data was found regarding the fraction of gasoline production that is used to produce gasoline 95 and 98, only gasoline in general. Therefore, these amounts were estimated based on the proportion of each gasoline that is demanded in Spain.

Table 33. Fraction of the total amount refined by refinery b that is used to produce product p.

$\alpha_{b,p}$				
	Products			
Refineries Spain	diesel	jet fuel	gasoline 95	gasoline 98
Petronor - Vizcaya - Spain - Repsol	0.43	0.08	0.174	0.016
Cartagena - Spain - Repsol	0.43	0.08	0.174	0.016
A Coruña - Spain - Repsol	0.43	0.08	0.174	0.016
Puertollano - Spain - Repsol	0.43	0.08	0.174	0.016
Tarragona - Spain - Repsol	0.43	0.08	0.174	0.016
Castellón - Spain - BP	0.38	0.08	0.21	0.02
La Rabida - Spain - Cepsa	0.4	0.08	0.092	0.008
San Roque - Spain - Cepsa	0.4	0.08	0.092	0.008

Table 34 presents the ex-refinery prices per m^3 of each product p in Portugal and Spain, which are represented in parameters PIMP and PEXP.

Table 34. Ex-refinery prices per m^3 of each product p in Portugal and Spain.

Ex-Refinery prices per m^3				
	jet fuel	diesel	gasoline 95	gasoline 98
Spain	622	547	545	545
Portugal	622	547	535	535

Table 35 estimates the annual demand for each product p in Portugal in 2019 based on the data regarding 2018 and the population of each Portuguese district.

Table 35. Estimated annual demand for products p in Portugal (tonnes).

Annual demand for product p in Portugal (tonnes)					
	Population	jet fuel	gasoline 95	gasoline 98	diesel
Aveiro	814 456		66 365	5 771	341 715
Beja	158 702		12 932	1 124	66 585
Braga	924 351		75 319	6 550	387 823
Bragança	140 385		11 439	995	58 900
Castelo Branco	196 989		16 051	1 396	82 649
Coimbra	541 166		44 096	3 834	227 053
Évora	174 490		14 218	1 236	73 210
Faro	569 714	307 078	46 422	4 037	239 031
Guarda	167 359		13 637	1 186	70 218
Leiria	560 484		45 670	3 971	235 158
Lisbon	2 884 984	926 079	235 079	20 442	1 210 432
Portalegre	120 585		9 826	854	50 593
Porto	2 397 191		195 332	16 985	1 005 772
Santarém	454 947		37 071	3 224	190 879
Setubal	880 765		71 768	6 241	369 536
Viana do Castelo	252 952		20 611	1 792	106 129
Vila Real	214 490		17 477	1 520	89 992
Viseu	378 784		30 865	2 684	158 924
Porto Airport		276 515			

Table 36 presents the annual demand for each product p in Spain from 2013 to 2017. Considering this data and using linear regression, the demand forecast for 2019 was established. The linear regression analysis is shown in Figure 12.

Table 36. Annual demand for each product p in Spain in thousand tonnes.

Annual demand for product p in Spain (thousand tonnes)				
	Products			
	jet fuel	diesel	gasoline 95	gasoline 98
Forecast - 2019	6,917	32,354	4,503	431
2017	6,412	30,814	4,475	389
2016	5,894	30,327	4,379	376
2015	5,501	29,785	4,307	340
2014	5,266	28,378	4,297	314
2013	5,130	28,229	4,336	314

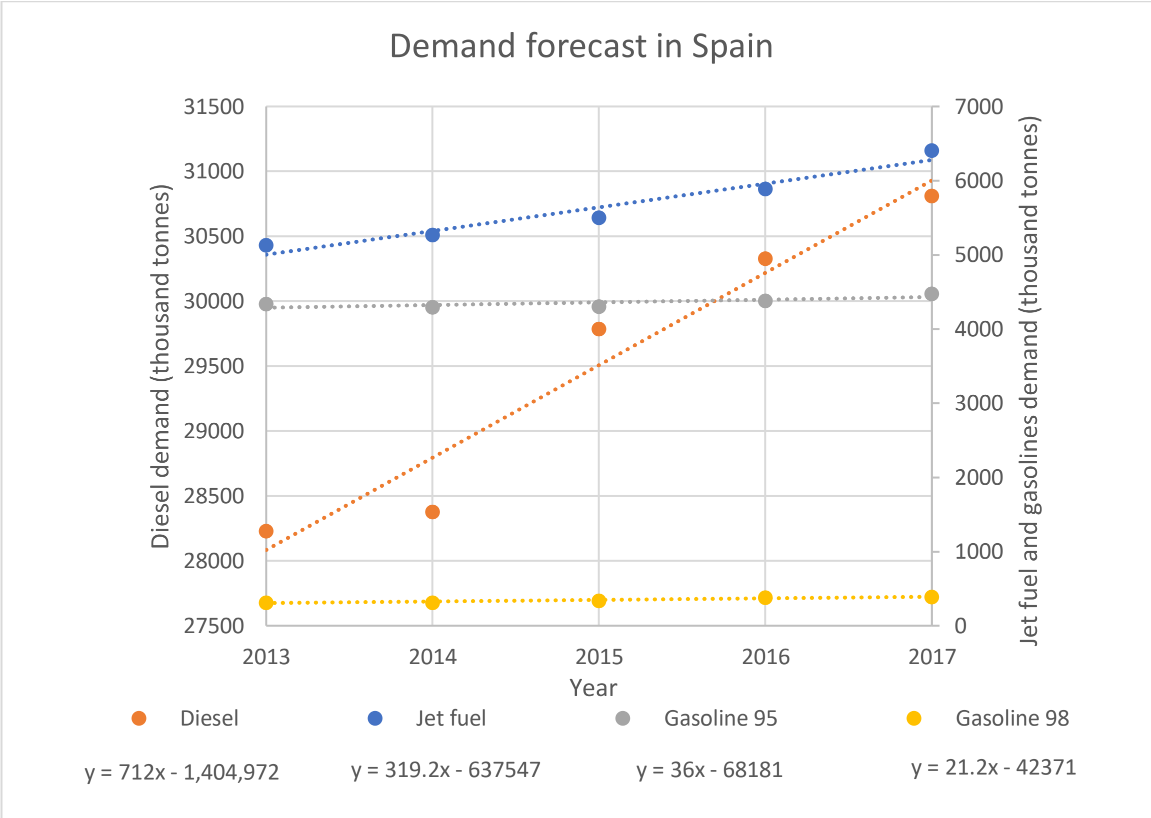

Figure 12. Linear regression analysis of demand forecast in Spain.

Table 37 presents the transportation costs considered in EUR/ton-km. These costs were acquired at Kazemi & Szmerekovsky (2015) and converted from USD to EUR using the conversion rate on December 31st 2013 (1 EUR = 1.38 USD), as the data in Kazemi & Szmerekovsky (2015) was established in 2013.

Table 37. Transportation costs considered in EUR/ton-km.

Transportation costs (EUR/ton-km)	
	C,T,TIMP
pipeline	0.0022
barge	0.0045
rail	0.0315
truck	0.0810

Table 38 presents the maximum fraction of each product that the Portuguese refineries can produce. As no information was found regarding each refinery separately, the same fractions were considered to both of them. Moreover, the maximum fraction is considered with an additional 2% in comparison to the fraction of each product produced in 2018, obtained at Galp's website (GALP, s.d.).

Table 38. Maximum fraction of each product that refineries in Portugal can produce.

$\psi_{p,a}$				
	Products			
Refineries	diesel	jet fuel	gasoline 95	gasoline 98
Sines	0.39	0.12	0.23	0.04
Matosinhos	0.39	0.12	0.23	0.04

Appendix C – Results obtained with the real case study

Table 39, Table 40 and Table 41 present the results obtained for the model implemented considering the real case study with one-year planning horizon. The Portuguese refineries were considered to be working at 100% of their capacity. As the model suggested no depot to be opened, variables X and V are 0. Moreover, according to the model there is no need to import any of the products considered and therefore, variable IMP is also 0. The results for variable γ reached the maximum allowed ψ, available at Table 38.

Table 39. Real case considering Portuguese refineries working at maximum capacity results for variable Y.

Variable Y (m^3/year)							
		gasoline 95			gasoline 98		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		98,743			8,586	
Sines	Tanquisado			268,835			23,377
Sines	Sines terminal	65,243			5,673		
Sines	Sines storage	11,756			1,021		
Matosinhos	Leixoes		431,946			37,560	
Matosinhos	Boa Nova						
		diesel			jet fuel		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		508,435				
Sines	Tanquisado			1,384,248			1,121,050
Sines	Sines terminal	335,941					
Sines	Sines storage	60,531					
Matosinhos	Leixoes		2,224,114				
Matosinhos	Boa Nova				251,377		

Table 40. Real case considering Portuguese refineries working at maximum capacity results for variable Z.

Variable Z (m^3/year)									
		gasoline 95		gasoline 98		diesel		jet fuel	
Origin	Destination	truck	barge	truck	barge	truck	barge	pipeline	barge
Leixões	Aveiro		60,331		5,246		310,650		
Leixões	Braga	68,471		5,954		352,566			
Leixões	Bragança	10,399		904		53,545			
Leixões	Coimbra	40,087		3,485		206,411			
Leixões	Guarda	12,397		1,078		63,834			
Leixões	Porto	177,574		15,440		914,338			
Leixões	Viana do Castelo		18,737		1,629		96,480		
Leixões	Vila Real	15,888		1,381		81,810			
Leixões	Viseu	28,059		2,440		144,476			
CLC - Aveiras de Cima	Castelo Branco	14,591		1,269		75,135			
CLC - Aveiras de Cima	Leiria	41,518		3,610		213,780			
CLC - Aveiras de Cima	Portalegre	8,932		776		45,993			
CLC - Aveiras de Cima	Santarem	33,700		2,930		173,526			
Tanquisado	Évora	12,925		1,123		66,554			
Tanquisado	Faro		42,201		3,670		217,300		279,161
Tanquisado	Lisbon		213,708		18,583		1,100,392		841,889
Sines - Terminal	Setubal		65,243		5,673		335,941		
Sines - Storage	Beja	11,756		1,021		60,531			
Boa Nova	Porto Airport							251,377	

Table 41. Real case considering Portuguese refineries working at maximum capacity results for variable EXP.

Variable EXP (m^3/year)		
Product	Origin	Amount (m^3)
gasoline 95	Sines	2,510,460
gasoline 95	Matosinhos	1,045,573
gasoline 98	Sines	475,260
gasoline 98	Matosinhos	219,399
diesel	Sines	2,721,562
diesel	Matosinhos	281,245
jet fuel	Sines	420,709
jet fuel	Matosinhos	519,502

Table 42, Table 43, Table 44 and Table 45 present the results obtained for the model implemented considering the real case study with 7-year planning horizon. The Portuguese refineries were considered to be working at 82% of their capacity. The results obtained for variable X for j4 was

1 and for j2 and j3 was 0. Therefore, in this case it is considered a pipeline between Sines storage and Faro. As the model suggested no depot to be opened, variable V is 0. Moreover, according to the model there is no need to import any of the products considered and therefore, variable IMP is also 0. The results for variable γ reached the maximum allowed ψ, available at Table 38.

Table 42. Results obtained for variable Y when considering the real case with 7-year planning horizon.

Variable Y (m^3/year)							
		gasoline 95			gasoline 98		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		691,205			60,104	
Sines	Tanquisado			1,586,435			137,950
Sines	Sines terminal	456,705			39,715		
Sines	Sines storage	377,706			32,842		
Matosinhos	Leixoes		3,023,624			262,926	
Matosinhos	Boa Nova						
		diesel			jet fuel		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		3,559,048				
Sines	Tanquisado			9,356,666			5,893,223
Sines	Sines terminal	2,351,592					
Sines	Sines storage	1,944,828			1,954,132		
Matosinhos	Leixoes		14,380,770				
Matosinhos	Boa Nova				1,759,640		

Table 43. Results obtained for variable Z (gasolines 95 and 98) when considering the real case with 7-year planning horizon.

Variable Z (m^3/year)							
		gasoline 95			gasoline 98		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Leixões	Aveiro			422,322			36,724
Leixões	Braga	479,302			41,681		
Leixões	Bragança	72,793			6,331		
Leixões	Coimbra	280,610			24,398		
Leixões	Guarda	86,780			7,547		
Leixões	Porto	1,243,021			108,086		
Leixões	Viana do Castelo			131,160			11,403
Leixões	Vila Real	111,217			9,672		
Leixões	Viseu	196,413			17,080		
CLC - Aveiras de Cima	Castelo Branco	102,142			8,883		
CLC - Aveiras de Cima	Leiria	290,627			25,270		
CLC - Aveiras de Cima	Portalegre	62,529			5,434		
CLC - Aveiras de Cima	Santarem	235,906			20,516		
Tanquisado	Évora	90,478			7,865		
Tanquisado	Lisbon			1,495,957			130,085
Sines - Terminal	Setubal			456,705			39,715
Sines - Storage	Beja	82,294			7,152		
Sines - Storage	Faro		295,412			25,690	

Table 44. Results obtained for variable Z (diesel and jet fuel) when considering the real case with 7-year planning horizon.

Variable Z (m³/year)							
		diesel			jet fuel		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Leixões	Aveiro			2,174,550			
Leixões	Braga	2,467,964					
Leixões	Bragança	374,818					
Leixões	Coimbra	1,444,882					
Leixões	Guarda	446,841					
Leixões	Porto	5,212,331					
Leixões	Viana do Castelo			675,366			
Leixões	Vila Real	572,676					
Leixões	Viseu	1,011,334					
CLC - Aveiras de Cima	Castelo Branco	525,948					
CLC - Aveiras de Cima	Leiria	1,496,460					
CLC - Aveiras de Cima	Portalegre	321,955					
CLC - Aveiras de Cima	Santarem	1,214,684					
Tanquisado	Évora	465,881					
Tanquisado	Lisbon			7,702,749			5,893,223
Tanquisado	Porto			1,188,035			
Sines - Terminal	Setubal			2,351,592			
Sines - Storage	Beja	423,722					
Sines - Storage	Faro		1,521,106			1,954,132	
Boa Nova	Porto Airport					1,759,640	

Table 45. Results obtained for variable EXP when considering the real case with 7-year planning horizon.

Variable EXP (m³/year)		
Product	Origin	Amount
gasoline 95	Sines	13,849,880
gasoline 95	Matosinhos	5,457,340
gasoline 98	Sines	2,679,287
gasoline 98	Matosinhos	1,212,024
diesel	Sines	11,549,400
diesel	Matosinhos	
jet fuel	Sines	1,002,346
jet fuel	Matosinhos	2,665,210

Table 46, Table 47, Table 48 and Table 49 present the results obtained for the model implemented considering the real case study with 10-year planning horizon. The Portuguese refineries were considered to be working at 82% of their capacity. The results obtained for variable X for j2 and j4 was 1 and for j3 was 0. Therefore, in this case it is considered a pipeline between CLC – Aveiras de Cima and Lisbon and another pipeline between Sines storage and Faro. As the model suggested no depot to be opened, variable V is 0. Moreover, according to the model there is no need to import any of the products considered and therefore, variable IMP is also 0. The results for variable γ reached the maximum allowed ψ, available at Table 38.

Table 46. Results obtained for variable Y when considering the real case with 10-year planning horizon.

Variable Y (m^3/year)							
		gasoline 95			gasoline 98		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		3,124,517			271,699	
Sines	Tanquisado			129,254			11,236
Sines	Sines terminal	652,436			56,736		
Sines	Sines storage	539,581			46,918		
Matosinhos	Leixoes		4,319,463			375,609	
Matosinhos	Boa Nova						
		diesel			jet fuel		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Sines	CLC - Aveiras de Cima		16,088,284			8,418,890	
Sines	Tanquisado			2,362,738			
Sines	Sines terminal	3,359,418					
Sines	Sines storage	2,778,327			2,791,618		
Matosinhos	Leixoes		20,543,950				
Matosinhos	Boa Nova				2,513,772		

Table 47. Results obtained for variable Z (gasolines 95 and 98) when considering the real case with 10-year planning horizon.

Variable Z (m^3/year)							
		gasoline 95			gasoline 98		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Leixões	Aveiro			603,318			52,463
Leixões	Braga	684,718			59,545		
Leixões	Bragança	103,990			9,045		
Leixões	Coimbra	400,872			34,854		
Leixões	Guarda	123,972			10,781		
Leixões	Porto	1,775,745			154,409		
Leixões	Viana do Castelo			187,372			16,290
Leixões	Vila Real	158,881			13,818		
Leixões	Viseu	280,590			24,400		
CLC - Aveiras de Cima	Castelo Branco	145,918			12,690		
CLC - Aveiras de Cima	Leiria	415,181			36,100		
CLC - Aveiras de Cima	Lisbon		2,137,081			185,836	
CLC - Aveiras de Cima	Portalegre	89,327			7,763		
CLC - Aveiras de Cima	Santarem	337,009			29,309		
Tanquisado	Évora	129,254			11,236		
Sines - Terminal	Setubal			652,436			56,736
Sines - Storage	Beja	117,563			10,218		
Sines - Storage	Faro		422,018			36,700	

Table 48. Results obtained for variable Z (diesel and jet fuel) when considering the real case with 10-year planning horizon.

Variable Z (m^3/year)							
		diesel			jet fuel		
Origin	Destination	truck	pipeline	barge	truck	pipeline	barge
Leixões	Aveiro			3,106,500			
Leixões	Braga	3,525,663					
Leixões	Bragança	535,454					
Leixões	Coimbra	2,064,118					
Leixões	Guarda	638,345					
Leixões	Porto	7,446,188					
Leixões	Viana do Castelo		964,809				
Leixões	Vila Real	818,109					
Leixões	Viseu	1,444,763					
CLC - Aveiras de Cima	Castelo Branco	751,354					
CLC - Aveiras de Cima	Leiria	2,137,800					
CLC - Aveiras de Cima	Lisbon		11,003,930			8,418,890	
CLC - Aveiras de Cima	Portalegre	459,936					
CLC - Aveiras de Cima	Santarem	1,735,263					
Tanquisado	Évora	665,545					
Tanquisado	Porto			1,697,193			
Sines - Terminal	Setubal			3,359,418			
Sines - Storage	Beja	605,318					
Sines - Storage	Faro		2,173,009			2,791,618	
Boa Nova	Porto Airport					2,513,772	

Table 49. Results obtained for variable EXP when considering the real case with 10-year planning horizon.

Variable EXP (m^3/year)		
Product	Origin	Amount
gasoline 95	Sines	19,785,540
gasoline 95	Matosinhos	7,796,200
gasoline 98	Sines	3,827,553
gasoline 98	Matosinhos	1,731,462
diesel	Sines	16,499,140
diesel	Matosinhos	
jet fuel	Sines	1,431,922
jet fuel	Matosinhos	3,807,443