Master's degree thesis

LOG953 Logistics

Integrated decision-making on the utilization of capacities throughout the push segment of vertically integrated petroleum companies

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Preface

This thesis represents the mandatory final part of the Master of Science Degree in Petroleum Logistics at Molde University College.

Firstly, I would like to express my deepest gratitude to Assoc. Prof. Yury Redutskiy, my supervisor, for his continuous support, encouragement, and guidance throughout the process of writing this thesis. I will be forever grateful for all these. I also wish to express my appreciation and thanks to all lecturers as well as all staff at Molde University College who helped me to obtain the knowledge, supported my study and my student life during the past two years.

I sincerely thank my family for their everlasting love, support, encouragement during the time I study away from home. Finally, I would like to express my endless gratefulness to God, who is always watching, protecting, leading me on my lifeway, who gave me this excellent opportunity to study in Norway, "Faith, prayer, study, and hard work make a winning combination" - Russell M. Nelson.

Lan Thanh Pham,

May 2020, Molde, Norway.

Summary

For industries requiring high capital investment and involves many stages such as the petroleum, vertical integration is considered as one of the most effective strategic approaches ensuring the full coordination of all stages, achieve better supply chain control. The petroleum industry offers an excellent platform for vertically integrating when the output of the previous stage is the input of the next stage.

The set goals of this thesis are solved using an exploratory research methodology and quantitative technique based on computational testing. The data for the computational example were collected from high-quality research with consulting experts to verify the appropriateness of data.

Firstly, the theories of supply chain management and vertical integration will be reviewed to build the foundation for the next steps as well as orientate for answering research questions. Then, the structure of a petroleum supply chain, vertical integration in supply chain management of petroleum companies, push and pull strategies are analyzed, providing crucial insights to formulate the mathematical model and collect data.

Next, a MILP model of integrating decision-making on the utilization of capacities throughout the push segment of vertically integrated petroleum companies will be proposed. The objective is minimizing the total cost, including costs of production, inventory holding, transporting, connection setup, and electricity consumption. Capacity decisions are integrated consist of output and inventory level at an FPSO, offload scheduling of shuttle tankers, incoming/outgoing amounts of crude oil from/to storage tanks, inventory levels at storage tanks, the flowrate transferring crude oil from storage tanks to a distillation unit will be made based on oil forecasted demand of this quarter. AMPL/CPLEX solver is used to solve the optimization model.

Finally, the limitations of the proposed model and conclusions of research will be pointed out. Future research in this direction will also be suggested.

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List of Abbreviations

BILP	Binary Integer Linear Programming
CDU	Crude oil Distillation unit
FPSO	Floating Production, Storage and Offloading unit
MIP	Mix Integer Programming
MILP	Mix Integer Linear Programming
MINLP	Mix Integer Non-Linear Programming
MIRP	Maritime Inventory Routing Problem
NLP	Non-Linear Programming
OPP	Order Penetration Point
PSC	Petroleum Supply Chain
SCM	Supply Chain Management
ST	Shuttle Tanker

1 INTRODUCTION

1.1 Background

The petroleum industry is significant from different points of view and involves major economic flows (Manzano 2005). It is also regarded as one of the largest industries in terms of capacity and the most sophisticated in terms of technique in the world (East Asia Forum 2016). The modern history of petroleum began in the 19th century with the refining of paraffin from crude oil (Owen 1975). Although petroleum products were first used for heating and lighting, with the development of diesel, petrol, and jet engines, demand for the industry's products has accelerated rapidly following the end of World War II.

According to BP Energy (2019), the energy consumption demand in general and hydrocarbon, in particular, continue to grows in all sectors, with industry and buildings account for three-quarters of the increase in energy demand. Oil consumption increases during the first half of the Outlook - perspective to 2040. It is much slower than in the past then will peak in the 2030s while natural gas consumption grows much faster than either demand of oil or coal and overtakes coal to be the second-largest source of global energy equivalent to oil by the end of the Outlook. The growth of energy demand comes from the increase in the worldwide population, the growing world economy, increasing urbanization, despite a volatile oil price, environmental controversies (BP Energy 2019). Hydrocarbons are used in many aspects of modern-day society, power our homes, vehicles. Hydrocarbons are also the raw materials for polymers, which are then used to produce plastic, fabrics, medicines, cosmetics, even solar panels. So far, there are no viable alternatives for essential petroleum products like petrochemicals and lubricants. Hence, it is evident that hydrocarbons present in every step of life, and the demand for hydrocarbons will continue to grow shortly.

Over a few recent decades, many argue that the petroleum industry has entered a recession, with the depletion of resources (Bentley 2002). Admittedly, these fears are not unfounded. According to U.S. Energy Information Administration (EIA) (2019), the global supply of crude oil, other liquid hydrocarbons, and biofuels is expected to meet the world's demand for liquid fuels until 2050. However, resource scarcity has not been considered as the cause of production constraints. In reality, there is still a great potential that comes from proven reserves; novel technologies allow to increase exploitation efficiency, further discoveries such as oil and gas in the Arctic region, oil sands, and oil shale reserves in North America.

Scientific and technical advances play a vital role in the petroleum industry, addressed all sorts of challenges: exploration, exploitation, and production; efforts to protect the environment; extend the reach of the sector and reduce project costs. The petroleum industry includes various links supplied by multiple individual service providers in their specialized fields. Therefore, supply chain management (SCM) is also one of the most significant challenges that the industry is facing. In today's world of business, petroleum companies cannot be productive and competitive as well as survive without taking the SCM concepts into account (Sahebi et al. 2014).

Societal changes, globalization, and technological advances are dramatically changing the business environment of most industries (Chan 2013). The market is becoming more fiercely competitive than ever. Businesses are forced to devise specific strategies. Obviously, instead of each stage acts in its local interests, coordination among all stages along the supply chain increases efficiency and reduces risks. Integrating the supply chain could be a solution for businesses to manage their organizations and relationships with other companies in the same chain. Managing the supply chain in an integrated and cohesive system is expected to reduce costs, improve competitiveness, and operational efficiency.

Considered as a giant industry with high profit, petroleum companies have a common belief that there is a correlation between vertical integration, size, and performance (Rey and Fernando 1995). The largest world petroleum companies such as Exxon, Shell, BP, etc. have been vertically integrated for a long time, undertake most stages in the supply chain, from exploration, production, and processing to transportation, marketing, and retailing to supply final products to end customers. Vertical integration is one of the strategic approaches to ensure the full coordination of all stages and achieve better control.

1.2 Statement of purpose

"Definiteness of purpose is the starting point of all achievement" (Hill and Stone 1991). The goal of this master's thesis analyzes the vertical integration in SCM of the petroleum industry to propose an integrated decision-making model on the utilization of capacities of the push processes in the petroleum supply chain (PSC). *"Well-formed questions are the key to good research"* (Curry 2015). Here are some research questions that will be clarified:

1. Why is there a need to coordinate the activities of the actors in a supply chain?
2. What are the context and driving forces of vertical integration in PSC?
3. How push and pull strategies are expressed in PSC?
4. Which activities can be coordinated, what are the capacities of the actors?
5. What is the planning level (tactical, operative, or both) suitable for the coordination of capacity utilization in a push-segment of PSC?

1.3 Research methodologies and Data collection

"Methodology in research can be considered to be the theory of correct scientific decisions" (Mouton and Marais 1996). The literature review is an integral part of the success of academic research, ensuring the research ability of the topic, providing an academically enriching experience to obtain more knowledge and understanding of the subject (Hart 2018). This review of the literature will allow us to answer the questions of the research and provide propositions in this thesis. For the literature research, the resources of Molde University College's library and the online databases such as ScienceDirect, ResearchGate, and ProQuest, lectures, documents, and textbooks provided or suggested by lecturers during courses are used. A review aims to highlight the importance and practical significance of the research problems allowing readers to understand why this research direction is pursued.

The choice of research design is based on the book *"Research methodology: Methods and techniques"* written by Kothari in 2004. Kothari (2004) categorize different research designs as three types: (1) research design in case of exploratory research studies; (2) research design in case of descriptive and diagnostic research studies, and (3) research design in case of hypothesis-testing research studies. The particular interest of this thesis is to explore the coordination in SCM of vertically integrated petroleum companies. The exploratory research methods will be used to formulate the problem for more precise investigation from an operation point of view, major emphasizing the discovery of ideas and insights, considering different aspects of issues under study.

Moreover, the theoretical quantitative method based on computational testing will be employed in formulating the mathematical model for the problem of integrated capacity decision-making in vertically integrated petroleum companies. The decomposition method could be used to more straightforward the problem into smaller ones. The MILP model combines sub-models according to their function in the chain (production, inventory, transportation, connection scheduling, and pumps' operation) plays as constraints with the objective function is minimizing total cost that will be solved by AMPL/CPLEX solver.

The data for computational runs is based on high-quality research and additional consulting with experts to verify the appropriateness of this example data. In the research model, both primary and secondary data such as the operational data of FPSO, shuttle tankers, storage tanks, pipeline, pump, the total demand of distillation unit for a quarter, costs of production, inventory holding, transportation, connection setup, electricity consumption will be used. Also, data and relevant information from articles published in academic journals, textbooks, and reports from official websites of subject-related organizations will involve.

1.4 Structure of the thesis

The rest of the thesis is set out as follows:

- Chapter 2 presents a theoretical framework of the research, about SCM and vertical integration in SCM. The first part offers the definition of SCM and relevant concepts, including hierarchical decision-making levels, groups of decision, push and pull strategies in SCM. In the second part, the description and driving forces of vertical integration in SCM will be described. The first chapter gives the necessary knowledge to build a platform for the study and orientate to answer the research questions in the next sections.
- Chapter 3 describes PSC and vertical integration in the petroleum companies in detail. An overview of the structure of the chain, with the sequences of the major nodes, links represent the interface between stages, and materials that flow through the supply chain will be reviewed in the first part. In the second part, the application of vertical integration in managing PSC consists of driving forces, the context, push and pull strategies will be analyzed. The purpose of this chapter is to clarify research questions and provide crucial insights to build the mathematical model and collect data.
- In chapter 4, a literature review about PSC coordination - specifically these four topics: maritime inventory problem, crude oil scheduling problem, integrating the management of crude oil supply, linking multiple segments, will be conducted. The objective of this chapter is to study what stages of PSC are feasible to coordinate and what methods have been applied by authors to build integrating decision-making models.

- In chapter 5, the mathematical model of the integration of decision-making on capacity utilization throughout a vertically integrated petroleum supply chain will be proposed. Problem description, mathematical model formulations will be presented. Computational run of the model, results, and discussions upon the results will also be performed in this chapter.
- The final chapter - chapter 6 gives the conclusion for the research about whether the defined objective has been fulfilled, research questions have been clarified yet. Limitations of this research will also be pointed out. Future research on the problem of integrating decision-making for vertically integrated petroleum companies will also be suggested.

2 SUPPLY CHAIN MANAGEMENT AND VERTICAL INTEGRATION THEORY OVERVIEW

2.1 Supply chain management and relevant concepts

2.1.1 Supply chain understanding

A supply chain includes all parties directly or indirectly involved in the process of meeting customer demands, not only suppliers, manufacturers, but also transportation, warehouses, distributors, retailers, and consumers (Chopra and Meindl 2016). Supply chains exist in both production and service, either in a single company or within an industry (Ram and Harrison 1995). The complexity of the supply chain varies widely depending on the field (Sengupta et al. 2006).

According to Oliver and Webber (1982), the term of SCM was initially introduced by consultants in the early 1980s. SCM has subsequently gained tremendous attention over the past few decades and has been defined by many different authors (Bryan and McDougall 1998; Chopra and Meindl 2001; Christopher 1992; La Londe and Masters 1994; Stevens 1989). For the research direction of this thesis, the definition suggested by Christopher (1992) is appropriate *"the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole."* A simple model of downstream and upstream supply chain involves both suppliers and customers in the SCM process is depicted in Figure 1.

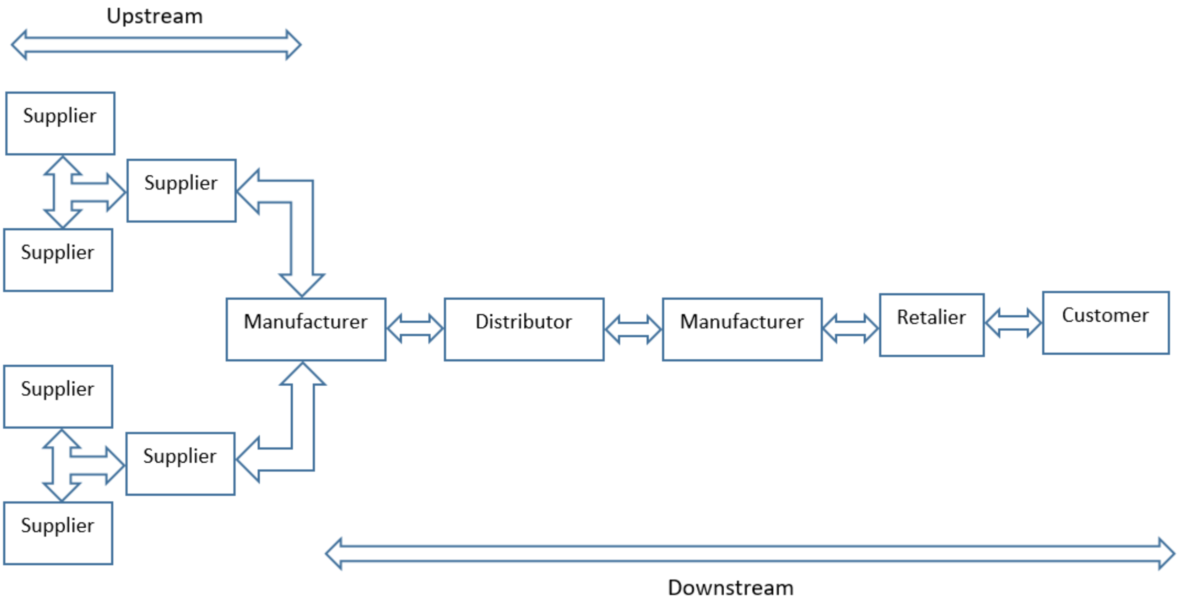

Figure 1. An example of a supply chain (adapted from (Christopher 1992))

To be more specific, SCM is a combination of approaches used to manage supply chain assets and resources. Assets and resources circulated along the supply chain often include materials, information, capital, technology, machinery, financial assets, and others. In other words, SCM is a strategic concept aiming at effectively linking a chain of relationships, from raw material suppliers, producers, transporters, warehousing, distributors, retailers to consumers. Thereby, the commodities can be produced and distributed in the right quantities, to the right place and at the right time, to minimize the total cost of the whole system while still satisfying the level of service requirements (Simchi Levi et al. 2003; Tan et al. 1998). SCM provides a panorama of the business system to help managers devise production development strategies that are most effective and deliver goods to consumers as affordably and quickly as possible.

The value generated by a supply chain is understood as the difference between the value of the final product to customers and the costs incurred throughout the supply chain to be able to provide that product, consist of research cost, producing cost, storage cost, shipping cost, selling cost, and others (Chopra and Meindl 2016). However, each stage in the supply chain tends to take action to maximize its profits without considering the impact on the whole chain, which is one of the weakest points of SCM. The goal of satisfying customers, as well as the opportunities that cooperation decisions brought, might be lost, leading to generate non-value adding activities related to excess time, labor, equipment, space, and inventories (Chopra and Meindl 2016). Therefore, to achieve the objective of SCM, suppliers, manufacturers, distributors, retailers should work in a collaborative, closely linked environment as departments of a company to respond adequately, quickly and accurately raw materials and goods that the next stage needs, avoid problems that arise with suppliers and reduce the risk of the supply-demand gap that the company faces during its operation. There is a need for a mechanism by which different partners in the supply chain have a collaboration.

As a common knowledge, poor coordination among the chain members cause dysfunctional operational performance: higher inventory costs, longer delivery times, higher transportation costs, higher levels of loss and damage, and lowered customer service (HL Lee et al. 1997). Moharana et al. (2012) indicate coordination is an interactive, joint decision-making process, where separate entities influence others' decisions more directly, aiming at achieving global optimization within a defined supply chain network. Lack of coordination occurs when decision-makers have incomplete information or incentives that are incompatible with the objectives of the whole system. From the perspective of the company, coordination involves the issues: ensuring supplier's effectiveness in terms of cost, timeliness, and quality; setting appropriate targets for inventory, capacity, and lead time; monitoring demand and supply conditions; communicating market and performance results to customers and suppliers (Chima 2007).

Entering the 21st century, SCM has become a strategic tool, with outstanding across speed, quality, cost, and flexibility (Ketchen Jr et al. 2008). Research from 196 organizations shows that SCM has helped improve the competitive advantage and organizational performance of researched subjects (S. Li et al. 2006). There are many businesses worldwide that have been successful in applying supply chains such as HP, Dell computers, Walmart, P&G, Seven-Eleven, Toyota (Chopra and Meindl 2016). The coordination of the activities among the actors plays a vitally important role and is indispensable in building an effective supply chain. The question is how to promote the effectiveness of SCM for each specific industry and enterprise.

2.1.2 Three hierarchical decision-making levels

SCM involves many issues, from the configuration, coordination to the continuous improvement (Chima 2007). Traditionally, SCM has three levels of decision: strategic, tactical, operational with the corresponding time horizon periods are long-term, mid-term, and short-term that different parts of the company will focus. *"The longer the time horizon a decision considers, the less frequent the decision is made and the greater its ramifications"* (Robertson et al. 2011). The strategic level - supply chain design or configuration involves a relatively long time horizon of over the next several years, dealing with establishing the optimal network, affecting the whole organization, and focusing on a significant investment. The tactical level - supply chain planning and scheduling might deal with the time horizon of a quarter to a year, revealing the best flow of materials, addressing issues such as production, inventory, and distribution. The operational level - supply chain control makes weekly or daily decisions (real-time management), or both; decisions regard ongoing operational activities and resource allocation.

2.1.3 Key groups of decisions in supply chain management

Harrison and Ganeshan (2001) categorize SCM decisions into four major areas: location, production, inventory, and transportation (distribution). More specifically, SCM entails making decisions about where to locate plants and distribution centers, what to produce, how much to produce at each site, what quantity of goods to hold in inventory at each stage of the process, what means of transport is used.

Location decisions: Facility location's decisions play a critical role in the efficient and effective operation of a supply chain. Poorly placed plants and warehouses can result in high costs and degraded service, no matter how well inventory policies, transportation plans, and information sharing policies (Daskin et al. 2005). Deciding where to place facilities, the number of facilities, the capacity assigned to each facility, involve the commitment to resources for the company's long-term plans and allow to visualize the channels through which the products are distributed to consumers (Chopra and Meindl 2016). Location decisions express the company's primary strategy of reaching the market and affecting sales, costs, and customer service (Harrison and Ganeshan 2001). Although these decisions are primarily strategic, they are closely related to tactical and operational levels.

Production decisions: Strategic decisions include: what products to produce, which plants to produce them in, allocation of suppliers to plants, plants to distribution centers, and distribution centers to customer markets, who will be the strategic partners, what parts will be self-produced and what will be outsourced from elsewhere? These decisions have a significant impact on the company's revenue, costs, and customer service. One of the critical strategic decisions is the capacity of the manufacturing facilities, expansion/reduction of the production equipment. Operational decisions will focus on the detailed production scheduling, including the construction of the master production schedules, scheduling production on machines, and equipment maintenance. Workload balancing and quality control measures at a production facility need special attention (Harrison and Ganeshan 2001).

Inventory decisions: Inventory decisions appear at any stage of the supply chain, from stockpiling raw materials, semi-finished products to final products (Harrison and Ganeshan 2001). The main goal of inventory is to deal with the mismatch between supply and demand, uncertain situations that may occur in the supply chain to effectively create a more responsive and more efficient supply chain (Chopra and Meindl 2016). Inventory decisions can be strategic planning when top management sets an objective; however, it can also be approached from a tactical perspective (Harrison and Ganeshan 2001). Specifically, how to determine a safe inventory level, the threshold at which the order should be placed. The determination of these levels of reserves is vitally important because it is a crucial factor in the quality of customer service.

Transportation (distribution) decisions: Transportation strategy, including frequency, routes, and contracting, are tactical decisions while shipping from suppliers and receiving inventory and distribution planning are operational decisions (Patel 2009). These decisions are closely related to the decisions about inventories due to when selecting suitable means of transport, there must be a trade-off between the cost of using the vehicle and the indirect cost of inventory holding arising when using such means (Chopra and Meindl 2016). For example, when using air freight, it is usually faster, more reliable, and requires fewer inventories but costs more. Sea transport would be much cheaper, but it would take more time, and more stocks would be needed in case of uncertainties. Therefore, the requirement of customer service level or geographical location will play a significant role in making these decisions because transportation costs often account for a high proportion of the total cost, if operated properly, it will bring high economic efficiency (Harrison and Ganeshan 2001).

2.1.4 Push and pull in supply chain

There are various strategies in SCM; one of the traditional ways to classify these strategies is dividing them into "push" and "pull" strategies. This classification originated from the manufacturing revolution of the 1980s, and progressive companies have started to employ a hybrid approach, combined push and pull in the last few years (Simchi Levi et al. 2003). Push/pull view of the supply chain is often used when considering strategic decisions relating to supply chain design (Chopra and Meindl 2016). Figure 2 illustrates the push and pull view of the supply chain.

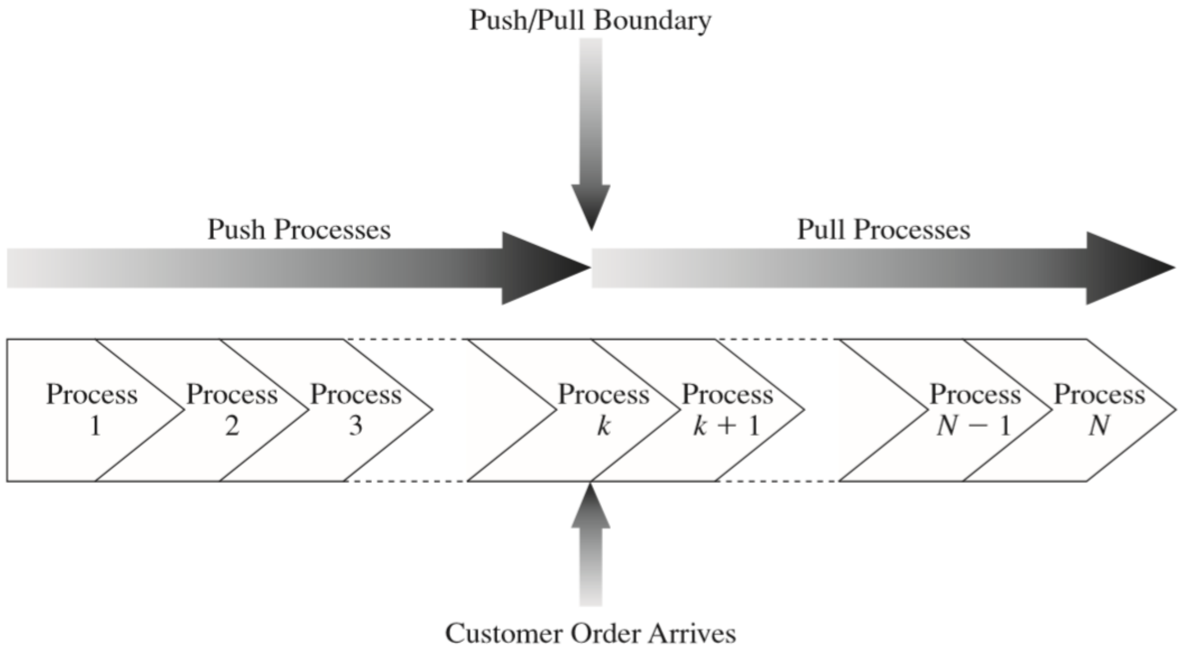

Figure 2. Push/Pull View of the Supply Chain (Chopra and Meindl 2016)

Push process starts with forecasts that are used to build the master production schedule, creating schedules for suppliers with types of parts, quantities, and delivery dates. All processes are performed based on the anticipation of customer demand; thus, it may also be referred to as speculative processes. The manager makes a plan of the activity levels, be it production, transportation, or any other planned activities (Chopra and Meindl 2016). In the push-based supply chain, due to production and distribution decisions are made according to long-term predictions, a slow reaction to the changes in the marketplace might happen (Ahn and Kaminsky 2005).

The pull process is initiated by customer order and referred to as reactive processes because they react to confirmed customer orders (Chopra and Meindl 2016). In the pull-based supply chain, information on actual orders will be transmitted quickly throughout the entire chain, coordination among different stages in a supply chain is required strictly, each stage to share appropriate information with other stages. Therefore, production and distribution can reflect real demand accurately. The manager makes plans of the level of available capacity and inventory, but not the actual amount to be executed (Chopra and Meindl 2016). Adequate customer demand information flow allows minimizing inventory level, lead time, and diminishing in variability, thus improve the ability to manage resources and reduces system costs comparing to similar push systems. However, it is challenging to take advantage of economies of scale in manufacturing and transportation since systems are not planned far ahead in time, like in a push system (Ahn and Kaminsky 2005).

Table 1. Strategic issues, reasons, and negative effects of shifting OPP forwards and backward (Olhager 2003).

	Competitive advantage addressed	**Reasons for forwarding shifting**	**Negative effects**
forwards	Delivery speed Delivery reliability Price	Reduce the customer lead-time Process optimization (improved manufacturing efficiency)	Rely more on forecasts (risk of obsolescence) Reduce product customization (to maintain in work-in-process and inventories levels)
backwards	Product range Product mix flexibility Quality	Increasing the degree of product customization Reduce the reliance on forecasts Reduce or eliminate work-in-process buffers Reduce the risk of obsolescence of inventories	Longer delivery lead times and reduced delivery reliability (if production lead times are not reduced) Reduced manufacturing efficiency (due to reduced possibilities to process optimization)

Push processes are operated in an uncertain environment in which customer needs are unpredictable. In contrast, pull processes work in a situation in which customer demands are known for sure, however, pull processes are often constrained by inventory levels and capacity decisions that were made in the push phase (Chopra and Meindl 2016). No real supply chain can be managed purely by either of these two. In actual, a hybrid approach that combines the best features of both push and pull rather than differentiating between the two must be applied, depending upon the manufacturing system (Ramachandran et al. 2002). *"In a hybrid push/pull system is operated in a push-type fashion that uses forecasts for the initial period and then in a pull-type fashion that uses the replenishment level for the remaining period"* (Hirakawa 1996). The interface between the push-based processes and the pull-based processes is often known as the push-pull boundary, decoupling point, or the order penetration point (OPP). Determining the appropriate positioning of the decoupling point is a vital design issue in SCM (Jeong 2011). Oversupply leads to inefficient capital investment, massive markdowns, and unnecessary handling costs (inventory risk) while losing sales is the consequence of excessive demand without responding promptly (supply risk) (Cachon 2004). The order penetration point can move forward or backward to the end customers depending on many reasons and effects (Olhager 2003), which are summarized in Table 1.

2.2 Vertical integration in supply chain management

2.2.1 Vertical integration understanding

The concept of vertical integration existing today came in the 1880s from Andrew Carnegie - a self-made steel tycoon and one of the wealthiest 19th century US. Carnegie created huge vertically integrated steel complexes starting from expanding his operations by buying iron mines and railroad companies, effectively lowering his costs and increasing productivity across the board. A large domestic market, competitive and cheaply available raw material, applying advanced technology to mass volumes had created conditions for this vertical integration (Biography.com Editors 2019; Desai 2001).

Harrigan (1983) defines vertical integration strategy as a combination of decisions whether a firm should provide goods and services in-house through its business units or purchasing them from outsiders. The decisions include the degree of vertical integration - how much of a particular product or service to transfer in-house or sell to outsiders and number of stages of processing, how far backward or forward within a vertical chain of activities to integrate. Forward integration is when a company at the beginning of the supply chain controls and owns "downstream" activities. Backward integration is when business at the end of the supply chain takes "upstream" on operations.

For SCM, Majumdar and Ramaswamy (1994) describe vertical integration as the overall scope in which different business activities in a supply chain are under the management of a single company. Kenton (2019) also suggests that vertical integration is a management strategy whereby a company owns and controls its supply chain, from suppliers, distributors to retail locations. Therefore, vertical integration allows companies to control all processes, achieve better information sharing, and improve efficiencies. It is the way companies choose to compete in every stage of the chain, from materials to customers. However, vertical integration requires significant amounts of capital investment, and companies might get too big so that the management of the overall process becomes more complicated, requiring highly qualified and experienced managers. Vertical integration is considered as a corporate strategy and a supply chain governance strategy, so it relates to organizational economics and strategic SCM (Guan and Rehme 2012).

2.2.2 Driving forces

Majumdar and Ramaswamy (1994) suppose vertical integration is driven by two major theoretical frameworks: traditional and transactional. From the conventional point of view, vertical integration is a response to technological and operational interdependencies between two successive stages of the activity chain. From the transactional framework point of view, businesses facing more considerable environmental uncertainty, and behavioral uncertainty, having higher asset specificity and frequencies of the transaction will be more likely hood to integrate (Alfred 1977; Bain 1968).

Profit-maximizing firms will undertake those activities that they find cheaper to administer internally than to purchase in the market (Klein et al. 1978). Companies are recommended to focus on the activities that it does best, mining companies focusing on mining, timber companies focusing on sawn timber production, manufacturing companies focusing on varied types of production, from producing components to assembling finished products. In this way, each company can keep up with the change rate and collect the new skills needed to compete in business. If the input material is unrelated, unique, or exclusive to the company's current business, vertical integration is unnecessary. However, although the input production is consistent with the company's current focus area, vertical integration is an appropriate solution only if internal suppliers are more competitive than external suppliers. On the other hand, if a company holds an exclusive right of an input, vertical integration is considered worthwhile (Chima 2007).

3 THE PETROLEUM SUPPLY CHAIN AND VERTICAL INTEGRATION IN PETROLEUM COMPANIES

3.1 The petroleum supply chain

A typical oil supply chain is depicted in Figure 3. At the highest level of the oil supply chain, exploration is the initial phase of operations. A prospective area is discovered by conducting seismic, geophysical, and geological operations and drilling of an exploration well. Appraisal, development phases follow successful exploration. The production phase occurs after successful exploration and development; hydrocarbons are extracted from a field. After production, the crude oil is then transferred to onshore terminals by sub-sea pipelines or shipped directly from overseas sources by vessels. Oil terminals are connected to refineries through a pipeline network. Crude oils might be from various sources with different quality and composition transmitted to refineries by this pipeline network (Schlumberger Oilfield Glossary).

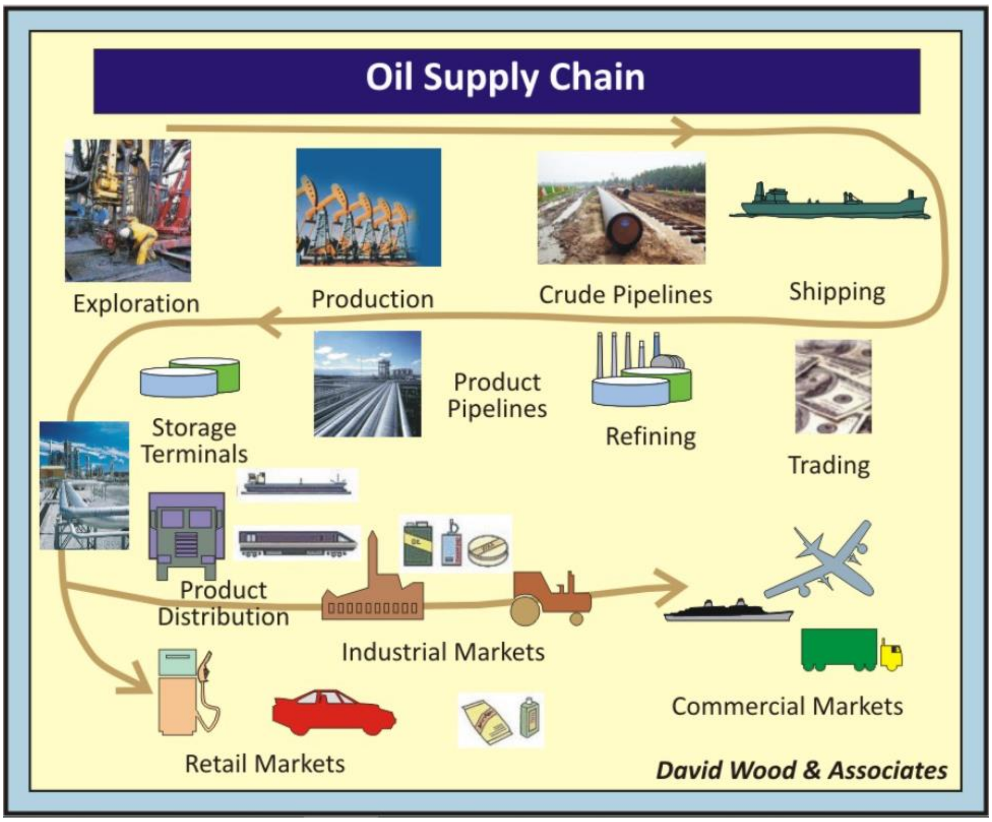

Figure 3. Oil supply chain (http://www.dwasolutions.com/images/OilSupplyChain.jpg)

A refinery is a system composed of docks, pipelines, a series of tanks to store the crude oil (and prepare the different blends), distillation units, and production units such as reforming, cracking, alkylating and hydro-treating, blenders, and tanks to store the raw materials and the final products (Saharidis et al. 2009). Refineries can be connected to take advantage of each refinery design within the complex (Neiro and Pinto 2003). At the refineries, crude oils are processed and blended to make various products such as gasoline, lubricants, and petrochemicals. Besides, some other refining products are semi materials of a variety of different processes such as benzene can be alkylated to ethylbenzene and cumene, which are then used as inputs for the production of styrene and phenol (Kuo and Chang 2008). Products produced at the refineries are sent to the distribution centers, up to this level, crude oil and products are often transported through pipelines. Marketing is the last stage in the oil supply chain, selling oil derivatives to end customers. From this level on, products can be transported either through pipelines or trucks, depending on consumer demands. In some cases, products are also transported through vessels or by train (Neiro and Pinto 2004).

The supply chain of the petroleum industry is often considered under two closely linked major segments: upstream and downstream. The upstream process involves the exploration, crude oil extraction, acquisition, and logistics management of delivering crude oil from remotely located oil wells to refineries. The downstream process starts at the refinery involves demand forecasting, refining, and logistics management of delivering refining products and semi-products to customers globally.

3.2 Vertical integration in petroleum companies

3.2.1 Driving forces for vertical integration in petroleum companies

For PSC, each link of the chain can be undertaken by a separate company or a unit of an integrated firm. The standard-issue along the links in the petroleum supply-chain is economics, the costs versus benefits of stages along the chain need to be weighed (Chima 2007). The objective of optimizing and planning PSC is to minimize the cost of production, operations, transportation, storage, and distributions, while satisfying customer demands and preserving market share, along with maximizing sales revenues (Elsaghier 2017).

The work of Jenkins and Wright (1998) consider the petroleum industry as a prime example of industry constrained by an inflexible supply chain. This inelasticity is derived from three features: (1) all the purchases of the product (quantity and location) are agreed typically in nine months before actual sale; (2) primary distribution using pipeline or coastal shipping from the refinery to the depot has the fixed capacity and no option to increase; (3) highly specialized secondary distribution with few alternatives sources of supply and capacity has to be booked on the take-or-pay agreement, takes the product from the supplier or pays the penalty to the supplier if not. Costs and risks increase as a result of more technical and operational difficulties in the new frontiers. In some remote areas, petroleum operations can take place 24/7; if the materials are not delivered on time, it can lead to significant consequences (Johnsen et al. 2007). Logistics is the only flexible element of the supply chain, which could be re-deployed to increase the responsiveness (Hassen and Szucs 2012; Jenkins and Wright 1998). The long lead time, manufacturing capacity, and limited means of transportation can also be the reasons for supply chain inflexibility (Hussain et al. 2006).

According to Hussain et al. (2006), the supply chain of the petroleum industry is extremely complex compared to others. While production is limited in several specific regions of the world, the product demand is global since hydrocarbon products are the essential raw material for many other industries. Crude oil has to take a long journey from the point of production to the end customer through different modes of transportation such as pipelines, vessels or tankers, and railroads. Long-distance between supply chain partners results in a long lead time of several weeks. Therefore, transportation costs, in-transit/safety stock inventory costs are often high (Hussain et al. 2006). It should be noticed that the depletion of existing reserves forces many companies to step up petroleum exploration and production activities to more remote, deeper, and smaller fields (Managi et al. 2004). The petroleum industry has high technical qualifications, with strict health, safety, security, and environmental requirements, which also adds to the complexity. When many services are outsourced to a variety of providers, complexity, and a fragmented supplier base can happen (Bresciani and Brinkman 2016).

The complexity and inflexibility are two main elements bear most of the uncertainties, deriving constraints, challenges for the petroleum industry, and the inflexible nature with many variables strive petroleum companies for vertical integration which gives a potential advantage by having greater control over the chain (Gainsborough 2006; Hassen and Szucs 2012; Hull 2002). This claim entirely copes with Majumdar and Ramaswamy (1994) description of driving forces of vertical integration presented above. Like other industries, the petroleum industry can maximize supply-chain efficiencies by collaborating and avoiding the situation that each company acts in its best interests. Petroleum companies often have large value transactions; the marginal profit can sharply increase if they manage the entire supply chain well. Vertical integration is inherent in the nature of the oil industry (Mitchell 1976). In fact, companies that are vertically integrated over the whole petroleum value system dominated the petroleum industry (Stabell 2001). An integrated firm will do better than its non-integrated competitors if high profits can be found in the supply chain (Klein et al. 1978; Williamson 1979).

Fully integrated petroleum companies own all the value-added steps associated with product and service packages. For a vertically integrated firm, the entire value chain is ultimately presented in a consolidated financial statement, so the drawback of vertical integration is the increase in the level of the financial risk associated with the business cycle of growth and recession. At the same time, it requires significant amounts of capital investment. For instance, reduced revenue (due to the period of falling oil price) may affect the entire operation of the whole supply chain. Other downsides of vertical integration may include the loss of experts when consolidating management and activities, or the failure to recognize opportunities in external markets because they are all implemented internally and reduced competitiveness due to a preference for choosing the internal market (Chima 2007).

Despite some shortcomings, there are still many benefits from vertical integration: controlling the quality of products better, shortening lead time, and increasing product availability by placing inventory closer to the final users, using reliable transportation mode to secure transportation, and reduce the bullwhip effect. That is, to reduce supply chain variability among customer demand, retailers, distributors, and manufacturers need greater cooperation along the value chain or access to new technologies, and other information is of strategic importance. Hence, the total profit margin of the company is increased, and customer satisfaction is enhanced. By weighing the benefit versus cost, a company can determine the ideal vertical alignment level (Chima 2007; Hull 2002).

3.2.2 The context of vertical integration in petroleum companies

As presented above, coordinating activities in the supply chain requires that each stage has information sharing that is consistent with other steps. The performance of the supply chain depends significantly on the coordination of the decision making of its members, and it is hard to imagine coordination without some form of information sharing (Chen 2003). For oil and chemical industry supply chain, vertical integration coordination promotes the layers of strategic planning, scheduling, and operational execution (Lasschuit and Thijssen 2004). vertical integration allows precise information is shared throughout the supply chain; vertically integrated companies are able to share their data to answer business questions, which were too time-consuming to resolve traditionally (Kelder 2016).

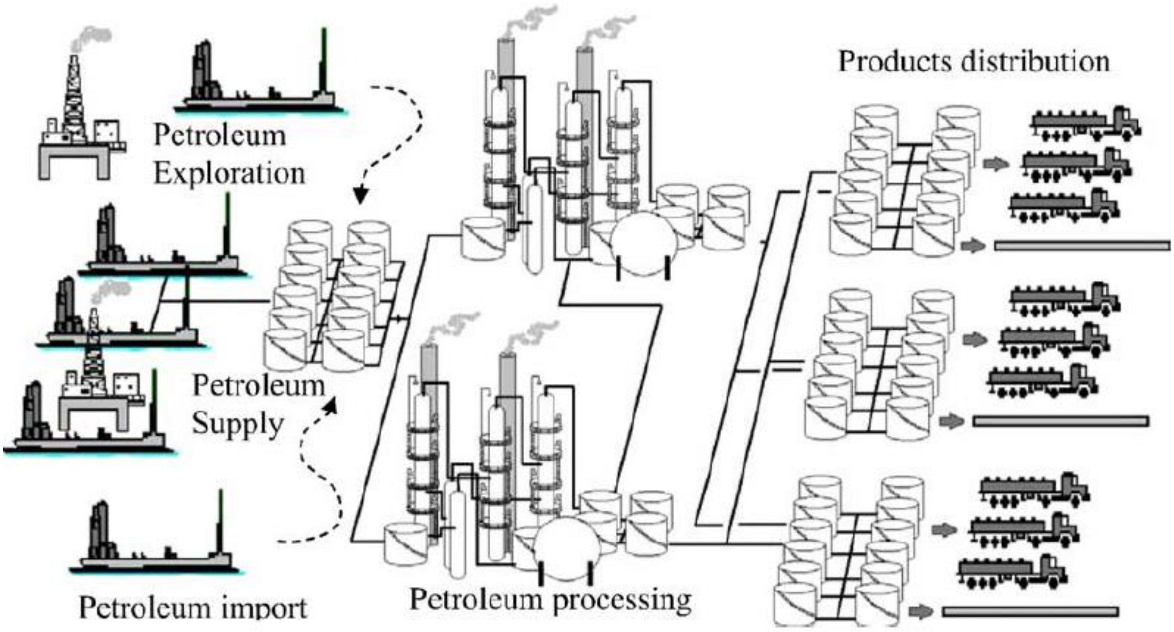

Figure 4. A supply chain of a vertically integrated petroleum company (Neiro and Pinto 2004)

The petroleum industry provides an excellent avenue for vertical integration where the output from one stage is the input to the other phase (Chima 2007). Typically, a supply chain of a vertically integrated petroleum company looks as demonstrated in Figure 4. Exploration operations create value through seismic, geophysical analysis, and identifying prospects. Production operations become the customers of exploration operations when the output of exploration becomes the input of production, including platforms installation, well drilling, and other technical infrastructures. Refining uses crude oils gained from production, and after many sophisticated stages of processing, the output of refinery is the input of marketing. Marketing involves advertising, finding customers, distributing gasoline, and other refined products, while the users of these products actually are customers (Chima 2007).

On the other hand, most of the work and activities in stages of PSC are repetitive. For example, petroleum companies drill many wells annually. Drilling and completing each well requires a drilling contractor and many other services. For the supply chain to serve the production, it is necessary to build drilling rigs, processing equipment, oil pipeline network, storage, transportation systems, etc. to conduct exploitation. Delaying in transferring piping equipment, or other accessories in the production line, can lead to downtime of several rigs, and cause enormous waste. Similar to the supply chain for oil refining, the delay in the supply of raw materials for refineries as well as the delay in the distribution stage, leading to inventories and production disruptions and causing enormous damage. Due to the close relationship and large scale of the PSC, functions could be managed in a more integrated, coherent, and balanced way. Vertical integration increases trust among actors and optimize the operations of the chain.

It should be noticed that natural gas extraction is not so complicated and cost as it often goes along with oil, however, transportation is a big challenge because gas can only be transferred by pipeline or converted into LNG to transport by vessels. Moreover, natural gas must be ordered by customers before being exploited from the reservoir; once natural gas has been produced, it must be transported to the market. Some problems of natural gas such as high transportation cost due to heavy use of pipelines and lack of pipeline network resulting in gas resources not available in all areas or safety in transportation have motivated new initiatives. Pipeline infrastructure development and shipping for natural gas, therefore, are more often outsourced. A model of role and responsibility in gas transport infrastructure development could be established, with the participation of three parties, the government, the system operator, and infrastructure owners. This liberalization will lead to not only cheaper gas to end-users, but also an increase in supply from smaller fields (Fjeldstad et al. 1998; Shaton 2017). Therefore, in this research, the petroleum supply chain implies the oil only.

3.3 Push/pull strategies in petroleum supply chain

As presented above, the supply chain can be operated based on the hybrid push-pull system. When designing processes of the supply chain, managers must determine whether these processes are part of the push or pull phase in the chain, depending on the timing of their execution relative to end-customer demand, to decide when the product is produced and transported to distribution centers as well as retail channels (Chopra and Meindl 2016). From the upstream of the supply chain (i.e., the raw material supplier) to the decoupling point, the supply chain plan is scheduled based on the demand forecast, which is the push strategy. From the decoupling point to the downstream of the supply chain (i.e., the end customer), the supply chain operations are driven by the customer orders, which is the pull strategy (Jeong 2011). The decoupling point marks the transformation of the supply chain, from a push-based system to a pull-based system.

The petroleum supply chain is fundamentally vertical integration, with a push system perspective (Gainsborough 2006; Hull 2002; Kunt et al. 2008; Stabell 2001). Integrated petroleum companies work on the principle of supply push or crude/feedstock driven, which means that crude oil produced or purchased would be sent to refineries in a region to be processed into products. Then, products such as gasoline, diesel, etc. were shipped to the corresponding marketing to be sold (Kunt et al. 2008). Product deliveries are often pulled from the refineries by retail demand. In other words, the pull strategy appears since activities of setting up for the deliverance of the products to consumers are executed. Therefore, for the petroleum supply chain, the decoupling point is placed in the downstream segment, and securing transportation can reduce the bullwhip effect (Hull 2002). Figure 5 illustrates the position of the decoupling point in the petroleum supply chain.

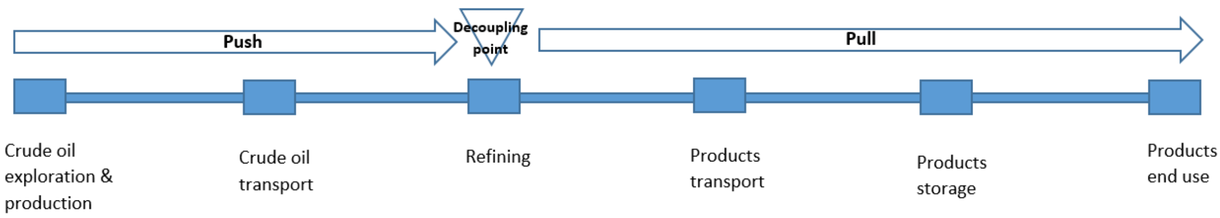

Figure 5. Decoupling point in the petroleum supply chain

In vertically integrated petroleum companies, refining plays a central role in PSC; this stage converts raw-material into finished products to satisfy customer orders (Joly 2012). The planning approach of the refinery is to consider demanded product volumes with intervals, along with actual market prices. The crude oil available is used to maximize an expected sales value made up of estimated product prices in the push-based system, while only demanded volume of products is given to the refinery production planning in the pull-based system (Bredström and Rönnqvist 2008). The available amount of crude oils gives some bounds; the sales modules are supposed to find product-market values, while demand volumes have information on how difficult or how costly it is to produce products. This information can be either direct product production cost with possible amounts or costs to produce single components that are later used to blend into products (Bredström and

Rönnqvist 2008). The refinery uses mathematical programming as a matter of routine in optimizing operations to make a decision about the number of shiploads of crude oil that should be bought from producing oil production fields over a three-months planning horizon, or to determine the optimal mixed produced outputs, transportation costs, and possible prices for the finished products (Röthlisberger 2005).

The company's image depends mostly on careful production planning and scheduling, committing to customer needs (Joly 2012). Integrating planning through several steps or parts improves the performance of the supply chain (Bredström and Rönnqvist 2008). However, incorporating all elements of the supply chain is not simple, requiring developing more extensive and more detailed models in parallel with methods capable of solving them. For the petroleum supply chain, it is challenging to integrate production planning and demand or sales planning in the same optimization model. Transferring information between the models and developing several alternatives are necessary and possible (Bredström and Rönnqvist 2008).

4 OVERVIEW OF THE RESEARCH AREA

Crude oil tanker scheduling problem has the characteristics of a maritime inventory routing problem (MIRP). The trips for a set of tankers between the production site and consumption site are scheduled to satisfy specific crude oil demands of processing units while maintaining inventory levels at both ports in safe operating ranges to avoid crude oil production, or refining processes are disrupted. The problem involving the crude oil unloading optimal operation, transferring crude oil from storage tanks to charging tanks, and making charging schedules for each CDU perhaps first described in (Heeman Lee et al. 1996) and called the crude-oil scheduling problem. In this chapter, firstly, studies belong to two distinct domains - MIRP, and crude oil scheduling problem will be reviewed sequentially. Then the research in integrating crude oil supply management from local production sites or imported from abroad to CDUs at the refinery site will be discussed next. Other efforts that do not consider the integrating problem of crude oil supply but tackle issues of linking multiple segments of the PSC will also be reviewed in the last section of this chapter.

4.1 Maritime inventory problem

The first review about ship routing, scheduling, and related models is founded in (Ronen 1983). Perakis and Bremer (1992) develop a model for the scheduling situation, describes an integer programming formulation for schedule optimization, including the feasible schedule generation process for Chevron Shipping Company. In (Bremer and Perakis 1992), these authors attempt to describe the processes of implementing the scheduling system presented in the previous article on the University of Michigan IBM 3090–600E computer to generate feasible schedules for each vessel and then use integer programming to solve for the optimal overall schedule. Bausch et al. (1998) propose a decision support system that is used daily to optimally dispatch shipments of bulk products by ships and barges among plants, bulk distribution terminals, and industrial customers. The paper describes a personal computer-based system allowing users to communicate with the system through EXCEL spreadsheets and Gantt charts, while the mathematical programming model is hidden from users. Ronen (2002) presents a MIP model to achieve cost-effective solutions for the shipments-planning problem faced by producers of large volume liquid bulk products. The author applies a cost-based heuristic algorithm to obtain acceptable solutions quickly. Camponogara and Plucenio (2014) introduce a MILP formulation for the problem of scheduling shuttle tankers. The research presents a family of valid inequalities to strengthen the proposed model; solving time is also reduced by using state-of-the-art solvers. Christiansen et al. (2013) review research on ship routing and scheduling and related problems during the new millennium and present four basic models in this domain. Diz et al. (2017) show how applying the MILP to model crude oil offloading, and supply problems can significantly improve the decision-making process in a Brazilian petroleum company. Recently, Agra et al. (2017) address short-sea MIRP (i.e., where ports are close to each other), and Papageorgiou et al. (2018) study deep-sea MIRP (i.e., where ports located in different continents). The former compares the uses of a discrete-time model and a classical continuous-time formulation while, in the latter, the utilization of several heuristics to find high-quality ship schedules and inventory policies are compared together.

4.2 Crude oil scheduling problem

The main objective of the crude oil scheduling problem is that the demands of CDUs must be satisfied, both in terms of total quantity and quality. Therefore, it is necessary to achieve an effective operating schedule, including the unloading of crude oil into storage tanks, the transfers between storage and charging tanks. The feed of CDUs performed by charging tanks (Assis et al. 2019). The short-term scheduling of refinery operations in a distribution complex, including ports, refineries, and pipeline infrastructure, has been studied in many works. In (Heeman Lee et al. 1996), a MILP model involving the optimal operation of crude oil unloading, its transfer from storage tanks to charging tanks, and the charging schedule for each processing unit of a single refinery are proposed. The papers (JM Pinto and Moro 2000) and (Jose Pinto et al. 2000) develop a nonlinear production planning model for a refinery that has several processing units, one type of tank which is used for both blending and storage produces a variety of intermediate streams with different properties. Más and Pinto (2003) introduce large-scale MILP models based on the decomposition strategy to solve issues of intermediate storage, settling tasks and allocation of crude oil by its qualitative characteristics. Magalhaes and Shah (2003) propose a MILP model giving a feasible schedule of tank allocations, sequence, and size of crude parcels to be pumped through the pipeline and timing of the operations that minimizing deviation from the planned procedure. The decomposition approach is also applied in (Jia and Ierapetritou 2004) and (W. Li et al. 2003) to analyze the problem of short-term scheduling of refinery operations into three domains: the crude-oil unloading and blending, the production unit operations and the product blending and delivery. Jia and Ierapetritou (2004) model each of the sub-problems based on a continuous-time formulation and then integrates these three by applying heuristic-based Lagrangean decomposition. W. Li et al. (2003) use a new modeling technique - iteratively solving the NLP and MIP models and solution strategy to schedule crude oil unloading and storage. Neiro and Pinto (2004) develop a large–scale MINLP model applied to a real-world corporation, which is the integration of model of different processing units at refineries, storage tanks at intermediate terminals, pipeline system connecting terminals from/to refineries or directly to distribution centers. The model is constrained by flowrates, flow properties, and operating conditions. Mendez et al. (2006) introduce a complicated MILP-based method that simultaneously addresses two problems: optimizing the off-line blending and the short-term scheduling problem in oil-refinery applications. In the work of Wu et al. (2008), the short scheduling problem for crude oil operations is addressed in a pull production way, where a target refining schedule resulting from production planning is given as a constraint to create an executable schedule. The refinery system is modeled by a timed hybrid Petri net, and an efficient heuristic algorithm is proposed to test the reliability of a target refining schedule. The research (Abraham and Rao 2009) introduces a generative model, including a flow network optimization model and the BILP model for scheduling production operations in an oil refinery. Evaluative models have applied simulation on the optimal results obtained from the generative model to derive the measure of performance. A new MINLP continuous-time formulation called the single-operation sequencing model, is introduced in (Mouret et al. 2009). Saharidis et al. (2009) propose an exact solution approach, with a novel time formulation for the scheduling of the refineries where several modes of blending and several recipe preparation alternatives are used. Recently, de Assis et al. (2017) propose an iterative two-step MILP-NLP algorithm based on piecewise McCormick relaxation and a domain-reduction strategy for handling bilinear terms to solve the problem of scheduling of operations in a crude oil terminal.

4.3 Integrated the management of crude oil supply

There are few studies on the integrated management of crude oil supply problems, from FPSOs to CDUs. (Aires et al., 2004) is probably the first research, integrates issues of lot-sizing of oil from production sites, allocation of oil to refineries, inventory control at maritime transshipment terminals and refineries, and planning/scheduling operations at CDUs in a vertically integrated petroleum company at the operational level. The authors call the problem as petroleum allocation. According to Aires et al. (2004), in the previous literature, the problem was considered separately under two sub-problems: ship scheduling and planning operations at refineries. The paper proposes a MILP model relying on a time/space discretization network to solve the problem the crude oil supply management at the operational level. The integrated problem of supplying crude oil presented in this paper overlaps strategic planning with operational demands. Rocha et al. (2009) apply an algorithm based on a heuristic called local branching to find a feasible solution with a local search procedure for the same problem studied in (Aires et al., 2004). In (Rocha et al. 2013), cascading knapsack inequalities are used to reformulate the inventory balance constraints for the problem of crude oil is shipped from platforms to terminals in cases with a limited number of classes of tankers. In (Rocha et al. 2017), a novel decomposition algorithm and reformulations based on a cascading knapsack structure are proposed to solve the petroleum supply planning problem in case more than two tankers are used to offload each platform. Robertson et al. (2011) focus on nodes involving unloading, storing, blending, and processing. The paper proposes a strategy to integrate two optimization problems: unit operation optimization problem and crude oil scheduling problem. The unit operation optimization problem is modeled as an NLP with the objective is maximizing the difference between the product revenue and the energy and environmental costs of the central refinery units. Crude oil scheduling problems modeled as a MILP with the objective is minimizing the logistical costs of unloading the crude oil over periods. Nonlinear simulation and multiple linear regression are used to derive refining cost and blending revenue. (Assis et al. 2019) integrates the management of crude oil supply at the operational level by considering the scheduling of vessels, the schedule of operations in the terminal, and the non-convex non-linear associated with the blending of crudes. The paper proposes a discrete-time MINLP model solved by an iterative MILP-NLP decomposition, relying on domain reduction, using bivariate piecewise McCormick envelopes to yield the MILP relaxation, and an NLP solver to reach feasible solutions.

4.4 Linking multiple segments of PSC

The significant economic benefits in improving the whole business operation have promoted many studies about the PSC coordination among production, transportation, refining, and distribution in the oil and gas industry. Sear (1993) proposes a linear programming network model, partly in mathematical and partly in qualitative terms in the making strategic logistics chain planning to solve the problem of crude oil purchase and transportation, processing of products and shipment, and depot operation while considers business risks associated with changes to the logistics infrastructure. In (Escudero et al. 1999), a multi-period supply, transformation, and distribution problem is introduced. A linear programming model to define optimal material flows of an oil company is proposed in this paper. A network with storage tanks, transformation sites, transshipment nodes, and destination depots are considered in the model. Uncertainties such as spot selling price, spot supply cost, and product demand are also taken into account. Dempster et al. (2000) formulate deterministic and stochastic models of strategic planning for logistic operations addressing multi-period supply, transformation, and distribution scheduling problems, with uncertainty in the product demands and spot supply costs in the oil industry. In the work of Persson and Göthe-Lundgren (2005), the shipment planning of bitumen products from a set of refineries to a set of depots is integrated into the process scheduling at the refineries. The paper suggests a solution method based on column generation, valid inequalities, and constraint branching. The article (Guyonnet et al. 2008) explores the potential benefits of the integration of three models: crude oil unloading, production planning, and product distribution. An overall MINLP integrating three models is presented. For unloading and production planning sections, authors use corresponding models developed in previous studies. For the distribution part, the model for truck transportation daily planning is formed by the authors of this research. Fernandes et al. (2012) propose a MILP model for the PSC involving tactical design decisions of production, storage, transportation, importation, and exportation volumes of crude oil and derived products.

5 INTEGRATED DECISION-MAKING MODEL

5.1 Problem description

The model developed in this research is mainly applied to the push processes of PSC, from the production site to the refinery site.

The production site is represented by an FPSO, which is a crude oil and natural gas production facility, mainly designed to operate in remote and deep-water locations. After processing, crude oil or gas is stored in the storage tanks of the FPSO before offloading periodically to shuttle tankers or transmitting the processed petroleum via pipelines. Shuttle tankers (STs) are used to transport crude oil from the offshore FPSO to the onshore storage site. A shuttle tanker is a specialized ship designed and often used as an alternative to underwater pipelines in harsh climates, remote locations, or deep-water. They are equipped with offloading equipment compatible with the oil field in question.

The onshore facilities include the storage base with several intermediate storage tanks, pipelines, and centrifugal pumps system to transfer crude oil from the tanks to a crude oil distillation unit (CDU). It is assumed here that operations are conducted given that specific crude oil demand is forecasted for the upcoming quarter of a year. Given these demand values, the FPSO starts production operation, and STs start loading operations at the FPSO and make the journey to transfer crude oil to the storage site. The production output, loading/unloading, infrastructure connection setup, inventory will be planned based on demand. Nodes considered in the mathematical model are illustrated in Figure 6.

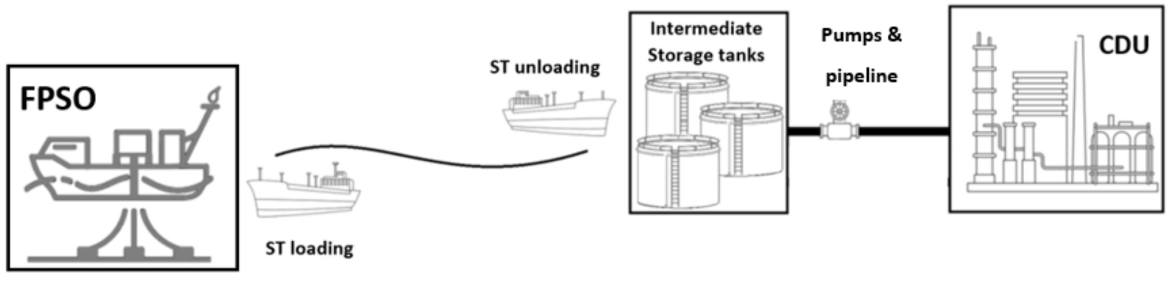

Figure 6. Nodes are considered in the mathematical model

To simplify the problem, here are the assumptions made:

- The model is applied traditional time representation approach, which is the discrete-time formulation. The scheduling time horizon is split into time intervals of equal size, and binary variables are used to specify if the action starts or finishes during that period (Saharidis et al. 2009). The quarter can be divided into T periods $t \in \{1...T\}$, which depends on the time an ST makes a full journey (loading/sailing/unloading and return). Time for loading and sailing is considered equal to time unloading and return (*p* days), and $T = \frac{90}{p}$, a period *t* lasts *p* days.
- The production at the FPSO takes place continuously from period 1 to *T*-1. The production is suspended temporarily in the last period of this quarter for maintenance. In each period from 1 to *T*-1, besides the production feeding load for STs to meet the demand of the CDU, the FPSO produces an excess amount of crude oil, adding to its inventory in each period. The inventory quantity of the final period (*T*) at the FPSO needs to reach a specified level to use for the first period of the next quarter. Decision variables here are production level and inventory level at the FPSO in each period.
- There are two available STs assigned to serve the FPSO continuously. STs are the same kind (speed and size) and are operated continuously sequentially from period 1 to *T* (FPSO allows one ST loading per period). When the first ST arrives at the onshore storage base, the second ST starts loading at FPSO and sailing to the storage site. Decision variables here are the amount of crude oil that an ST loads from the FPSO and offloads to storage base in period *t*.
- The onshore facilities consist of the storage base for intermediate storage, pipeline and pump system, and the CDU. At the intermediate storage base, storages tank $z \in \{1...NZ\}$ holds an initial inventory amount that enough to meet CDU demand in the first period. ST offload to tanks at the storage site from period 1 to *T*. An amount of inventory is kept in each period from 1 to *T*, and the loading amount of STs in the period *T* will be kept serving CDU demand for the first period of the next quarter. An operating period of the refinery site (make the connection between ST and storage tanks, storage tanks, and a CDU, transfer oil from storage tanks to CDU) is assumed equal to the time between two deliveries (*p* days), same as the operation period of FPSO and STs. This part uses the idea of the short term refinery scheduling problem - scheduling solution approach proposed in (Robertson et al. 2011), decisions made are scheduling connections between

ST and tanks, tanks and CDU at refinery site, and incoming/outgoing amount to/from tanks.

- Each pipeline segment begins with a pump station that works in the same operating mode, and each pump develops the same pressure. Hazen-Williams formula is employed to calculate pressure losses (in Pa) approximation due to friction in a segment of a long-distance transmission pipeline:

$$\Delta P(r, L, D) = 7.68 \cdot 10^{-9} \cdot \rho \cdot g \cdot \left(\frac{r}{C}\right)^{1.85} \cdot \frac{L}{D^{4.89}} \quad (1)$$

Where

r is the flow rate through the pipe (m^3/d)

L is pipe's length (m)

D is pipe's internal diameter (m)

ρ is fluid density, kg/m3 fluid density (kg/m^3)

g is standard gravity acceleration (m/s^2)

C is pipe's grade (depending on its age, 120 for new pipes)

In this decision-making model, the Hazen-Williams formula (1) is utilized in such a way that the pressure drop ΔP and the flow rate r are variables while the remaining notations are used as parameters. The nonlinear part $r^{1.85}$ is linearized by means of the piecewise-linear approximation resulting in *a* simpler description of crude oil flow rate. The breakpoints (argument values for the approximation), a binary variable, a continuous variable, and relevant constraints will be introduced to linearize the function $r^{1.85}$. The idea of modeling pump operation (developed power, developed pressure difference, the efficiency of the pump and motor, the workload of the motor, and frequency of the electric current operating the pump) is inspired by (Redutskiy 2017).

5.2 Mathematical model formulation

Table 2. Notations for the model

Set and indices	
index *t*; $t \in \{1..T\}$	Set of periods of the considered time horizon
index *z*, $z \in \{1..NZ\}$	Set of intermediate storage tanks
index k, $k \in \{1..M\}$	Set of pieces in piecewise linear approximation to determine flow rate from storage base to the refinery during a given period

Parameters	
FPSO:	
F^{Inv0}	The amount of initial inventory at FPSO (m^3). It is also the required inventory level for the last period of this quarter which will be used for the first journey of next quarter.
F^{PR}	Designed production flow rate per day of FPSO (m^3/day)
F^{S}	The designed maximum storage capacity of FPSO (m^3)
F^{Pc}	The average expense to produce 1 m^3 crude oil at FPSO ($/m^3)
F^{IHc}	Average inventory holding expense for 1 m^3 crude oil at FPSO ($/m^3)
Shuttle tankers:	
p	The number of days in a period (time of ST departures from FPSO and arrivals at the refinery site).
ST^{Cap}	Designed maximum loading capacity of ST (m^3)
ST^{Tc}	The average expense to transport 1 m^3 crude oil from FPSO to refinery site (loading, sailing, unloading, return) by ST ($/m^3)
Storage base:	
T_z^{Cap}	The storage capacity of tank *z* (m^3)
T_z^{Inv0}	The initial inventory of tank *z* (m^3)
setupCost	The facility set up cost to connect ST to tanks and tanks to CDU ($)
Pipeline and Pump:	
L	Length of a pipeline segment (or distance between two consecutive pump stations) (m^3)
Diam	Pipeline internal diameter (m)
$\bar{R} = \frac{Dem}{T.p}$	The average flow rate of crude oil to transport from the storage base to the refinery (m^3/d)
η	Pump efficiency (dimensionless)
E^{c}	Price of electricity per kWh, ($/kWh)
NP	Number of pipeline segments starting with a pump (segments between the storage base and the refinery)
CDU:	

Dem	The total demand for refinery site for a quarter (90 days) (m^3).
Piecewise linear approximation:	
M	Number of pieces in piecewise linear approximation
a_k	argument values for the approximation
Decision variable:	
FPSO:	
$\boldsymbol{F_t^P}$	Amount of crude oil produced at FPSO in period *t* (m^3) (no production in period *T*)
$\boldsymbol{F_t^{Inv}}$	The inventory level that FPSO holds in period *t* (m^3)
Shuttle tankers:	
$\boldsymbol{ST_t^L}$	Amount of crude oil that ST offloads to storage base in period *t* (m^3)
Storage base:	
$\boldsymbol{C_{z,t}}$	1, if the connection between tank *z* and ST is established during period *t*, 0 otherwise
$\boldsymbol{X_{z,t}}$	Amount of crude oil sent from ST to tank *z* in period *t* (m^3)
$\boldsymbol{I_{z,t}}$	Inventory level of tank *z* at the end of period *t* (m^3)
CDU:	
$\boldsymbol{D_{z,t}}$	1, if the connection between tank *z* and CDU is established during period *t*, 0 otherwise
$\boldsymbol{Y_{z,t}}$	Amount of crude oil sent from tank *z* to CDU in period *t* (m^3)
Pipeline and Pumps:	
$\boldsymbol{R_t}$	Flow rate from storage base to the CDU in period *t* (m^3/d)
$\Delta\boldsymbol{P_t}$	Pressure losses in period *t* / pressure developed by a pump (MPa)
$\boldsymbol{PP_t}$	Pump’s operational power (kW)
Piecewise linear approximation:	
$\boldsymbol{pwa_{k,t}^1}$	Continuous variables for piecewise-linear approximation
$\boldsymbol{pwa_{k,t}^2}$	Binary variables for piecewise-linear approximation

The objective function (2) minimizes the total operational cost of the PSC (pushed processes) during the quarter of a year. These costs include production cost at FPSO, inventory holding cost at FPSO, cost of trips, inventory holding costs at intermediate storage tanks, setup cost of establishing a connection between two entities (ST-to-storage tanks, and storage tanks-to-CDU), electricity consumption cost of the pump system to transfer crude oil from tanks to CDU.

$$\begin{aligned}\min Total_{cost} = {} & \sum_{t=1}^{T-1} F^{Pc} \cdot \boldsymbol{F_t^P} + \sum_{t=1}^{T} F^{IHc} \cdot \boldsymbol{F_t^{Inv}} + \sum_{t=1}^{T} ST^{Tc} \cdot \boldsymbol{ST_t^L} \\ & + \sum_{t=1}^{T}\sum_{z=1}^{NZ} T^{IHc} \cdot \boldsymbol{I_{z,t}} + setupcost \cdot \left(\sum_{t=1}^{T}\sum_{z=1}^{NZ} \boldsymbol{C_{z,t}} + \sum_{t=1}^{T}\sum_{z=1}^{NZ} \boldsymbol{D_{z,t}}\right) \\ & + NP. \frac{\sum_{t=1}^{T} 24 \cdot E^c \cdot p \cdot \Delta \boldsymbol{P_t}}{\eta}\end{aligned} \tag{2}$$

The constraint specified (3) declares that the inventory level at FPSO in period 1 is equal to the initial inventory plus production amount in period 0 of FPSO minus offload amount of ST in period 2.

$$\boldsymbol{F_{t=1}^{Inv}} = F^{Inv0} + \boldsymbol{F_{t=1}^P} - \boldsymbol{ST_{t=1}^L} \tag{3}$$

The following constraint (4) expresses the inventory level in period *t* is equal to accumulated inventory from the previous period plus the difference between the amount of crude oil produced at FPSO in period *t* and the amount of ST offload in period *t*.

$$\boldsymbol{F_t^{Inv}} = \boldsymbol{F_{t-1}^{Inv}} + \boldsymbol{F_t^P} - \boldsymbol{ST_t^L}, \qquad t \in \{2 \ldots T\} \tag{4}$$

There is no production in the last period *T*, which is shown in (5).

$$\boldsymbol{F_{t=T}^P} = 0 \tag{5}$$

The inequality (6) states that the amount of crude oil that ST offloads to storage tanks in the first period must not exceed the amount of crude oil hold by FPSO in the beginning.

$$\boldsymbol{ST_{t=1}^L} \leq F^{Inv0} \tag{6}$$

Production output during period *t* must not be exceeding the maximum amount of oil that can be produced in *p* days is shown in (7).

$$\boldsymbol{F_t^P} \leq p \cdot F^{PR}, \qquad t \in \{1..T-1\} \tag{7}$$

The total amount of crude oil produced plus the initial inventory at the FPSO platform, plus initial inventory at the storage base, should be greater than or equal to the required demand of CDU showed in the following constraint is presented in (8).

$$\sum_{t=1}^{T} \boldsymbol{ST_t^L} \geq Dem \tag{8}$$

The following technological constraint (9) is to ensure storage capacity for FPSO.

$$\boldsymbol{F_t^{Inv}} \leq F^S, \qquad t \in \{1..T\} \tag{9}$$

Inventory level in the last period must reach a specified amount to ensure the operation of the first period in the next quarter (10).

$$\boldsymbol{F_{t=T}^{Inv}} \geq F^{Inv0} \tag{10}$$

The constraint (11) limits the amount of crude oil offloaded in all periods, and it must not exceed the loading capacity of ST.

$$\boldsymbol{ST_t^L} \leq ST^{Cap}, \qquad t \in \{1..T\} \tag{11}$$

The following logical constraint (12) is to make sure all the incoming crude to refinery site at time *t* is contained by some tank *z*. The amount of crude oil offloaded at the refinery site in period T will be added to inventory and used for the first period of the next quarter.

$$\sum_{z=1}^{NZ} \boldsymbol{X_{z,t}} = \boldsymbol{ST_t^L}, \qquad t \in \{1..T\} \tag{12}$$

Two following logistical constraints (13) and (14) are to balance the inventory of tank *z* in period *t*.

$$\boldsymbol{I_{z,t=1}} = T_z^{Inv0} + \boldsymbol{X_{z,t=1}} - \boldsymbol{Y_{z,t=1}}, \qquad z \in \{1...NZ\} \tag{13}$$

$$\boldsymbol{I_{z,t}} = \boldsymbol{I_{z,t-1}} + \boldsymbol{X_{z,t}} - \boldsymbol{Y_{z,t}}, \qquad z \in \{1...NZ\}, t \in \{2...T\} \tag{14}$$

The next logistical constraint (15) declares the total inventory level of all tanks *z* in the final period *T* must reach the required amount.

$$\sum_{z=1}^{NZ} \boldsymbol{I_{z,t=T}} = \sum_{z=1}^{NZ} T_z^{Inv0}, \qquad z \in \{1...NZ\} \tag{15}$$

The storage capacity of the tank *z* during period *t* must be ensured (16).

$$\boldsymbol{I_{z,t-1}} + \boldsymbol{X_{z,t}} \leq T_z^{Cap}, \qquad z \in \{1..NZ\}, t \in \{2..T\} \tag{16}$$

The following constraint (17) shows the connection between the variables corresponding to the amount of crude oil sent from an ST to a tank (continuous variable) and connections of ST to a tank (binary variable). Here, *M* is a big number.

$$\boldsymbol{X_{z,t}} \leq M \cdot \boldsymbol{C_{z,t}}, \qquad z \in \{1..NZ\}, t \in \{1..T\} \tag{17}$$

Similarly, the connection between the variables corresponding to the amount of crude oil sent from a tank to the CDU (continuous variable) and connections of the tank to the CDU (binary variable) is presented in (18).

$$\boldsymbol{Y_{z,t}} \leq M \cdot \boldsymbol{D_{z,t}}, \qquad z \in \{1..NZ\}, t \in \{1..T\} \tag{18}$$

The following constraint (19) is the logical relation between binary variables representing connections of ST-to-tanks and tanks-to-CDU. A tank cannot receive crude oil from a ST and fill a CDU in the same period.

$$\boldsymbol{C_{z,t}} + \boldsymbol{D_{z,t}} \leq 1, \qquad z \in \{1..NZ\}, t \in \{2..NT\} \tag{19}$$

Decisions on the flow rate of crude oil transported from the storage base to the refinery are expressed in (20).

$$\boldsymbol{R_t} \geq \frac{\sum_{z=1}^{NZ} \boldsymbol{Y_{z,t=T}}}{p}, \qquad t \in \{1..NT\} \tag{20}$$

Hazen-Williams formula shown in constraint (21) is employed to estimate pressure losses approximation in a segment of a long-distance transmission pipeline.

$$\Delta \boldsymbol{P_t} = 7.68 \cdot 10^{-15} \cdot \rho \cdot g \cdot \frac{L}{Diam^{4.89}} \cdot \frac{1}{120^{1.85}} \cdot \sum_{k=1}^{M} a_k^{1.85} \cdot \boldsymbol{pwa^1_{k,t}}, \qquad t \in \{1..NT\} \tag{21}$$

Here, $7.68 \cdot 10^{-15}$ is Hazen-Williams formula coefficient, crude oil density $\rho = 850$ kg/m^3, 120 is the "pipeline grade" in Hazen-Williams formula (depending on its age, 120 is new pipes), the part $\sum_{k=1}^{M} a_k^{1.85} \cdot \boldsymbol{pwa^1_{k,t}}$ is the piecewise linear approximation of $\boldsymbol{R_t}^{1.85}$ from Hazen-Williams formula.

From (22) to (27) are constraints for piecewise linear approximation in determining the flow rate during every period of the planning horizon.

$$\boldsymbol{pwa^1_{1,t}} \leq \boldsymbol{pwa^2_{1,t}}, \qquad t \in \{1..NT\} \tag{22}$$

$$\boldsymbol{pwa^1_{k,t}} \leq \boldsymbol{pwa^2_{k-1,t}} + \boldsymbol{pwa^2_{k,t}}, \quad k \in \{2..M-1\}, t \in \{1..NT\} \tag{23}$$

$$\boldsymbol{pwa^1_{M,t}} \leq \boldsymbol{pwa^2_{M-1,t}}, \quad t \in \{1..NT\} \tag{24}$$

$$\sum_{k=1}^{M} \boldsymbol{pwa^2_{k,t}} = \mathbf{1} \quad t \in \{1..NT\} \tag{25}$$

$$\sum_{k=1}^{M} \boldsymbol{pwa_{k,t}^{1}} \quad = \mathbf{1} \quad t \in \{1..NT\} \tag{26}$$

$$\boldsymbol{R_t} = \sum_{k=1}^{M} a_k \cdot \boldsymbol{pwa_{k,t}^{1}}, \quad t \in \{1..NT\} \tag{27}$$

The final constraint (28) is to calculate the power (in kW) developed by the pump to transport the crude oil from the storage base to the CDU through a pipeline segment.

$$\boldsymbol{PP_t} = \frac{10^3 \cdot \bar{R}}{24 \cdot 60 \cdot 60} \cdot \Delta \boldsymbol{P_t} \tag{28}$$

The AMPL code of the model file and run file is specified in Appendix A.

5.3 Data for the computations

The developed mathematical model is further tested in a study example. The data for this example is based on high-quality research and additional consulting with experts to verify the appropriateness of this example.

Depending on loading/sailing time and unloading/return time p = 9 days, the current quarter is divided into 10 periods (each period lasts 9 days). The production at the FPSO takes place continuously from period T = 1 to 9 and suspends temporarily in the last period T = 10. The total forecasted demand for crude oil in this quarter is 1 600 000 m^3.

The initial inventory level at FPSO in this quarter and the amount required for the first period of the next quarter is 170 000 m^3. The designed storage capacity of FPSO is 317 000 $m^{3,}$ while the flowrate is 28 600 m^3/day. The production cost and the inventory holding cost of FPSO are correspondingly \$2.5 per m^3 and \$0.5 per m^3.

The main shuttle tanker size classes are Aframax, Suezmax, and Very Large Crude Carriers (VLCC). Aframax is generally considered to be tankers between 90 000 and 110 000 DWT. Suezmax is almost exclusively used in reference to shuttle tankers, which is now between 130 000 and 160 000 DWT, and VLCC are generally deemed to be tankers above 200 000 DWT (Rodriguez et al. 2009; Tusiani 1996). The model will be tested on Suezmax and VLCC with the transportation capacities of 180 000 m^3 and 250 000 m^3 correspondingly. The transportation cost of Suezmax is assumed to be \$0.25/m^3, while for VLCC, it is \$0.23/m^3.

At the storage base, the initial inventory level in the first period and the required inventory level in the final period are 180 000 m^3. The inventory holding cost is the same for all capabilities, as \$0.5 per m^3. The model will also test six different cases of storage capacity at the storage base as follows.

1. Eleven tanks have the same designed storage capacity of 30 000 m^3, the initial inventory levels of the first to sixth tanks are 30 000 m^3. The seventh to eleventh tanks are empty.
2. Twelve tanks have the same designed storage capacity of 30 000 m^3, the initial inventory levels of the first to sixth tanks are 30 000 m^3. The seventh to twelfth tanks are empty.
3. Six tanks have the same designed storage capacity of 60 000 m^3, the initial inventory levels of the first to third tanks are 60 000 m^3. The fourth to sixth tanks are empty.
4. Seven tanks have the same designed storage capacity of 60 000 m^3, the initial inventory levels of the first to third tanks are 60 000 m^3. The fourth to seventh tanks are empty.
5. Four tanks have the same designed storage capacity of 90 000 m^3. The initial inventory levels of the first and second tanks are 90 000 m^3. The third and fourth tanks have no initial inventory.
6. Five tanks have the same designed storage capacity of 90 000. The initial inventory level of the first and second tanks are 90 000 m^3. The third, fourth, and fifth tanks have no initial inventory.

The distance between the intermediate storage base and the CDU is 200 km. The pipeline consists of 10 equal-length segments (each 20 km long) connecting the storage base and the CDU. The model will test five options for long-distance transmission pipeline diameter with corresponding connection setup cost values, as shown in Table 3:

Table 3. Pipeline diameter and corresponding connection setup costs

Pipeline diameter		**Connection setup cost**
(inch)	**(m)**	**($)**
10	0.2540	3 000
16	0.4064	6 000
24	0.6096	9 000
30	0.7620	18 000
36	0.9144	27 000

The Data representation in AMPL is presented in Appendix A

5.4 Results of the optimization run

The model formulated in the previous section has been run in AMPL 60 times for the various values of the following parameters:

- Two alternative shuttle tanker sizes with the corresponding transportation costs.
- Six alternatives for storage capacity at the storage base.
- Five options of long-distance transmission pipeline diameter with the corresponding infrastructure setup costs.

Since the non-linear expressions in the model are linearized by applying the piecewise linear approximation, the resulting MILP model may be solved with the help of AMPL/CPLEX solver. The total cost and percentage of component costs including crude oil production cost at FPSO (denoted as %P), inventory holding cost at FPSO and storage base (%I), transportation cost of STs (%T), connection setup cost (%S), and electricity consumption cost to transfer crude oil from storage base to CDU (%E) for the 60 runs are summarized in Table 4 and Table 5.

Table 4. Total cost and component cost percentages of 30 scenarios using Suezmax shuttle tankers

Suezmax shuttle tanker – 180 000 m³ ***ST^{Tc} = \$0.25/m³***																										
		pipeline diameter (m)																								
		0.2540					***0.4064***					***0.6096***					***0.7620***					***0. 9144***				
Onshore storage capacity	***11 tanks – 30 000 m³***	\$20 017 400					\$7 688 380					\$6 794 300					\$7 637 120					\$8 570 580				
	$T^{Inv0}_{1\ to\ 6}$ ***= 30 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{7\ to\ 11}$ ***= 0 m³***	30	6.1	2	1.6	70.3	52	16	5.2	8.4	18.4	58.9	18.1	5.9	14.3	2.9	52.4	16.1	5.2	25.5	0.9	46.7	14.3	4.7	34	0.3
	12 tanks – 30 000 m³	\$19 898 500					7 569 480					\$6 675 400					\$7 518 220					\$8 451 680				
	$T^{Inv0}_{1\ to\ 6}$ ***= 30 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{7\ to\ 12}$ ***= 0 m³***	20.1	5.6	2	1.6	70.7	52.8	14.6	5.3	8.6	18.7	59.9	16.6	6	14.6	2.9	53.2	14.7	5.3	25.9	0.9	47.3	13.1	4.7	34.5	0.3
	6 tanks – 60 000 m³	\$19 736 500					\$7 245 480					\$6 189 400					\$6 546 220					\$6 993 680				
	$T^{Inv0}_{1\ to\ 3}$***= 60 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{4\ to\ 6}$***= 0 m³***	20.3	5.6	2	0.8	71.3	55.2	15.3	5.5	4.5	19.6	64.6	17.9	6.5	7.9	3.1	61.1	16.9	6.1	14.8	1	57.2	15.9	5.7	20.8	0.4
	7 tanks – 60 000 m³	\$19 736 500					\$7 245 480					\$6 189 400					\$6 546 220					\$6 993 680				
	$T^{Inv0}_{1\ to\ 3}$***= 60 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{4\ to\ 7}$***= 0 m³***	20.3	5.6	2	0.8	71.3	55.2	15.3	5.5	4.5	19.6	64.6	17.9	6.5	7.9	3.1	61.1	16.9	6.1	14.8	1	57.2	15.9	5.7	20.8	0.4
	4 tanks – 90 000 m³	\$19 682 500					\$7 137 480					\$6 027 400					\$6 222 220					\$6 507 680				
	$T^{Inv0}_{1\ to\ 2}$***= 90 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{3\ to\ 4}$***= 0 m³***	20.3	5.6	2	0.5	71.4	56	15.5	5.6	3	19.8	66.4	18.4	6.6	5.4	3.2	64.3	17.8	6.4	10.4	1	61.5	17	6.1	14.9	0.4
	5 tanks – 90 000 m³	\$19 682 500					\$7 137 480					\$6 027 400					\$6 222 220					\$6 507 680				
	$T^{Inv0}_{1\ to\ 2}$***= 90 000 m³***	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	$T^{Inv0}_{3\ to\ 5}$***= 0 m³***	20.3	5.6	2	0.5	71.4	56	15.5	5.6	3	19.8	66.4	18.4	6.6	5.4	3.2	64.3	17.8	6.4	10.4	1	61.5	17	6.1	14.9	0.4

Table 5. Total cost and component cost percentages of 30 scenarios using VLCC shuttle tankers

VLCC shuttle tanker – 250 000 m³ ***ST^{Tc} = $0.23/m³***																									
	pipeline diameter (m)																								
	0.2540					***0.4064***					***0.6096***					***0.7620***					***0. 9144***				
Onshore storage capacity: ***11 tanks – 30 000 m³*** $T^{Inv0}_{1\ to\ 6}$ ***= 30 000 m³*** $T^{Inv0}_{7\ to\ 11}$ ***= 0 m³***	$19 985 400					$7 656 380					$6 762 300					$7 605 120					$8 538 580				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20	6.1	1.8	1.6	70.4	52.2	16	4.8	8.5	18.4	59.2	18.2	5.4	14.4	2.9	52.6	16.1	4.8	25.6	0.9	46.8	14.4	4.3	34.2	0.3
12 tanks – 30 000 m³ $T^{Inv0}_{1\ to\ 6}$ ***= 30 000 m³*** $T^{Inv0}_{7\ to\ 12}$ ***= 0 m³***	$19 866 500					$7 537 480					$6 643 400					$7 486 220					$8 419 680				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20.1	5.6	1.9	1.6	70.8	53.1	14.7	4.9	8.6	18.7	60.2	16.7	5.5	14.6	2.9	53.4	14.8	4.9	26	0.9	47.5	13.2	4.4	34.6	0.3
6 tanks – 60 000 m³ $T^{Inv0}_{1\ to\ 3}$***= 60 000 m³*** $T^{Inv0}_{4\ to\ 6}$***= 0 m³***	$19 704 500					$7 213 480					$6 157 400					$6 514 220					$6 961 680				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20.3	5.6	1.9	0.8	71.4	55.5	15.4	5.1	4.5	19.6	65	18	6	7.9	3.2	61.4	17	5.6	14.9	1	57.5	15.9	5.3	20.9	0.4
7 tanks – 60 000 m³ $T^{Inv0}_{1\ to\ 3}$***= 60 000 m³*** $T^{Inv0}_{4\ to\ 7}$***= 0 m³***	$19 701 900					$7 210 880					$6 154 800					$6 511 620					$6 959 080				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20.3	5.6	1.9	0.8	71.4	55.5	15.3	5.1	4.5	19.6	65	18	6	7.9	3.2	61.4	17	5.6	14.9	1	57.5	15.9	5.3	21	0.4
4 tanks – 90 000 m³ $T^{Inv0}_{1\ to\ 2}$***= 90 000 m³*** $T^{Inv0}_{3\ to\ 4}$***= 0 m³***	$19 650 500					$7 105 480					$5 995 400					$6 190 220					$6 475 680				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20.4	5.6	1.9	0.5	71.6	56.3	15.6	5.2	3	19.9	66.7	18.5	6.1	5.4	3.2	64.6	17.9	5.9	10.5	1	61.8	17.1	6.7	15	0.4
5 tanks – 90 000 m³ $T^{Inv0}_{1\ to\ 2}$***= 90 000 m³*** $T^{Inv0}_{3\ to\ 5}$***= 0 m³***	$19 650 500					$7 105 480					$5 995 400					$6 190 220					$6 475 680				
	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E	%P	%I	%T	%S	%E
	20.4	5.6	1.9	0.5	71.6	56.3	15.6	5.2	3	19.9	66.7	18.5	6.1	5.4	3.2	64.6	17.9	5.9	10.5	1	61.8	17.1	6.7	15	0.4

As for the choice of the ST size, the number of tanks at the storage base, and the pipeline diameter, the optimal solution is using VLCC STs, four storage tanks with a capacity of 90 000 m3, and pipeline diameter of 0.6096 m (24"). The **total cost is $5 995 400** with the components are approximately **$4 000 000 (66.7%) for production cost**, **$1 109 000 (18.5%) for inventory holding cost**, **$368 000 (6.1%) for transportation cost**, **$324 000 (5.4%) for setup cost**, and **$194 500 (3.2%) for electricity consumption cost**. Some further discussions will be presented in the next section. From Table 6 to Table 12 are detailed results for this optimal solution. Some detailed, further discussions will be presented in the next section.

Table 6. FPSO crude oil production and inventory level over time

Period	**Crude oil production over time** F_t^P **(m³)**	**FPSO inventory level over time** F_t^{Inv} **(m³)**
t=1	0	0
t=2	180 000	0
t=3	180 000	0
t=4	180 000	0
t=5	180 000	0
t=6	180 000	0
t=7	185 200	5 200
t=8	257 400	92 600
t=9	257 400	260 000
t=10	0	170 000

Table 7. Amount offloaded to shuttle tankers over time

Period	**Amounts offloaded to ST** ST_t^L **(m³)**
t=1	170 000
t=2	180 000
t=3	180 000
t=4	180 000
t=5	180 000

t=6	180 000
t=7	180 000
t=8	170 000
t=9	90 000
t=10	90 000

Table 8. Shuttle tankers - to - Storage tanks connections

Period / Tank	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
Z1	0	1	0	1	0	1	0	1	0	0
Z2	0	1	0	1	0	1	0	1	0	0
Z3	1	0	1	0	1	0	1	0	1	0
Z4	1	0	1	0	1	0	1	0	0	1

$C_{z,t}$ = 1, if the connection between tank z and ST is established during period t, 0 otherwise.

Table 9. Storage tank - to - pipeline connections

Period / Tank	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
Z1	1	0	1	0	1	0	1	0	1	0
Z2	1	0	1	0	1	0	1	0	1	0
Z3	0	1	0	1	0	1	0	1	0	0
Z4	0	1	0	1	0	1	0	1	0	0

$D_{z,t}$ = 1, if the connection between tank z and ST is established during period t, 0 otherwise.

Table 10. Inventory levels at storage base over time

Tank / Period	Storage tank inventory levels $I_{z,t}$ (m^3)			
	Z1	**Z2**	**Z3**	**Z4**
1	0	0	80 000	90 000
2	90 000	90 000	0	0
3	0	0	90 000	90 000
4	90 000	90 000	0	0
5	0	0	90 000	90 000

6	90 000	90 000	0	0
7	0	0	90 000	90 000
8	90 000	80 000	0	0
9	0	0	90 000	0
10	0	0	90 000	90 000

Table 11. Incoming and outgoing amounts of crude oil to/from storage tanks

Tank / Period	**Incoming amounts to storage tanks $X_{z,t}$ (m^3)**				**Outgoing amounts from storage tanks $Y_{z,t}$ (m^3)**			
	Z1	**Z2**	**Z3**	**Z4**	**Z1**	**Z2**	**Z3**	**Z4**
1	0	0	80 000	90 000	90 000	90 000	0	0
2	90 000	90 000	0	0	0	0	80 000	90 000
3	0	0	90 000	90 000	90 000	90 000	0	0
4	90 000	90 000	0	0	0	0	90 000	90 000
5	0	0	90 000	90 000	90 000	90 000	0	0
6	90 000	90 000	0	0	0	0	90 000	90 000
7	0	0	90 000	90 000	90 000	90 000	0	0
8	90 000	80 000	0	0	0	0	90 000	90 000
9	0	0	90 000	0	90 000	80 000	0	0
10	0	0	0	90 000	0	0	0	0

Table 12. Flow rate from storage base to the CDU over time

Period	**Flow rate R_t(m^3/d)**
t=1	20 000
t=2	18 888.9
t=3	20 000
t=4	20 000
t=5	20 000
t=6	20 000
t=7	20 000
t=8	20 000
t=9	18 888.9
t=10	0

5.5 Discussion of the results

Analyzing the resulting costs in Table 4 and Table 5, some remarks can be made as follows:

- The pipeline diameter the most strongly influence on the total cost. According to the Hazen-Williams formula (1), the pipeline pressure losses are inversely proportional to the diameter value. As a result, the pump's operational power, as well as electricity consumption, become reduced. On the other hand, it should be noticed that a large pipeline diameter corresponds to a higher connection setup cost, which leads to an increase in the total cost. The most efficient pipeline size balancing the cost components and giving the lowest total cost on all six cases of storage capacity at onshore storage base and two classes of shuttle tankers is 0.6096 m (24").
- For the onshore storage base, with a storage capacity equivalent to 360 000 m^3, using fewer tanks with a larger capacity will be more cost-effective. Specifically, four tanks - 90 000 m^3 will give less cost than six tanks - 60 000m^3 or twelve tanks - 30 000m^3 due to creating fewer ST - tanks and tanks - CDU connections. In the cases of storage tanks have capacity at 30 000 m^3, using twelve tanks gives relatively lower cost than using eleven tanks while in the cases of tanks have storage capacity at 60 00 m^3, using seven tanks instead of six tanks does not give much difference, seven give slightly less cost or equal to 6 tanks. For the cases of tanks have storage capacity at 90 000 m^3, there is absolutely no difference in cost when using 4 or 5 tanks.
- The transportation capacity of Aframax ST is not enough to meet this high crude oil demand in only ten periods. Therefore, the model is only tested on Suezmax and VLCC. When demand is 1 600 000 m^3 as in the computational example, two different sizes of STs do not cause an impact on the amount of crude oil is loaded/unloaded to/from STs over time. The decrease in transportation cost, as well as the total cost, comes from the unit cost to transfer 1 m^3 of crude oil of VLCC is lower than for Suezmax (\$0.23/m^3 versus \$0.25/m^3).

Table 6 shows that the production at FPSO is maintained stably from period 2 to 6. The production rate reaches 18 000 m^3/day. Then the production rate increases to 18 520 m^3/day in period 7 and at 25 740 m^3/day in periods 8 and 9. The production is suspended temporarily in period 10 for maintenance work as the assumption in the beginning. There is no inventory at FPSO from period 1 to 6 to save the inventory holding cost. The inventory level increases sharply in periods 7, 8, 9, and finally is kept at 170 000 m^3 in the last period as the requirement.

According to Table 7, the amount of crude oil that ST offloads in the first period coming from FPSO inventory. From period 2 to 6, STs transport all crude oil produced at FPSO (180 000 m^3 for each period) to the storage base. The amount of crude oil loaded and unloaded in the second half of the quarter decreases, from 180 000 m^3 in period 7 to 90 000 m^3 in period 10.

Table 8 and Table 9 illustrate the connections between ST-to-tanks and tanks-to-CDU. In this optimal solution, the connection setup cost is reduced due to using fewer storage tanks; hence, the number of connections also decreases. The total number of connections made when using four tanks (90 000 m^3) is 36 while using twelve tanks (30 000 m^3) is 108.

Table 10 and Table 11 show the inventory levels and the incoming/outgoing amounts of crude oil to/from four storage tanks during ten periods. The total inventory level of all tanks in the final period is satisfied at 180 000 m^3, and the constraint of a tank cannot simultaneously receive crude oil from STs, and discharge to a CDU is not violated.

Flow rate from storage base to the CDU over time is demonstrated in Table 12. The maximum flow rate is 20 000 m^3/d, and the minimum is 18 888.9 m^3/d. In the final period, there is no flow to the CDU.

The analysis has revealed that (for the data of storage capacity at the storage base), the problem becomes infeasible if the total storage capacity of tanks is less than 1.0303 times of the FPSO storage capacity. The minimum required storage capacity is 326 600 m^3. The extra capacity needed for the storage base can be attributed to the lags related to switching tanks to which the shuttle tankers are offloading, and from which the pump stations are transporting petroleum to the refinery. This number works for all 60 runs that have been tested (two sizes of ST, six cases of tank numbers - two for each tank size, five pipeline diameters). One thing should be noticed that the initial inventory level at each tank should ensure enough space to receive while other tanks are busy to discharge.

6 CONCLUSIONS

Members of the supply chain depend on each other in terms of resources and information-This dependency is increasing over time with the rise of globalization, outsourcing, and technological advances. The benefits of these trends are apparent but, at the same time, posing many challenges. To overcome these current challenges, supply chain members need to coordinate closely together to minimize costs and risks. Choosing an effective coordination strategy is extremely important.

The complexity and inflexible nature of the industry are the driving forces that strive petroleum companies integrate vertically to achieve better control along the chain. Each stage in PSC is both the customer using the output of the previous stage and the supplier of input materials for the next stage. Therefore, the petroleum industry owns an excellent context to integrate vertically.

In the first half of the PSC, from production site to refinery site, PSC is operated on the push strategy. The amount of crude oil produced or purchased would be transported to refineries based on demand forecast. Refining plays a central role in PSC, converting crude oil into finished products to satisfy customer orders. In the latter half of the PSC, from the refinery site to the end customers, PSC is operated on the pull strategy. Refining operations and product delivery are pulled by the confirmed retail demand.

The activities that have been coordinated in the optimization model are production planning at FPSO, inventory management at FPSO and storage base, crude oil transportation by ST, connection setup scheduling between ST and tanks, tanks and CDU, planning the incoming/outgoing amounts of crude oil to/from each storage tank, and the operation of pumps to transfer crude oil from storage base to the CDU. The capacities of the actors that are integrated into the decision-making model are the transportation capacity of the shuttle tankers, the storage capacity at the storage base, and the long-distance transmission pipeline diameter.

The model is built at the tactical planning level, medium-term planning of production at an oilfield, inventory management, transportation, and distribution from the oilfield to refinery site for one quarter of a year. The operational issues, including the scheduling of operations in the intermediate storage base, pumps’ operation, flow rate planning, are also taken into account.

The mathematical model has ignored uncertain parameters such as the stochasticity of transportation and loading/unloading time due to environmental impacts. Nonlinear equations encourage the development of a more efficient algorithm for pumps' operation are also skipped to simplify the model. The time horizon can be expanded to one year with four quarters, different demand for each quarter. Maintenance factors and perhaps other aspects of the operational level might also be integrated into the model.

This master thesis project has analyzed different issues of vertical integration strategic approach in petroleum supply chain management. The mathematical model for simultaneously making decisions regarding capacity utilization has been covered within a MILP model. The non-linear expressions in the model are linearized by applying the piecewise linear approximation. The AMPL/CPLEX solver gives a solution to the developed model within only a few seconds.

Reference list

Abraham, J. N., and Rao, K. S. (2009). Integration of generative and evaluative models for production scheduling of lube oil plants in a petroleum refinery. *Applied mathematical modelling, 33*(3), 1213-1227.

Agra, A., Christiansen, M., and Delgado, A. (2017). Discrete time and continuous time formulations for a short sea inventory routing problem. *Optimization and Engineering, 18*(1), 269-297.

Ahn, H.-S., and Kaminsky, P. (2005). Production and distribution policy in a two-stage stochastic push-pull supply chain. *Iie Transactions, 37*(7), 609-621.

Alfred, C. (1977). The visible hand: the managerial revolution in American business. *Cambridge, MA, Harvard University Press, 51*, 107-108.

Assis, L. S., Camponogara, E., Menezes, B. C., and Grossmann, I. E. (2019). An MINLP formulation for integrating the operational management of crude oil supply. *Computers & Chemical Engineering, 123*, 110-125.

Bain, J. S. (1968). Industrial Organization. John Willey & Sons. *Inc. New York*.

Bausch, D. O., Brown, G. G., and Ronen, D. (1998). Scheduling short-term marine transport of bulk products. *Maritime Policy & Management, 25*(4), 335-348.

Bentley, R. W. (2002). Global oil & gas depletion: an overview. *Energy policy, 30*(3), 189-205.

Biography.com Editors. (2019). Andrew Carnegie Biography. Retrieved from https://www.biography.com/business-figure/andrew-carnegie

BP Energy. (2019). BP Energy Outlook, 2019 edition. *London, United Kingdom2019*.

Bredström, D., and Rönnqvist, M. (2008). Coordination of refinery production and sales planning.

Bremer, W., and Perakis, A. (1992). An operational tanker scheduling optimization system: model implementation, results and possible extensions. *Maritime Policy & Management, 19*(3), 189-199.

Bresciani, G., and Brinkman, M. (2016). Five strategies to transform the oil and gas supply chain. Retrieved from https://www.mckinsey.com/industries/oil-and-gas/our-insights/five-strategies-to-transform-the-oil-and-gas-supply-chain

Bryan, G., and McDougall, D. (1998). Optimize your supply chain for best-possible operations. *Wood Technology, 7*, 35-39.

Camponogara, E., and Plucenio, A. (2014). Scheduling dynamically positioned tankers for offshore oil offloading. *International Journal of Production Research, 52*(24), 7251-7261. doi:10.1080/00207543.2014.916828

Chan, D. (2013). The challenges facing management in a rapidly changing business environment. Retrieved from https://www.cass.city.ac.uk/faculties-and-research/research/cass-knowledge/2013/november/the-challenges-facing-management-in-a-rapidly-changing-business-environment

Chen, F. (2003). Information sharing and supply chain coordination. *Handbooks in operations research and management science, 11*, 341-421.

Chima, C. M. (2007). Supply-chain management issues in the oil and gas industry. *Journal of Business & Economics Research (JBER), 5*(6).

Chopra, S., and Meindl, P. (2001). Strategy, Planning, and Operation. *Supply Chain Management*.

Chopra, S., and Meindl, P. (2016). *Supply Chain Management--Strategy, Planning and Operation*: Tsinghua University Press. wheat soybean others land for no use.

Christiansen, M., Fagerholt, K., Nygreen, B., and Ronen, D. (2013). Ship routing and scheduling in the new millennium. *European Journal of Operational Research, 228*(3), 467-483.

Christopher, M. (1992). *Logistics and supply chain management*: Financial Times/Irwin Professional Pub.

Curry, L. (2015). Fundamentals of qualitative research methods. *Yale School of Public Health*.

Daskin, M. S., Snyder, L. V., and Berger, R. T. (2005). Facility location in supply chain design. In *Logistics systems: Design and optimization* (pp. 39-65): Springer.

de Assis, L. S., Camponogara, E., Zimberg, B., Ferreira, E., and Grossmann, I. E. (2017). A piecewise McCormick relaxation-based strategy for scheduling operations in a crude oil terminal. *Computers & Chemical Engineering, 106*, 309-321.

Dempster, M., Pedron, N. H., Medova, E., Scott, J., and Sembos, A. (2000). Planning logistics operations in the oil industry. *Journal of the Operational Research Society, 51*(11), 1271-1288.

Desai, A. (2001). The evolution of vertically integrated organizations: the role of historical context. *Management Decision, 39*(3), 233-243. doi:10.1108/EUM0000000005454

Diz, G. S. d. S., Oliveira, F., and Hamacher, S. (2017). Improving maritime inventory routing: application to a Brazilian petroleum case. *Maritime Policy & Management, 44*(1), 42-61.

East Asia Forum. (2016). World Petroleum Industry. Retrieved from https://www.economywatch.com/world-industries/petroleum/world.html

Elsaghier, E. H. (2017). *Planning and optimising of petroleum industry supply chain and logistics under uncertainty.* Sheffield Hallam University,

Escudero, L. F., Quintana, F. J., and Salmerón, J. (1999). CORO, a modeling and an algorithmic framework for oil supply, transformation and distribution optimization under uncertainty. *European Journal of Operational Research, 114*(3), 638-656.

Fernandes, L. J., Relvas, S., and Barbosa-Póvoa, A. P. (2012). Design and planning of downstream petroleum supply chains. In *Computer Aided Chemical Engineering* (Vol. 30, pp. 432-436): Elsevier.

Fjeldstad, Ø., Stabell, C., and Kolbjørnsrud, V. (1998). Gas Mediators in Europe: A New Competitive Landscape? *Norwegian School of Management, unpublished discussion note*.

Gainsborough, M. (2006). Building World-class Supply Chain Capability in the Downstream Oil Business. *Oil and Gas Processing Review*, 29-32.

Guan, W., and Rehme, J. (2012). Vertical integration in supply chains: driving forces and consequences for a manufacturer's downstream integration. *Supply chain management: An international Journal*, *17*(2), 187-201.

Guyonnet, P., Grant, F. H., and Bagajewicz, M. J. (2008). Integrated model for refinery planning, oil procuring, and product distribution. *Industrial & Engineering Chemistry Research, 48*(1), 463-482.

Harrigan, K. R. (1983). Strategies for vertical integration. Lexington, MA: DC Heath & Company. In: Lexington Books (reprinted in 2003 as Vertical Integration, Outsourcing and ….

Harrison, T. P., and Ganeshan, R. (2001). An Introduction to Supply chain Management. *Penn State University, University Park, USA, http://silmaril. smeal. psu. edu*.

Hart, C. (2018). *Doing a literature review: Releasing the research imagination*: Sage.

Hassen, K., and Szucs, D. (2012). Supply Chain Optimization in the Oil Industry: A Case Study of MOL Hungarian Oil and Gas PLC. In.

Hill, N., and Stone, W. C. (1991). *Success through a positive mental attitude*: Simon and Schuster.

Hirakawa, Y. (1996). Performance of a multistage hybrid push/pull production control system. *International Journal of Production Economics, 44*(1-2), 129-135.

Hull, B. (2002). A structure for supply-chain information flows and its application to the Alaskan crude oil supply chain. *Logistics Information Management, 15*(1), 8-23.

Hussain, R., Tiravat, A., and Basheer, K. (2006). Supply chain management in the petroleum industry: challenges and opportunities. *International Journal of Global Logistics & Supply Chain Management, 1*(2), 90-97.

Jenkins, G. P., and Wright, D. S. (1998). Managing inflexible supply chains. *The International Journal of Logistics Management, 9*(2), 83-90.

Jeong, I.-J. (2011). A dynamic model for the optimization of decoupling point and production planning in a supply chain. *International Journal of Production Economics, 131*(2), 561-567.

Jia, Z., and Ierapetritou, M. (2004). Efficient short-term scheduling of refinery operations based on a continuous time formulation. *Computers & Chemical Engineering, 28*, 1001-1019. doi:10.1016/j.compchemeng.2003.09.007

Johnsen, S., Ask, R., and Roisli, R. (2007). *Reducing risk in oil and gas production operations.* Paper presented at the International Conference on Critical Infrastructure Protection.

Joly, M. (2012). Refinery production planning and scheduling: The refining core business. *Brazilian Journal of Chemical Engineering, 29*(2), 371-384.

Kelder, M. (2016). Vertical integration and information sharing - IT/OT integration, integrated product management system. Retrieved from https://www.aiche.nl/aiche-past-proceedings/42-2016-5-26

Kenton, W. (2019). Vertical integration. Retrieved from https://www.investopedia.com/terms/v/verticalintegration.asp

Ketchen Jr, D. J., Rebarick, W., Hult, G. T. M., and Meyer, D. (2008). Best value supply chains: A key competitive weapon for the 21st century. *Business Horizons, 51*(3), 235-243.

Klein, B., Crawford, R. G., and Alchian, A. A. (1978). Vertical integration, appropriable rents, and the competitive contracting process. *The journal of Law and Economics, 21*(2), 297-326.

Kothari, C. R. (2004). *Research methodology: Methods and techniques*: New Age International.

Kunt, T., Grupa, M., and Varvarezos, D. (2008). *Integrating refinery production planning with primary and secondary distribution network optimization.* Paper presented at the 5th international conference on foundations of computer-aided process operations (FOCAPO 2008), Massachusetts, USA.

Kuo, T.-H., and Chang, C.-T. (2008). Application of a mathematic programming model for integrated planning and scheduling of petroleum supply networks. *Industrial & Engineering Chemistry Research, 47*(6), 1935-1954.

La Londe, B. J., and Masters, J. M. (1994). Emerging logistics strategies: blueprints for the next century. *International journal of physical distribution & logistics management, 24*(7), 35-47.

Lasschuit, W., and Thijssen, N. (2004). Supporting supply chain planning and scheduling decisions in the oil and chemical industry. *Computers & chemical engineering, 28*(6-7), 863-870.

Lee, H., Padmanabhan, V., and Whang, S. (1997). The Bullwhip Effect in Supply Chains: Sloan Management Review. *Clase de Cadena de Suministros*.

Lee, H., Pinto, J. M., Grossmann, I. E., and Park, S. (1996). Mixed-integer linear programming model for refinery short-term scheduling of crude oil unloading with inventory management. *Industrial & Engineering Chemistry Research, 35*(5), 1630-1641.

Li, S., Ragu-Nathan, B., Ragu-Nathan, T., and Rao, S. S. (2006). The impact of supply chain management practices on competitive advantage and organizational performance. *Omega, 34*(2), 107-124.

Li, W., Hui, D., Hua, B., and Tong, Z. (2003). PLANT-WIDE SCHEDULING AND MARGINAL VALUE ANALYSIS FOR A REFINERY.

Magalhaes, M. V., and Shah, N. (2003). *Crude oil scheduling.* Paper presented at the Proceedings of the 4th Conference on Foundations of Computer-Aided Process Operations.

Majumdar, S. K., and Ramaswamy, V. (1994). Explaining downstream integration. *Managerial and Decision Economics, 15*(2), 119-129.

Managi, S., Opaluch, J. J., Jin, D., and Grigalunas, T. A. (2004). Technological change and depletion in offshore oil and gas. *Journal of environmental economics and management, 47*(2), 388-409.

Manzano, F. S. (2005). *Supply chain practices in the petroleum downstream.* Massachusetts Institute of Technology, Engineering Systems Division, Más, R., and Pinto, J. M. (2003). A mixed-integer optimization strategy for oil supply in distribution complexes. *Optimization and Engineering, 4*(1-2), 23-64.

Mendez, C. A., Grossmann, I. E., Harjunkoski, I., and Kaboré, P. (2006). A simultaneous optimization approach for off-line blending and scheduling of oil-refinery operations. *Computers & chemical engineering, 30*(4), 614-634.

Mitchell, E. J. (1976). Vertical integration in the oil industry. *Books*.

Moharana, H. S., Murty, J., Senapati, S., and Khuntia, K. (2012). Coordination, collaboration and integration for supply chain management. *International Journal of Interscience Management Review, 2*(2), 46-50.

Mouret, S., Grossmann, I. E., and Pestiaux, P. (2009). A novel priority-slot based continuous-time formulation for crude-oil scheduling problems. *Industrial & engineering chemistry research, 48*(18), 8515-8528.

Mouton, J., and Marais, H. (1996). Basic concepts in the methodology of the social sciences. Pretoria. In: HSRS Publishers.

Neiro, S. M., and Pinto, J. M. (2003). *Supply chain optimization of petroleum refinery complexes.* Paper presented at the Proceedings of the 4th International Conference on Foundations of Computer-Aided Process Operations.

Neiro, S. M., and Pinto, J. M. (2004). A general modeling framework for the operational planning of petroleum supply chains. *Computers & Chemical Engineering, 28*(6-7), 871-896.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International journal of production economics, 85*(3), 319-329.

Oliver, R. K., and Webber, M. D. (1982). Supply-chain management: logistics catches up with strategy. *Outlook, 5*(1), 42-47.

Owen, E. W. (1975). Trek of the oil finders: a history of exploration for petroleum.

Papageorgiou, D. J., Cheon, M.-S., Harwood, S., Trespalacios, F., and Nemhauser, G. L. (2018). Recent progress using matheuristics for strategic maritime inventory routing. In *Modeling, Computing and Data Handling Methodologies for Maritime Transportation* (pp. 59-94): Springer.

Patel, H. (2009). An Introduction to Supply Chain Management.

Perakis, A., and Bremer, W. (1992). An operational tanker scheduling optimization system: background, current practice and model formulation. *Maritime Policy & Management, 19*(3), 177-187.

Persson, J. A., and Göthe-Lundgren, M. (2005). Shipment planning at oil refineries using column generation and valid inequalities. *European journal of operational research, 163*(3), 631-652.

Pinto, J., Joly, M., and Moro, L. (2000). Planning and Scheduling Models for Refinery Operations. *Computers & Chemical Engineering, 24*, 2259-2276. doi:10.1016/S0098-1354(00)00571-8

Pinto, J., and Moro, L. (2000). A planning model for petroleum refineries. *Brazilian Journal of Chemical Engineering, 17*(4-7), 575-586.

Ram, G., and Harrison, T. P. (1995). An introduction to supply chain management. In.

Ramachandran, K., Whitman, L., and Ramachandran, A. B. (2002). *Criteria for determining the push–pull boundary.* Paper presented at the Industrial Engineering Research Conference. Orlando, FL, USA.

Redutskiy, Y. (2017). Integration of oilfield planning problems: infrastructure design, development planning and production scheduling. *Journal of Petroleum Science and Engineering, 158*, 585-602.

Rey, B., and Fernando. (1995). *The effects of vertical integration on oil company performance*: Oxford Institute for Energy Studies.

Robertson, G., Palazoglu, A., and Romagnoli, J. A. (2011). A multi-level simulation approach for the crude oil loading/unloading scheduling problem. *Computers & Chemical Engineering, 35*(5), 817-827.

Rocha, R., Grossmann, I. E., and de Aragão, M. V. P. (2009). Petroleum allocation at PETROBRAS: Mathematical model and a solution algorithm. *Computers & Chemical Engineering, 33*(12), 2123-2133.

Rocha, R., Grossmann, I. E., and de Aragão, M. V. P. (2013). Cascading knapsack inequalities: reformulation of a crude oil distribution problem. *Annals of Operations Research, 203*(1), 217-234.

Rocha, R., Grossmann, I. E., and de Aragão, M. V. P. (2017). Petroleum supply planning: reformulations and a novel decomposition algorithm. *Optimization and Engineering, 18*(1), 215-240.

Rodriguez, C. E. P., de Souza, G. F. M., Gilberto, F., and Martins, M. (2009). *Risk-based analysis of offloading operations with FPSO production units.* Paper presented at the Proceedings of the 20th International Congress of Mechanical Engineering. Gramado, Brazil.

Ronen, D. (1983). Cargo ships routing and scheduling: Survey of models and problems. *European Journal of Operational Research, 12*(2), 119-126.

Ronen, D. (2002). Marine inventory routing: Shipments planning. *Journal of the Operational Research Society, 53*(1), 108-114.

Röthlisberger, S. (2005). *Excellent Supply Chains in the Oil Industry: Royal Dutch/Shell.* (Master Of Engineering In Logistics And Supply Chain Management),

Saharidis, G. K., Minoux, M., and Dallery, Y. (2009). Scheduling of loading and unloading of crude oil in a refinery using event-based discrete time formulation. *Computers & Chemical Engineering, 33*(8), 1413-1426.

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

Schlumberger Oilfield Glossary. Retrieved from https://www.glossary.oilfield.slb.com/

Sear, T. (1993). Logistics Planning in the Downstream Oil Industry. *Journal of the Operational Research Society, 44*. doi:10.1057/jors.1993.2

Sengupta, K., Heiser, D. R., and Cook, L. S. (2006). Manufacturing and service supply chain performance: a comparative analysis. *Journal of supply chain management, 42*(4), 4-15.

Shaton, K. (2017). Essays on upstream gas transport infrastructure planning and appraisal.

Simchi Levi, D., Kaminsky, P., and Simchi Levi, E. (2003). *Designing and managing the supply chain: Concepts, strategies, and case studies*: McGraw-Hill.

Stabell, C. (2001). New models for value creation and competitive advantage in the petroleum industry.

Stevens, G. C. (1989). Integrating the supply chain. *international Journal of physical distribution & Materials Management, 19*(8), 3-8.

Tan, K. C., Kannan, V. R., and Handfield, R. B. (1998). Supply chain management: supplier performance and firm performance. *Journal of Supply Chain Management, 34*(3), 2.

Tusiani, M. D. (1996). *The Petroleum shipping industry: a nontechnical overview* (Vol. 1): PennWell Books.

U.S. Energy Information Administration (U.S. Energy Information Administration (EIA)). (2019). *International Energy Outlook 2019 with projections to 2050*. Retrieved from https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

Williamson, O. E. (1979). Transaction-cost economics: the governance of contractual relations. *The journal of Law and Economics*, *22*(2), 233-261.

Wu, N., Zhou, M., and Chu, F. (2008). A Petri net-based heuristic algorithm for realizability of target refining schedule for oil refinery. *IEEE Transactions on Automation Science and Engineering*, *5*(4), 661-676.

Appendix A

Code for the AMPL Model-file:

```
#############Sets and indices#############
set Z; # set of shuttle tanker

#############Parameters##################
param T; # number of periods
param p; # number of days in a period

###FPSO####
param F_Inv0; # initial inventory at FPSO (m3)
param F_PR; # flow rate per day of FPSO (m3/day)
param F_S;  # storage capacity designed of FPSO (m3)
param F_Pc; # production cost at FPSP($/m3)
param F_IHc;# inventory holding cost at FPSO ($/m3)

###SHUTTLE TANKER###
param ST_Cap; # loading capacity designed  of ST (m3)
param ST_Tc; # transportation cost of ST ($/m3)

###STORAGE BASE####
param T_Cap{Z}; # storage capacity of tank z (m3)
param T_IHc; # inventory holding cost of tanks ($/m3)
param T_Inv0{Z}; # initial inventory of tank z (m3)
param setup_cost; # cost to connect ST vs tanks, tanks vs CDU ($)

###CDU###
param Dem; # total demand of CDU for a quarter (m3)

###PIPELINE and PUMPS####
param Length; # length of a pipeline segment
param Diam; # pipeline internal diameter
param FlowRateAvg := Dem/(T*p); # average flow rate
param PumpEfficiency; # 45%
param ElectricityPrice; # $ per kW*h
param NPumps; # number of pipeline segment

###PIECEWISE LINEAR APPROXIMATION###
param M; # number of pieces in piecewise linear approximation
param a{k in 1..M}=1/M*(k-1)*(Dem/T)*2; # argument values for
approximation

######Variables########

###FPSO####
var F_P{t in 1..T}>=0; # amount oil produced at FPSO in period t (m3)
var F_Inv{t in 1..T}>=0; # inventory level FPSO holds in period t (m3)

###SHUTTLE TANKER###
var ST_L{t in 1..T}>=0; # amount ST offloads in period t (m3)

###STORAGE BASE####
var C{Z,t in 1..T}binary; # 1, if tank z is connected to ST in period t,
0 otherwise

var X{Z,t in 1..T}>=0; # amount of crude oil sent from ST to tank z in
period t
```

```
var I{Z,t in 1..T}>=0; # inv level of tank z at the end of period t (m3)


###CDU###
var D{Z,t in 1..T}binary;
# 1,if tank z is connected to CDU in period t, 0 otherwise

var Y{Z,t in 1..T}>=0;
# amount of crude oil sent from tank z to CDU in t

###PIPELINE and PUMPS####
var Rate{t in 1..T} >= 0; # flow rate from storage base to CDU in period
t

var dP{t in 1..T} >= 0; # pressure losses in t/pressure developed by a
pump

var PumpPower{t in 1..T} >= 0; # pump's operational power

###PIECEWISE LINEAR APPROXIMATION###
var pwa1{1..M, 1..T} >= 0; # continuous approximation variable
var pwa2{1..M, 1..T} binary; # binary approximation variable

#############Objective function############

minimize Total_Cost:
        sum{t in 1..T}F_Pc*F_P[t] + sum{t in 1..T}F_IHc*F_Inv[t]

      + sum{t in 1..T}ST_Tc*ST_L[t] + sum{t in 1..T, z in Z}T_IHc*I[z,t]

      + setup_cost*(sum{z in Z, t in 1..T}C[z,t]+sum{z in Z, t in
1..T}D[z,t])
      + NPumps * sum{t in 1..T} 24 * ElectricityPrice * p * PumpPower[t]
/ PumpEfficiency;

#######Constraints##########
###FPSO, SHUTTLE TANKER, STORAGE BASE, and CDU description###

# inventory level at FPSO in period 1
subject to Inv_F_t1:
      F_Inv[1] = F_Inv0 + F_P[1] - ST_L[1];

# inventory at FPSO in periods 2 through T
subject to Inv_F_t2_to_T{t in 2..T}:
      F_Inv[t] = F_Inv[t-1] + F_P[t] - ST_L[t];

# no production during last period T
subject to Production_LastPeriod:
      F_P[T] = 0;

# offloaded amount in t=1 must not excess initial inv of FPSO
subject to ST_Load_t1:
      ST_L[1] <= F_Inv0;

# production capacity of FPSO
subject to Pro_Cap_F{t in 1..T-1}:
      F_P[t] <= p * F_PR;

# the refinery's demand must be satisfied
subject to Total_demand:
      sum{t in 1..T}ST_L[t] >= Dem;
```

```
# ensure storage capacity for FPSO
subject to Storage_Capacity{t in 1..T}:
      F_Inv[t] <= F_S;

# inv level in the last period at FPSO
subject to Inv_F_final_period:
      F_Inv[T] >= F_Inv0;

# limit amount of crude oil offloaded in each period
subject to ST_cap{t in 1..T}:
      ST_L[t] <= ST_Cap;

# incoming crude oil is contained by some tanks
subject to ST_to_Tanks{t in 1..T}:
      sum{z in Z}X[z,t] = ST_L[t];

# balance the inv of tank z during period 1
subject to Balance_Inv_t1{z in Z}:
      I[z,1] = T_Inv0[z] + X[z,1] - Y[z,1];

# balance the inv of tank z, t=2..T
subject to Balance_Inv_t2{z in Z,t in 2..T}:
      I[z,t] = I[z,t-1] + X[z,t] - Y[z,t];

# inv of all tanks in T reaches required amount
subject to Inv_T_final_period:
      sum{z in Z}I[z,T] = sum{z in Z}T_Inv0[z];

# storage capacity of the tank z
subject to Tank_cap{z in Z,t in 2..T}:
      I[z,t-1] + X[z,t] <= T_Cap[z];

# having flow from ST to tanks if having connection
subject to Tanks_flow{z in Z, t in 1..T }:
      X[z,t] <= 1e12*C[z,t];

# having flow from Tanks to a CDU if having connection
subject to CDU_flow{z in Z, t in 1..T}:
      Y[z,t] <= 1e12*D[z,t];

# tank cannot be discharged crude oil from ST and fill CDU simultaneously
subject to Connection{z in Z, t in 1..T}:
      C[z,t] + D[z,t] <= 1;


### PIPELINE and PUMPS description###

subject to LongDistanceTransportationFlowRate{t in 1..T}:
      Rate[t] >= sum{z in Z}Y[z,t] / p;

# Hazen-Williams formula for pressure losses
subject to PipelineFrictionLosses{t in 1..T}:
      dP[t] = 1e-6 * sum{k in 1..M} a[k]^1.85 * pwa1[k,t]
            * 7.68e-9 * 850 * 9.80665 * (1/120)^1.85 * Length
/(Diam^4.89);

# here, 1e-6 converts dP from Pa to MPa
# 7.68e-9 is Hazen-Williams formula coefficient
# 9.80665 is standard acceleration due to Earth's gravity
# 120 is the "pipeline grade" in Hazen-Williams formula
```

```
# (sum{k in 1..M} a[k]^1.85 * pwa1[k,t]) is the PW approximation of
Rate[t]^1.85


# power developed by the pump to transport the crude oil through a
pipeline segment
subject to PowerRequiredToTrasport{t in 1..T}:
	PumpPower[t] = 1e3 * FlowRateAvg / (24*60*60) * dP[t];

###PIECEWISE LINEAR APPROXIMATION description###

subject to PWLapproximation1{t in 1..T}:
	pwa1[1,t] <= pwa2[1,t];

subject to PWLapproximation2{t in 1..T, k in 2..M-1}:
	pwa1[k,t] <= pwa2[k-1,t] + pwa2[k,t];

subject to PWLapproximation3{t in 1..T}:
	pwa1[M,t] <= pwa2[M-1,t];

subject to PWLapproximation4{t in 1..T}:
	sum{k in 1..M}pwa2[k,t] = 1;

subject to PWLapproximation5{t in 1..T}:
	sum{k in 1..M}pwa1[k,t] = 1;

subject to PWLapproximation6{t in 1..T}:
Rate[t] = sum{k in 1..M}a[k] * pwa1[k,t];
```

Representation of the Data in AMPL:

```
set Z:= Z1 Z2 Z3 Z4 Z5 ;

param T:=10;
param p:=9;

param Dem:=16e5;

param F_Inv0:=1.7e5;
param F_PR:=28600;
param F_S:=317000;

param ST_Cap:=2.5e5;
#analysis for Suezmax 180000m3 and VLCC 250000 m3

param T_Cap default 9e4;
# 30000m3 (11 and 12 tanks,60000m3 (6 and 7 tanks),90000m3 (4 and 5
tanks)
param T_Inv0 := Z1 9e4  Z2 9e4 Z3 0 Z4 0 Z5 0;


param setup_cost:= 27000;
# 0.2540:$3000, 0.4064:$6000 0.6096:$9000, 0.7620:$18000, 0.9144:$27000
param F_Pc:=2.5;
param F_IHc:=0.5;
param ST_Tc:=0.23;
# Suezmax: $0.25/m3, VLCC:0.23/m3
param T_IHc:=0.5;
param ElectricityPrice := 0.08;
```

```
param NPumps:=10;
param Length := 20000;
param Diam := 0.9144;
param PumpEfficiency := 0.45;
param M := 10;
```

Code for the AMPL Run-file:

```
reset;
model PSC.mod;
data PSC.dat;
option solver cplex;
solve;

display Total_Cost>PSC.sol;

printf "Crude oil production over time: " > PSC.sol;
display F_P >PSC.sol;

printf "Amounts offloaded to shuttle tankers: " > PSC.sol;
display ST_L >PSC.sol;

printf "FPSO inventory level over time: " > PSC.sol;
display F_Inv >PSC.sol;

printf "Shuttle tanker - to - storage tank connections: " > PSC.sol;
display C >PSC.sol;

printf "Storage tank - to - pipeline connections: " > PSC.sol;
display D >PSC.sol;

printf "Storage tank inventory levels: " > PSC.sol;
display I >PSC.sol;

printf "Incoming amounts to storage tanks: " > PSC.sol;
display X >PSC.sol;

printf "Outgoing amounts from storage tanks: " > PSC.sol;
display Y >PSC.sol;

printf "Flow rate from storage base to the refinery in period t: " >
PSC.sol;
display Rate >PSC.sol;

printf "% FPSO production cost: " > PSC.sol;
display sum{t in 1..T}F_Pc*F_P[t]/Total_Cost*100>PSC.sol;

printf "% FPSO + tanks inv holding cost: " > PSC.sol;
display (sum{t in 1..T}F_IHc*F_Inv[t]+sum{t in 1..T, z in Z}T_IHc*I[z,t])
/Total_Cost*100>PSC.sol;

printf "% ST transportation cost: " > PSC.sol;
display (sum{t in 1..T}ST_Tc*ST_L[t]) /Total_Cost*100>PSC.sol;

printf "% connection setup cost: " > PSC.sol;
display setup_cost*(sum{z in Z, t in 1..T}C[z,t]+sum{z in Z, t in
1..T}D[z,t])/Total_Cost*100>PSC.sol;

printf "% electricity consumption cost: " > PSC.sol;
display (NPumps * sum{t in 1..T} 24 * ElectricityPrice * p * PumpPower[t]
/ PumpEfficiency)/Total_Cost*100>PSC. sol;
```