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Introduction

The petroleum supply problem involves planning of shipments of crude oil from platforms to refineries on a daily basis. This must be done by taking into account strategic planning and operational constraints in the petroleum supply chain as follows. Crude oil can either be locally produced or imported from abroad. Local crude oil comes from production sites, mostly offshore, and is transported either by tankers or pipelines. Imported oil is only transported by tankers. After reaching maritime terminals, domestic crude oils are either exported, or shipped to PETROBRAS refineries. At the refineries, petroleum is processed in crude distillation units (CDUs) on daily scheduled production campaigns. These campaigns are defined by consumption rates of different petroleum categories, and start and finish dates to completing them. Figure 1.1 gives an overview of this whole process.

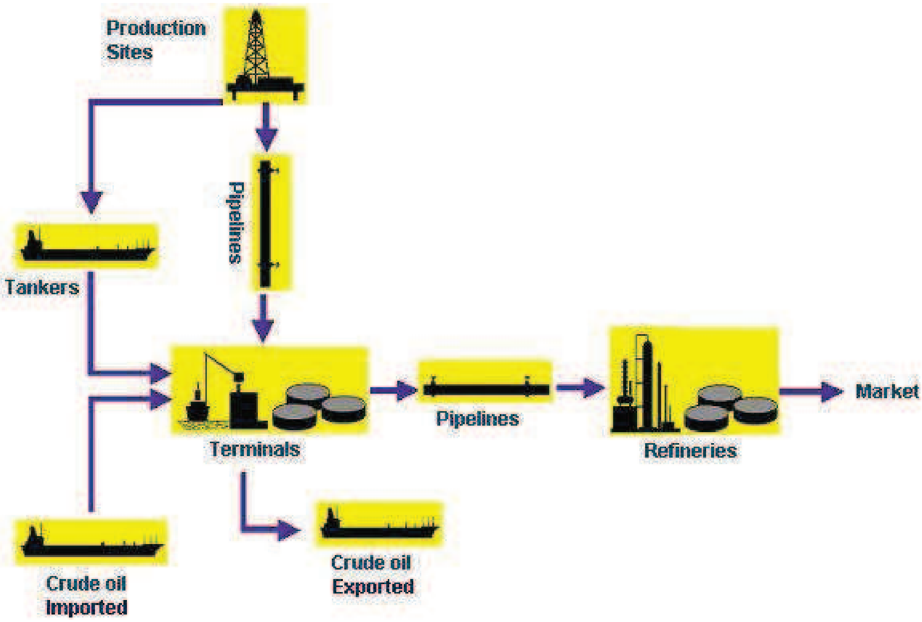

Figure 1.1: Infrastructure of PETROBRAS' Petroleum Supply Chain

The petroleum supply planning at PETROBRAS represents a big challenge. Firstly, we have the size of the network as PETROBRAS has assets spreading all over the territory of Brazil. Secondly, these operations have to be planned for an average horizon of 72 days. At present, these operations are planned manually, i.e., the user has to determine the offloading of each platform and tries to match it with the planned crude oil processing at the refineries. Consequently, since a large number of simplifications is needed, this leads to suboptimal operations. Moreover, as some constraints need to be disregarded, the flow of information in the supply chain is not properly accounted for at the low levels. As a consequence the integration between the strategic and operational levels is compromised.

Applications of mathematical programming in the petroleum industry date back from the 1950's with the work of Charnes et al. [Cha52] and Sysmonds [Sys55]. Since then, we have seen an enormous advancement of algorithms and modeling techniques to solve problems related to the petroleum industry. Today we can say that the relevance of mathematical programming tools are common ground among all oil companies [For03]. However, most of the tools are focused on specific parts of the petroleum supply chain, often leading to a lack of integration. Lasschuit and Thijssen [Las04] stress the importance of achieving a full integration in the oil and chemical supply chain and describe a tool developed by Shell Global solutions with this objective. Pinto and Neiro [Pin04] point out the significance for the oil industry to have a broader view of the supply chain and propose a general framework for modeling operations in the supply chain. Nonetheless, the offshore portion of the problem is not considered. The model presented in this thesis is built with the requirement of integration in mind, and intends to close the gap between the strategic and operational levels at PETROBRAS.

We should mention that the problem addressed in this work is particular to the PETROBRAS logistic process, and to the best of our knowledge, no reference can be found in the literature that treats a similar problem in its whole extension. Typically, this problem is divided into two sub problems: inventory and ship scheduling [Bro87, Mil87], and planning operations at refineries [Lee96, Pin00, Wen03]. In this study we have chosen to model the entire problem. Needless to say, if some simplifications are not performed, any real instance of this problem would remain out of reach.

A challenge that people often have when faced by a such large-scale problem is what to do other than write down a model and hope for commercial solvers being able to do the rest of the work. In this thesis we take a different path from this traditional approach. First, we take good care of understanding well the problem to propose a model that accounts for the situation encountered in practice. Second, we try to identify problem structures that can be exploited in order to get the most of the commercial solver at hand. This approach is very interesting because it allows us to bridge the gap between the theoretical research and the real problem, an objective always looked for, but rarely achieved.

It is important to stress that our main goal in this thesis is to solve efficiently the Petroleum Supply Planning problem. Besides fully accomplishing this hard task, we propose a novel decomposition algorithm and reformulations inducing cascading knapsack inequalities that turn out to be quite general and that can be applied to a wide range of problems.

1.1 Thesis Organization

This dissertation is organized into eight chapters as following:

- In Chapter 2, we describe the problem, which is the main objective of this research. We also stress its importance in the integration of the petroleum supply chain at PETROBRAS and we outline each element considered in our mathematical model. We finish this chapter stating in mathematical terms the problem we intend to solve.
- In Chapter 3, we present the initial mathematical model proposed to solve our problem. Additionally, we provide a solution example to give a better picture of the decisions involved in this real industry application. An extension of the original problem is proposed with the flexibility of campaigns in refineries. We introduce this aspect into our model and we show its advantage over the traditional fixed campaigns. Although the number of binary variables has increased with this extension, the computational time to solve our problem is not greatly hurt due to the simple structure of this model extension and the tightness of the proposed changeover cut.
- In Chapter 4, we discuss some traditional decomposition algorithms, namely, Dantzig and Wolfe, Benders decomposition and Lagrangean relaxation. In this chapter we present the basic ideas of these methods and we show their limitations to solve general large-scale mixed integer programming. This chapter is important to pave the way for the introduction of the novel decomposition algorithm in Chapter 5.
- In Chapter 5, a novel decomposition algorithm is presented. This algorithm is proposed as an alternative to overcome the drawback of the traditional decompositions to cope with problems where both the master and the subproblems are integer programs. Our decomposition algorithm

relies on the idea of decomposing the problem by copying variables, and instead of generating cuts using some straightforward ideas, e.g., Canonical cuts or No-good constraints, we apply disjunctive programming theory to derive them. This method is originally proposed to solve the petroleum supply planning. However, we realize that it is rather general and a broad class of problems can be addressed by this algorithm. Still in this chapter, we further improve the basic idea of this algorithm by using the Repairing MIP Infeasibility method to provide an upper bound, in the case of a minimization problem, in order to apply it as a heuristic to find good solutions to large-scale problems. We conclude this chapter with some computational results on the Generalized Assignment and the Parallel Machine Scheduling problems.

- In Chapter 6, we study the cascading knapsack inequalities, a structure commonly found in some inventory-production-distribution problems. To motivate our discussion we present a simple problem closely related to the petroleum supply planning problem. First, we show that the cascading knapsack inequalities are not evident in a straightforward inventory balance formulation, but they come to light after a simple inventory reformulation. Second, we derive tighter reformulations for some special cases, where each platform can be offloaded by one or two classes of tankers. We end this chapter with a computational study showing the clear advantage of these tighter reformulations.
- In Chapter 7, we discuss how we solve the petroleum supply planning problem. We sum up all the developments we have made in previous chapters, besides presenting some new valid inequalities and an extended formulation based on the way people solve this problem manually. We show computational results for ten real instances of this problem for three different scenarios, namely: platforms offloaded with more than two classes of tankers, platforms offloaded with exactly two classes of tankers and platforms offloaded by one class of tanker. For each scenario we give the best solution option and we comment on the trade-off of considering more classes of tankers to offload each platform.
- In Chapter 8, we close our dissertation with general conclusions, the contributions made and future directions to continue this research.