1 Introduction

The competitive nature of the refining industry is a pressing motive for achieving an optimal operation and for continuing the search for opportunities to improve economic performance. This requires a high level of decision-making not only on a single facility scale but also on an enterprise-wide scale. In this sense, planning for the refinery operations should be carried out in a way to allow for the proper integration of the decisions among all operating facilities at different time horizons and for the efficient utilization of available resources. Such an approach provides an enhanced coordination and objectives alliance towards achieving a global optimal production strategy (Chopra and Meindl, 2004).

Integration and coordination are key components in enterprise-wide optimization (Song and Yao, 2001; Shapiro, 2004; Grossman, 2005). The benefits from integrated planning of multiple sites not only appear in economic terms but also in terms of process flexibility (Shah, 1998). Amos *et al*. (1993) forecasted a potential benefit of $0.80 to $1.80 per barrel of crude oil feedstock for integrated planning. Shobrys and White (2002) stated that oil companies estimate incentives of up to $1 per product barrel for better integration of planning and control for gasoline blending. Grein (1980) categorized the integration benefits as reduction in manufacturing lead time, reduction in average inventory, reduction in labor cost, reduction in production cost, and improvement in capacity. The understanding of such integration benefits has attracted attention in the research area of supply chain planning. Planning is basically an activity in which production targets are set and market forecasts, resource availability, and inventories are considered. In general, planning is categorized into three time frames: strategic (long term), tactical (medium term), and operational (short term). Long-term planning covers the time horizon from one to several years, medium-term ranges from a few months to a year, and short-term covers up to 3 months (Grossmann *et al*., 2001). Strategic planning determines the structure of the supply chain (e.g. facility location). Tactical planning is concerned with decisions such as the assignment of production targets to facilities and the transportation from facilities to distribution centers. On the other hand, operational planning determines the assignment of tasks to units at each facility, considering resource and time constraints (Maravelias and Sung, 2009). These planning levels are conventionally viewed to be related in a hierarchical fashion with strategic planning decisions imposing goals, targets, and constraints on tactical decisions, which are in turn implemented and supported via a number of operational execution functions (Al-Qahtani and Elkamel, 2010a). A way to pose the integration need is by recognizing the natural hierarchy among these steps and the fact they may not operate with the same level of information. Therefore, systematic methods for efficiently managing the oil supply chain must be exploited (Neiro and Pinto, 2004).

Due to the dynamic nature of the refining business, oil refineries are increasingly interested in improving the planning of their operations. Planning applications in the oil chain are of particular interest due to their inherently uncertain nature, high economic incentives, and strategic importance. Although planning in the oil industry was traditionally developed with well established deterministic models, these models have been recently extended to include uncertainties in parameters. In fact, Ben-Tal and Nemirovski (2000) stress that optimal solutions of deterministic models may become infeasible even if the nominal data is only slightly perturbed. This idea is supported by Sen and Higle (1999), who affirmed that under uncertainty the deterministic formulation, in which uncertain random variables are replaced by their expected values, may not provide a solution that is feasible with respect to the random variables. Thus, uncertainties are inevitable and prevalent in mathematical modeling and also in enforcing the planning model to realistic solutions.

The oil industry is subject to uncertainties such as fluctuations in oil production, prices, and product demand. In optimization models for the oil industry, uncertainties have been noted by several academic studies conducted over the past few years (for example, Escudero *et al.*, 1999; Dempster *et al.*, 2000; Neiro and Pinto, 2005; Pongsakdi *et al.*, 2006; Khor and Elkamel, 2008; and Lakkhanawat and Bagajewicz, 2008 – just to cite the most recent works). Despite these contributions for optimization problems under uncertainty at different planning levels, no refinery planning models that consider the integrated planning of multirefinery networks under uncertainty and which deals with the interactions between tactical and operational decisions were found in the literature. Therefore, the refinery integrated planning problem under uncertainty is still an open issue, which is relevant for both mathematical modeling and actual applications.

1.1. Research objectives

The purpose of the present thesis is to address the problem of integration and coordination under uncertainty in the oil supply chain at different decision levels. This study aims at establishing integrated approaches for the tactical and operational planning of multisite refining networks. In this regard, a tactical and an operational mathematical programming models are proposed with the objective of maximizing the expected total profit over a given time horizon. Furthermore, the two distinct levels (tactical and operational) result in a bilevel hierarchical decision-making framework that can be effectively utilized for incorporating uncertainty in the dominant random parameters at each planning level. As the nature of the uncertainty is different in the various levels of the decision making, uncertainties in demand for refined products, oil prices, and product prices account for economic risk at the tactical level. At the operational level, oil supply and process capacity unit uncertainties address the operational risk. Both tactical and operational problems have been formulated as two-stage stochastic linear programs with a finite number of realizations. In this approach, decision variables are cast into two groups, first and second stage variables (Dantzig, 1955). The first stage variables are decided prior to the actual realization of the random parameters. Once the uncertain events have unfolded, further operational adjustments can be made through values of the second stage.

Since the bilevel integrated approach of the oil supply chain under uncertainty has been little explored in the literature, this is the main contribution of this thesis. Actually, uncertainty is an important motivation to the integrated planning of oil refineries. Whereas the optimality is the main issue in the formulation of the two models separately, the integrated approach is more interested in viability issues, because in the solution of the two models separately, the tactical level does not consider the operational uncertainties which may lead to high costs at the operational level and changes in the tactical solution with implications to the oil supply and logistical constraints.

Two modeling approaches for the integration of the tactical and the operational models are considered. The master model (tactical) determines common issues among process and once these common issues are determined, the slave model (operational) optimizes individual processes (Zhang and Zhu, 2006). If the flow of information is only from the master problem towards the slave problem then the approach is named as *hierarchical*. If there is a feedback loop from the slave model back to the master problem in the hierarchical approach, then the approach is *iterative* (Maravelias and Sung, 2009). The formulation ignoring the slave's objective (single-level formulation) is a much more frequent type of occurrence in the applied literature, but Candler and Townsley (1978) demonstrated the potential error implicit in such an approach by an example of energy minimizing in the United States economy. They solved the master problem ignoring the slave's objective. The optimal master variable values were then plugged into the slave problem and optimal slave variables were found. Evaluating the master problem objective given the optimal slave variables led to an objective function value which was approximately 69% of the expected value. Thus, large errors are introduced by ignoring slave problem structure. So, the single-level formulation can be visualized as a centralized decision making system, where the highest level in the hierarchy has power to dictate the decisions and have them executed by the lower levels. A more realistic formulation would recognize the role of the lower levels as part of the process and confining them within the execution of the orders from their superiors. The iterative formulation takes into account the reaction of the lower level decision makers and solves the problem of coordinating the decision making process in a decentralized system by improving the objective of the highest level of a hierarchical organization, while dealing with the tendency of the lower levels of the hierarchy to improve their own objectives. The decisions of the lower level are not dictated by their superiors, but the superior can influence those operations by allocating required resources. The hierarchical nature of the problem is reflected by the order imposed on the choice of the decisions; the highest level makes its decision first, followed by the next highest, until the lowest one (Ben-Ayed, 1993).

An industrial scale numerical study from the Brazilian oil industry was conducted to evaluate the proposed tactical and operational models for refinery planning under uncertainty.

1.2.
Research methodology

This thesis is a model-based quantitative research (Bertrand and Fransoo, 2002) because the work focused on the development of a mathematical model for the integrated planning of oil refineries. Bertrand and Fransoo (2002) classified quantitative operations management research as axiomatic or empirical research. Axiomatic research emphasizes the process of obtaining solutions by the model and make sure that these solutions provide insights on the structure of the problem, whereas the empirical research is concerned with fitting the model and the observations of the reality. Typically, axiomatic research is normative. Normative research aims at establishing policies, strategies, and actions. The empirical research can be either normative or descriptive. Descriptive research aims at analyzing models and describing the causal relationships that may exist in the reality. In this context, the present thesis can be classified as an empirical descriptive study that uses a case study for data collection and validation of the results. The methodology adopted in this study can be summarized by the following steps (Law and Kelton, 1991; Bertrand and Fransoo, 2002):

- Conceptualization: involves the interpretation of reality in a conceptual model and must include the overall objectives of the study;
- Data collection: consists of historical data collection about the operating procedures and model parameters currently in use in the planning firm, besides of data on the performance of the existing system (for validation purposes);
- Modeling: representation of the conceptual model by a scientific model;
- Experiment: the process of obtaining a solution to the scientific model;
- Validation: check if the model solution is an accurate representation of the actual system being studied. This step includes discussions and analysis with decision makers of the company, as the necessary adjustments to fit the model to the real system;

- Documentation and feedback: analysis and documentation (thesis writing) of consistency between the solution obtained and the conceptual model.

Figure 1 summarizes the steps of the methodological approach used in this thesis. The arrows connecting the steps illustrate the possibility of returning to previous steps for corrections or improvements in modeling.

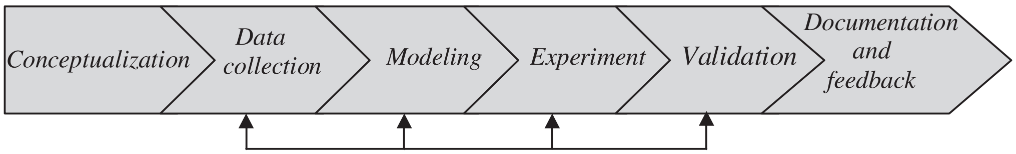

Figure 1. Methodological approach (adapted from Law and Kelton, 1991)

1.3. Overview of the thesis

The remainder of this thesis is organized as follows. An overview of the refining industry is presented in Chapter 2. Next, Chapter 3 describes a literature review in the area of refinery planning models with emphasis on the main techniques to deal with optimization under uncertainty. Chapter 4 presents the tactical and the operational models for refinery planning under uncertainty and offers results and discussions in the context of a case study using real data from the Brazilian oil industry. Next, Chapter 5 discusses the need for integration in the oil supply chain and details the integration approaches adopted in this work. In Chapter 6, these approaches are applied to the two models previously presented in Chapter 4, including a numerical example. The thesis ends with concluding remarks in Chapter 7.