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A new model and a reformulation for the crude distillation unit charging problem with oil blends and sequence-dependent changeover costs

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ABSTRACT

In this paper, we address the problem of planning the crude distillation unit charging process with oil blend. It is well known that blending and splitting operations can lead together to both non-linearities and concavities in mathematical programming models. As result, many proposed models for this problem use simplifying assumptions to keep the formulation computationally tractable. However, we show the existence of splitting operations that can lead to inconsistencies in the solutions obtained by the previous MILP models from the literature. Then, we propose a way to address this issue through an aggregated inventory capacity combined with a disaggregation algorithm. Furthermore, we develop a mathematical reformulation that improves the solving efficiency of the method. Then, we report experiments that show that the reformulated MILP model presents significant gains concerning linear relaxation gaps and run times, and the disaggregation algorithm leads to feasible solutions for all the tested instances.

1. Introduction

The crude oil supply process is a crucial part of the oil & gas supply chain, since it supports the connection between the upstream and the downstream stages, i.e. the link between the exploration and production of crude oil and the refining and distribution of its derivatives.

Due to its complexity, this process is usually managed through the hierarchical logistic planning, which is composed by three sequenced and interdependent levels: strategical, tactical and operational (Miller, 2002; Rocha et al., 2009). The decisions made in a previous level directly affect the next one, since they are used as inputs to the next decision-making process.

In the first level, the entire supply chain is regarded in a monthly granularity and a long-term horizon, in order to decide the required amount of produced and imported crude oil streams to attend the refineries portfolios and expected processing yields, which are defined in the petroleum derivatives production planning in order to meet the demand of each market place to be supplied. In a daily basis and a medium-term horizon, the next level splits the aggregated monthly amounts into transportation lots between platforms and refineries. Finally, the operational level unfolds the previous decisions in a short-term and more detailed schedule, defining the crude oil tankers which are going to perform the transportation of the settled lots from platforms to waterway terminals, and the schedule of the pumping lots through the pipelines network from the storage tanks of the waterway terminals to the charging tanks of the refineries, meeting the demand of crude oil blends which continually supply the crude distillation units (CDU) as the planned processing campaign.

In this paper, we study an operational optimization model for the CDU supply process. The research problem consists of scheduling the pumping lots since the tanker arrivals at the waterway terminal berths until the crude oil blend supply for the crude distillation units at the refineries. The crude oil lots are pumped from the vessels to the terminal storage tanks, and then to the refinery charging tanks. The percentage of each different crude oil type that composes the total volume in the tanks at the terminals and refineries are controlled, aiming to assure the quality demanded for the crude oil blend that charges continually the CDUs along the time. The blend composition settles the yields of the derivatives obtained from the distillation process.

The optimization objective is to find out the minimum cost schedule, regarding the costs of waiting times for berthing, unloading, tank inventories (at the terminals and refineries), and charging tank changeovers. The constraints are summarized in the following groups: tanker arrivals and departure rules at the waterway

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terminals; balance and operational limits concerning the inventory in the tankers, terminal storage tanks and refinery charging tanks, including controlled components; demand meeting for the crude oil blend; and operational rules for the CDU charging process.

This problem has already been addressed in Lee et al. (1996) and Yüzgeç et al. (2010), both being considered as a basis to the model proposed in the present paper. Both references regard the following assumptions: the time is discretized; the amount of crude oil remaining in the pipeline is neglected; changeover times are neglected since they are small in comparison with the scheduling horizon; there is perfect mixing in both the storage and the charging tanks, and the additional mixing time is neglected; and concerning the components control, nonlinear mixing equations are reformulated into linear ones, which is possible since this scheduling system involves only mixing operation without splitting operations (Quesada and Grossmann, 1995).

There are two main contributions in this article. First, it presents a new model to the problem that drives a discussion towards the statement in Lee et al. (1996) and Yüzgeç et al. (2010) that this scheduling system involves only mixing operations without splitting operations, consequently allowing the reformulation of nonlinear mixing equations into linear ones. We show that the obtained solutions may indeed contain splitting operations in two dimensions: stages and times. Because of that, the component flows may violate the assumption of perfect mixing in the tanks in an arbitrary way, i.e., the compositions sent from the same source to different branches may be different from each other, each composition being decided by the solver under the linear constraints that are imposed by the model. This behavior, which we call *false split*, does not necessarily correspond to any non-homogenous splitting cause by particularities of the chemical process. This fact occurs because the linear constraints are not sufficient to perfectly represent the set of feasible solutions determined by the perfect mixing assumption. To fix this problem, a different way to handle the flow splitting issue has been developed which avoids the non-linearity through the aggregation of the storage tanks in the Mixed Integer Linear Programming (MILP) formulation. Then, after the MILP model is solved, a disaggregation algorithm is executed to obtain the detailed pumping schedule.

In other front, the MILP formulations found in the literature present more emphasis on the problem representation perspective than on the computational cost and solving efficiency. It can be noticed by the large linear relaxation gaps and non-negligible run times on solving the proposed instances, which are significantly small comparing to realistic ones. It is worth mentioning that the proposed approach previously described can be applied using the same MILP formulation found in the previous works. For that, it suffices to replace the storage tanks by a single aggregated one, and post-process the obtained solution with the proposed disaggregation algorithm. So, as the second main contribution, we develop a reformulation concerning the performance of the MILP solvers when using this formulation. To improve this performance, we propose a reformulation of the changeover variables, based on the approach introduced by Pochet and Wolsey (2006) for the pigment sequencing problem, in order to provide a better quality for both the linear relaxation gaps and the obtained feasible solutions. To evaluate the new formulation, we create 48 instances based on the case study presented in Leiras (2010). Then, we report experiments that show a significant evolution with respect to the original model.

As an example concerning the comparison between the size of instances from the literature and tested instances in the present work, the largest instances contained in Lee et al. (1996), Jia and Ierapetritou (2004), Karuppiah et al. (2008), Yüzgeç et al. (2010), and Chen et al. (2012) present 12 time periods, 3 vessels, 3 tanks on each stage (terminal and refinery), and 2 controlled components. Although, the largest instance solved to optimality by the developed reformulation presents 20 time periods, 6 vessels, 6 storage tanks on each stage, and 3 controlled components.

1.1. Literature review

The problem of scheduling and planning in petroleum companies has appeared since the introduction of linear programming (Symonds, 1955; Manne, 1956; Saharidis et al., 2009). However, the MILP formulation developed by Lee et al. (1996) has been chosen among the main references as a starting point for the reformulation proposed in this article.

Based on Pochet and Wolsey (2006), this problem can be classified as production planning, featuring characteristics of multi-stage discrete lot sizing with multiple items, inventory management with Wagner–Whiting costs (Pochet and Wolsey, 2010), blending, and scheduling with sequence-dependent changeovers. The Wagner–Whiting costs are non-speculative, i.e. constant unit production costs and non-negative unit holding costs (the production and inventory costs at time t are equal or greater than the production cost at time $t+1$, so there is no incentive based on these costs to produce and storage items in order to meet future demand).

Besides the deterministic MILP models with discrete time representation, focus of the present paper, several other approaches have been developed for the problem, e.g. mixed integer non-linear programming (MINLP) models (Karuppiah et al., 2008; Mouret et al., 2011), heuristics and simulation methods (Chryssolouris et al., 2005; Leiras, 2010), continuous representation of time (Reddy et al., 2003, 2004; Jia and Ierapetritou, 2004; Rejowski and Pinto, 2008; Chen et al., 2012), stochastic models in chance constrained or robust optimization (Wang and Rong, 2009; Cao et al., 2009, 2010), as well as hybrid approaches combining some of these issues (Pan et al., 2009).

The previously cited works were not selected for a more detailed comparison against the developed model based on the following reasons: different scope of the problem (Rejowski and Pinto, 2008), since it is focused on detailing the representation of the pipeline operation, including pumping costs and pipeline segments; absence of modeling the changeover costs (Jia and Ierapetritou, 2004; Karuppiah et al., 2008; Mouret et al., 2011), since they are the most relevant costs in the practical instances; significant inferior performance of solvers (Reddy et al., 2003, 2004; Chen et al., 2012; Pan et al., 2009), since they present results only for small instances, most of them with only one level of storage tanks; usage of techniques other than mono-objective (Chryssolouris et al., 2005; Leiras, 2010), respectively simulation and multi-objective optimization; and usage of techniques that are focused on modeling uncertainty (Wang and Rong, 2009; Cao et al., 2009, 2010). To the best of our knowledge, this is the first model proposed in the literature that handles both blending and changeover costs, using MILP formulation without the false split issue. Our choice for the linear formulations (as Lee et al., 1996; Yüzgeç et al., 2010) is related to the solver performance since there is a broader collection of formulations, decomposition techniques and solution algorithms found in the literature (e.g. Pochet and Wolsey, 2006) that allows to solve larger problems. Thus, in addition to the results presented in this paper, we believe that future works will be able to improve even more the solution times.

In the context of MILP models, we highlight the work of Saharidis et al. (2009) that developed an optimization model using an event-based time representation. This reference addresses a different modeling approach which regards only one stage for the storage tanks and there are blending operations without charging tanks (flows sent from the tanks directly to CDUs via manifold). Furthermore, Yüzgeç et al. (2010) changed the formulation of Lee et al. (1996) in order to capture additional problem characteristics and fixed some inconsistencies of the instances. It presented for the