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Refinery planning and scheduling - An overview

by

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Abstract In this report we give an overview of recent literature on the planning and scheduling of refinery activities. Planning of refinery activities ranges from determining which crude oil types to acquire to which products that should be produced and sold in the market. The scheduling ranges from scheduling of crude oil unloading and blending to blending of components to finished products. This overview treats three different categories of activities; planning and scheduling of crude oil unloading and blending, production planning and process scheduling, and product blending and recipe optimization. The focus will be on identifications of problems, the models outlined for the specified problems and the computational difficulties introduced by the models. A final section discusses an agenda for future research.

1 Introduction

Building a modern refinery is a huge investment that puts its owner in a position where high fixed cost must be covered for a lengthy future. Because of this investment and fixed cost, efficient use of refinery resources is important both for short-term and long-term profitability. In addition, refineries incorporate complex equipment and produce complicated chemical reactions, posing difficult challenges for determining the best use of the refinery capacity.

Apart from the complexity of the refinement and the challenges of determining efficient processes within the refinery itself, other factors play key roles in the search for profits within the industry. The markets for crude oil and petroleum products have developed over the decades and have shown to be sensitive both to political issues and disruptions and variations in demand and supply. The market for oil related products is well-developed and this includes also the freight market. The latter is important since crude oils and products are dependent on transport to their intermediate and final destinations. Accordingly, profitability will also be affected by transportation costs.

The supply chain of an integrated oil company stretches from the production and purchasing of crude oil to customers buying petrochemical products or fuel for heating or transport. There are many decisions that must be made along the supply chain such as what crude oil mix to buy and sell, what components and products should be produced, and whether they should be kept for internal use, stored, or sold to external players.

To address the challenges in the oil and gas supply chain quantitative models and mathematical programming techniques have been developed for several decades and their use has significantly increased the ability to plan and control refinery activities and to increase profits.

From a refinery management perspective there is a difference between planning and scheduling. At the planning stage, the time horizon is typically several weeks or months, and the decisions typically concern purchase of crude oils and the production and sales of products. Since the markets associated with refinery operations are volatile, the use of correct and updated information is important because this will strongly affect the capability to identify market opportunities. The identification of market opportunities is crucial for increased profitability. The capability of identifying market opportunities will be dependent on a company's ability (given current condition: prices, production decisions, available crude, etc) to determine its decision to buy, refine, and sell its products. To make such decisions, the company must consider already booked and planned production, together with future prices.

Due to the complexity involved in different refinery operations throughout the supply chain, the refinery scheduling problem is often separated into three different sub-problems, see figure 1 below. The first sub-problem involves the crude oil unloading from vessels or pipelines, its transfer to storage tanks and the charging schedule for each crude oil mixture to the distillation units. The second sub-problem consists of production unit scheduling, which includes both fractionation and reaction processes. The third sub-problem is related to the blending, storage and lifting of final products.

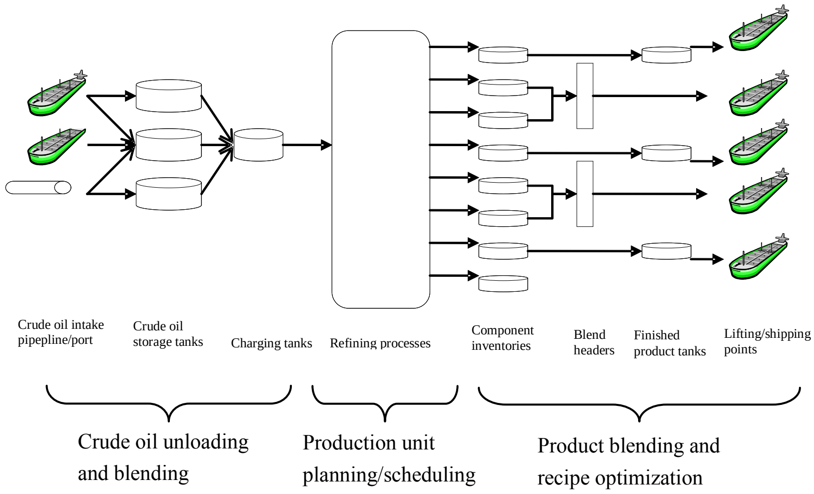

Figure 1: Three subsystems of an oil refinery

Historically, refiners have built organizations based on the processes associated with planning and scheduling. To drive operational efficiency, major refining companies are now putting increased focus on managing supply chain activities as an integrated process, closely connecting refinery planning and scheduling to improve communication and total plant operation.

In this report we will give an overview of the latest literature on refinery planning and scheduling and also make some suggestions for future research. A previous survey of literature on production planning and scheduling models for refinery operations can be found in e.g. Pinto et al (2000). The focus of the report will be on the identifications of problems, the type of models outlined to solve the identified problems and the computational difficulty introduced by the models (it will not discuss how the computational difficulties are met). The overview is organized in three different parts, which correspond to the sub-problems mentioned earlier. Literature that focuses on modelling the whole refinery supply chain is also discussed. This can be found under the production planning section.

2 Crude oil selection and crude oil scheduling

The planning and scheduling of crude oil operations in a refinery is a critical task that can save the refinery millions of dollars per year (Kelly and Manne (2003 a, b)). Crude oils vary significantly in compositions, product yields, properties, and prices, and their acquisition accounts for a large portion of the refineries' cost. A key issue for a refinery is therefore to identify and process optimal crude blends that maximize profit margins (Li et al (2007)).

Typically, an oil refinery receives its crude oil through a pipeline that is linked to a docking station, where oil tankers unload. The unloaded crude oil is stored at the refinery in crude oil tanks. The crude oils are stored in these tanks, at least for a minimum amount of time (to allow the separation of the brine), before the mix of crude oils is transferred to charging tanks or directly blended and processed in the distillations tower.

In general two types of ships supply crude to a refinery; very large crude carriers (VLCCs) that may carry multiple parcels of different crudes and small vessels carrying single crude. Due to its size the VLCCs often dock at a single buoy mooring (SBM) station offshore whereas the small vessels berth at the jetties. The pipeline connecting the SBM station with the crude tanks normally has a substantial holdup (Li et al (2007)), while the holdup in the jetty pipeline is not that critical.

The shipping schedule for the crude oil tankers is determined by the procurement and logistic department in conjunction with the crude oil purchase. Due to lengthy waterborne transit times, this schedule is done a long time before the crude oil tankers arrive at the refinery. In the case that the crude oil carrier transport different crude oil parcels, the unloading sequence is also predetermined due to logistic considerations. Before a VLCC can unload, it must first eject the crude that resides in the SBM pipeline. This crude can, as suggested in Reddy et al (2004b), be modeled as an extra crude oil parcel from the carrier. A general assumption is that the holdup of the jetty pipeline is negligible. In the literature, it is typically assumed that the holdup of the SBM pipeline is negligible.

The crude oil scheduling is based on the current information on arrival of crude oil vessels or carriers, crude composition in different tanks, and the optimal crude feed to the crude distillation units (CDUs) from the production plan.

2.1 Selection of crude oils

The main goal of the crude selection is to find a feasible crude blend that maximizes the profit of the planned production in the time horizon considered, taking into account the current storage of crude oil at the refinery and the crude tankers scheduled to arrive at the refinery. The "wrong" crude mix can cost a refiner both in excess feedstock expense and lost product revenue. To find the right crude mix the scheduler has to take into account both processing and economic considerations. After the selection of crude oils, the crude procurement and logistics departments have to secure the crudes and schedule them for delivery.

The monthly planning model, updated with more advanced crude blending simulations, is often used as a decision tool in order to determine the optimal crude oil mix. Each refinery has built up its own history of how different crudes have performed for their refinery in the past. This information is then used in the crude blending simulation to achieve an optimal crude slate. Both Stommel and Snell (2007) and Ishizuka et al (2007) present good discussions and describe general rules for how leading companies handle the selection and the scheduling of crude oil.

In the literature, crude oil selection has been considered as part of the production planning problem. The literature, however, neglects one important component. The complex nonlinear blending relation of different crude oil mix is omitted in the planning problem due to the increase in problem complexity. In the industry these relations are usually solved using in-house or more commercial simulation tools. The general review of literature related to production planning is presented in a later section.

2.2 Scheduling of crude oils

The objective of crude oil scheduling is to minimize the operational cost while meeting the target crude oil load to the CDU. For the scheduling one assumes a fixed arrival schedule for vessels, knowledge of the quantity and quality of crude oil at the vessels and the crude oil mix at the crude tanks, the minimum settling time for the brine at the tanks, minimum and maximum level of crude in the tanks, minimum and maximum flow rate in the pipeline, and the target feeding-rate (quality and quantity) of the crude oil blend for the CDU. It is also common to assume that a tank cannot receive and feed crude at the same time.

Given these facts, the objective of the crude oil scheduling is then to determine the unloading schedule for each vessel (this includes the timing, rates, and which tank to transfer the oil parcels to); the transfer schedule of crude oil mix between storage and charging tanks (if both are present in the refinery); the inventory levels and crude oil concentration for all storage and charging tanks; and finally the charging schedule for each CDU (how much should be transferred to each CDU from each charging tank).

To model the crude oil scheduling we need a large number of binary allocation variables to consider the discrete scheduling decisions, such as selecting a tank to receive a crude oil mix and non-linear constraints to calculate the crude oil composition for the storage and charging tanks. So far, the models proposed for crude oil scheduling have not considered non-linear crude properties. The non-linear property constraints are approached by linear constraints that consider key crude component concentrations or blending indexes that are linear on a volumetric or weighted basis. Even if we assume linear crude properties, the crude oil scheduling results in a complex mixed integer non-linear (MINLP) model. The non-linear terms are bi-linear and originate from the mass balance and crude mix composition constraints for the storage and charging tanks and the feed from these tanks. A non-linear term $f(x,y,z)$ is said to be bi-linear if it is linear with respect to each of its variables, i.e. $f(x,y,z)=x*y+y*z+z*x$.

Several authors have discussed different models and methods to solve this crude oil blending and scheduling problem, taking into account different degree of refinery complexity. The scheduling problem can be modeled using either a continuous time approach or a discrete time approach. The discrete time formulation tends to rely on an excessive number of time periods to achieve the required accuracy, while continuous time formulation results in complex models that require several assumptions or specialized algorithmic solution techniques. Recent trends in scheduling models for chemical processes have, however, moved toward continuous time formulations to avoid the high number of integer variables found in discrete time models. The continuous time modeling is particularly suited to crude oil scheduling since refinery activities can range from some minutes to several hours (Joly et al, 2002). A review that compares discrete and continuous time approaches of scheduling for chemical processes is provided by Floudas and Lin (2004).

One of the first models presented for the crude oil scheduling is a discrete mixed-integer linear programming (MILP) presented by Lee et al (1996). They consider one docking station, a set of storage tanks, a set of charging tanks and a set of CDUs. The objective is to find a schedule that meets the predetermined crude slate for the CDU, while minimizing total operating cost (unloading cost, cost for demurrage, tank inventory cost and changeover cost for the CDUs). In addition, the crude mix in the charging tanks should be within predefined quality measures with regard to key component concentration. Their linear reformulation of the bi-linear mass balance constraints is, however, not rigorous enough to ensure that the crude mix composition for the storage and charging tanks is the same as the composition of the flow from the tanks. This inconsistency is denoted as "composition discrepancy" by Li et al (2002) and Reddy et al (2004a). In general, composition discrepancy may occur when individual component flows are used in a linear reformulation for the bi-linear mass balance term for storage and charging tanks where mass accumulates. Li et al (2002) proposed a discrete mixed integer non-linear programming (MINLP) model that extended the model in Lee et al (1996) by reducing the number of discrete decision variables (they replace two bi-index binary variables with one tri-index binary variable) and by including new features as multiple jetties and allowing the possibility for two tanks to feed a crude distillation unit. The solution approach outlined for the MINLP model may, however, fail to find a feasible solution even if one exists (Reddy et al (2004a), Kelly and Mann (2003a, b)).

Jia and Ierapetritou (2003, 2004) outline a continuous time MILP model for the crude oil scheduling, using only linear terms for the crude mix operations as in Lee et al (1996). They assume no cost for crude or tanks changes, one tank feeding one CDU at a time (and vice versa). The objective is to minimize demurrage, unloading and inventory cost. As for Lee et al (1996), the MILP model may suffer from composition discrepancies. The crude composition in the storage and charging tank may not match its feed to the charging tanks and to the CDU.

Moro and Pinto (2004) propose a continuous time MINLP formulation for the crude oil scheduling. The model considers one pipeline to unload the crude oil, settling time in the crude tanks to separate brine from the oil, and, at most, two crude oil tanks feeding the CDU. They propose to measure the quality of the CDU stream by limiting the concentration of the critical components in the feed to the CDU. Their objective is to maximize the CDU feed rate while minimizing the crude tank operating costs. Moro and Pinto (2004) also proposed a MILP approach of the MINLP model where the bilinear crude mixing term is linerarized by discretizing the amounts or types of crude oils present in the storage tanks. The MILP approach suffers, however, from an increasing number of binary variables as the number of discretization interval increases. Reddy et al (2004a) developed, in parallel to Moro and Pinto (2004), a continuous time MINLP formulation considering multi-parcel vessels loading at one SBM, pipelines that transfer the crude parcels from the SBM to the crude storage and charging tanks that again feed the CDU's. Multiple storage tanks can feed one CDU (and vice versa). They also discuss how SBM parcels can be created to take into account that before a vessel can unload, the crude in the SBM pipeline (the SBM parcel) has to be transferred to a storage tank. The objective of the scheduling model is to maximize gross profit (profit of products-cost of crude oils) while minimizing the operating cost (CDU changeover cost, demurrage, penalty for running under the crude safety stock).

In addition to the features considered in the continuous time model, the discrete-time model outlined by Reddy et al (2004b) accounts for multiple vessels unloading to a set of jetties and transfer of crude oil between the storage tanks. They also present a novel approach for dealing with parcel unloading, which uses fewer binary variables than earlier work (Li et al 2002, Lee et al 1996). In addition, they allow more than one unloading allocation in any time period, thus utilizing the entire time period to the maximum extent. The objective for their scheduling model is to maximize the crude margin (total value of cuts from the crude distillation units minus the cost of purchasing, transporting and processing the crude) minus the operating costs (changeover, demurrage, penalty for running under the crude safety stock). The unloading cost and inventory cost is not considered since the amount of crude is fixed for the scheduling horizon. The demand for crude oil for each CDU has, however, to be satisfied. Their solution approach improves the solution approach proposed by Li et al (2002) but may still fail to find a feasible solution even if one exists. Li et al (2007) improved the MINLP formulation of Reddy et al (2004a) in two ways. First, constraints that disallow uncontrolled changes in the CDU feed rates are inserted. Second, linear blending indexes, weight- and volume based, are used to better approximate the non-linear crude oil properties.

From this literature we see that the crude scheduling problem is approached with both MILP and MINLP models and solved either with standard MILP and MINLP solvers or with tailor-made solution approaches. A global optimization algorithm for the crude scheduling problem would be preferable, but considering the large sizes of practical problems and the need for quick solutions, that will require considerable effort and is a great challenge for future research. The main difficulty is to deal with the large number of integer variables in the model and the complexity of non-linear blending and crude oil mixing operations.

Note that disruptions such as crude arrival delay could make any given schedule infeasible and necessitate rescheduling of operations. Adhitya et al (2007) discuss how to reschedule in order to make only minimal changes to the scheduled operations rather than undergo a total reschedule.

3 Production planning and scheduling

The refinery is built up of different processing units that transform a variety of input streams into several output streams. The flow rate and product specification, e.g. octane number and sulphur content, of each output stream is determined by the flow rate and product specification of the unit feed and the operating mode of the processing unit. Nonlinearity arises from mixing the feed and, in the yield, from the processing. The change of operating mode of a processing unit results in a period with reduced capacity and disturbance in the yield (quality and quantity) of the processing. Reduced capacity and disturbance in the yield also occur for a start up after a period with maintenance. To correctly model the disturbance caused by a change in operating mode is difficult, usually the issue is relaxed by incurring a setup cost for each change in mode.

For a general refinery, the planning specifies which crude or intermediate products to purchase and which products to produce. The planning decisions are taken based on forecast of future demand, and usually planning takes into account a two or three months time horizon. The production plan is used in a rolling horizon setting to take into account updated information regarding refinery and markets. The decisions related to scheduling of refinery activities are generally performed on the basis of shorter time horizons, i.e., days or weeks, to determine the specific timings of the operations.

3.1 Production planning

To support production planning decision making, refineries generally use commercial packages based on linear one-periodic models that rely on constant yields (PIMS from Aspen Tech and RPMS from Honeywell, Process Solutions). This has motivated researchers to outline models that give a more accurate representation of the refinery processes or activities. In this section, literature that takes into accounts multiple periods and different degrees of nonlinearity in the mixing and processing operations are presented. Papers that consider a supply chain perspective and uncertainty in market data are also presented.

One of the first contributions to consider nonlinearity in the production planning is that of Moro et al (1998). Moro proposes a framework where every unit in the refinery is represented as an entity and the complete refinery topology is defined by connecting the unit streams. For the processing units nonlinearity can be considered in the blending relations and in the process equations. A general MINLP model is discussed for a diesel production planning problem, but this is only partly outlined in the paper. Detailed blending and processing formulations are presented only for the hydro-treating unit. They report that the refinery plan obtained from the MINLP model improved the performance of the case company significantly compared to the current operating decision that was based on experience and manual calculations. The same planning model is discussed in Pinto and Moro (2000), here with results from a new case study.

Neiro and Pinto (2005) formulate a MINLP model that extends the planning model discussed in Moro et al (1998) to account for multiple time periods and uncertainty in market data. Uncertainty is considered in the product demand, the product price and the cost of crude oil. The uncertainty is expressed in scenarios, and the objective function includes weighted values of each scenario based on the probability for each scenario to occur. For each time period, the main decisions are which crude oil to select, how to operate the processing units and how much of the final products to hold in inventory. They show an exponential increase in solution time with the number of time periods as well as with the number of scenarios. In the work listed above, only subsystems of the gas and oil supply chain have been considered in a reasonable level of detail. Neiro and Pinto (2004) propose a framework for modeling the whole petroleum supply chain, including crude oil suppliers, distribution centers and several complex conversion refineries interconnected by intermediate and end product streams. This study outlines a large scale one periodic MINLP planning model for the system addressing crude oil purchasing, production units processing, inventory management, logistics, and end product sales decisions. Neiro and Pinto (2004) consider non-linear blending for the different processing units and storage tanks, and non-linear operating conditions in accordance to the yield from the processing units. They consider a supply chain with four refineries connected with pipelines and storage tanks, each with different capacity and topology.

Refinery planning and the refinery scheduling are generally performed sequentially, mainly due to the complexity of the refinery sub-problems. When determining the refinery production plan, many of the scheduling constraints are uncertain. To obtain a feasible schedule which utilizes resources in, or close to, an optimal fashion, it is important that the company determine a plan which makes this possible. If the planning and scheduling is done sequentially, there is no guarantee that the production plan can give an operable schedule. Kuo and Chang (2008) have addressed this issue and present a MILP planning model that addresses stream allocations and processing run modes for several scheduling intervals. By considering the whole refinery supply chain and splitting the planning period in several sub intervals, Kuo and Chang, are better able to match the planning and scheduling decisions and improve the performance of the supply chain scheduling activities.

Environmental regulations and the risks of climate change pressure refineries to minimize their greenhouse gas emissions. Refineries also face more stringent product specifications on oil products which typically increase their energy consumption and CO2 emissions. Szklo and Schaeffer (2007) address this problem, also with a specific focus on the Brazilian refining sector. Holmgren and Sternhufvud (2008) discuss different possibilities for reduction of CO2 emissions for petroleum refineries in Sweden. More analytical approaches to this problem have also been addressed. Babusiaux (2003), Nejad (2007), Pierru (2007), and Babusiaux and Pierru (2007) have proposed different methods for allocating the CO2 emissions among the different refinery products produced.

Elkamel et al (2008) propose a MILP for the production planning of refinery processes. They consider how to find suitable CO2 mitigation options for the processing units that meet both a CO2 emission target and the final product demand while maximizing profit.

Zhang and Hua (2007) propose a MILP model for a multi-period planning model that considers the integration of the processing system and the utility system for the refinery industry. The objective here is to determine an optimal material and energy flow in order to maximize the overall profit.

Uncertainty is present in different forms in the different sub-system in the refinery. Some of the latest work that considers uncertainty in the planning and scheduling of refinery activities is by Neiro and Pinto (2005, 2006), Pongsakdi et al (2006) and Zimberg and Testuri (2006).

Pongsakdi et al (2006) address the planning of crude oil purchasing and its processing based on the network structure proposed by Pinto et al (2000). Uncertainty is considered both in product prices and product demands. The stochastic problem is modeled as a linear two stage stochastic model with recourse and is solved using a special implementation of the average sampling algorithm introduced by Aseeri and Bagajewicz (2004). Test results show that in comparison to the stochastic solution the deterministic solution has a lower expected gross refinery margin and a larger risk. The profit is maximized taking into account product revenues, crude oil costs, inventory costs, and cost of unsatisfied demand.

Zimberg and Testuri (2006) consider the crude oil procurement and processing for a case company that has a specific focus on the bunker fuel oil production. Generally, the gas oil, diesel and fuel oil products are more dependent on the right crude oil mix than the gasoline products. A simplified two stage stochastic process is considered. The first stage decision, purchasing of crude oil, is taken two months before the second stage decisions, the processing of the crude oil and blending of intermediate products. A case study that compares the deterministic (mean values) and stochastic solution of the problem is presented. The risk is not considered, only the expected refinery margin. Neiro and Pinto (2005, 2006), as previously discussed, take into consideration uncertainty in product demand, product prices and crude oil cost. The uncertainty is modeled in discrete scenarios and weighted according to the probability of occurrence.

Pitty et al (2008) and Koo et al (2008) develop a decision support for an integrated supply chain, which in this case means that it handles activities such as crude oil supply and transportation in addition to intra-refinery activities. The decision support is based on a simulation-optimization framework and takes stochastic variations in transportation times, yields and prices into account. Pitty et al present the complete dynamic model whereas Koo et al use the decision support to optimize the design and operation in three different supply chain related cases.

Current research has to a large degree been focused on modeling and analyzing different types of refinery planning problems and has used commercial solvers as GAMS (OSL, DICOPT, CONOPT) with the different solution approaches they offer to solve the outlined problems. Nonlinearity is considered in some degree and for some problems multiple periods is proposed. Also a supply chain view has been considered. Some recent papers consider decomposition strategies to solve the large complex non linear planning problem. Future research should consider methods for solving the complex MINLP problems more efficiently and focus on more advanced methods that consider uncertainty in market data.

3.2 Production scheduling

In the literature, MILP models are generally outlined for production scheduling problems. The models focus on part of the refinery activities and incorporate different degree of details regarding the blending and processing in the processing units. The models are generally solved using standard commercial solvers as GAMS (CPLEX, OSL, DICOPT, CONOPT). Pinto et al (2000) propose a discrete MILP model for the production and distribution scheduling of diesel. The scheduling system considered a set of crude distillation units that produce specified intermediate (or end) products for storage in a set of intermediate tanks before they are mixed and sent through pipelines to supply the consumer market where there is a known demand. The proposed MILP model considers linear blending relations. Results are reported for a case company considering market demand for three different types of diesel oil. A scheduling horizon of one day considering one hour time intervals is addressed.

Joly et al (2002) outline both a discrete MINLP model and a discrete MILP model for the scheduling problem that considers decisions related to mixing, storage and distribution. The system configuration includes one deasphalting unit, one cracking unit, two diluents storage tanks, fifteen storage tanks for final products, and two pipelines. The non-linear terms in the MINLP model refer to the calculation of viscosity in the oil mix and are linearized in the MILP model. The models produced similar results in terms of solution quality, while the solution time for the MILP model was a bit longer. Moro and Pinto (2000) and Joly et al (2002) also discuss a scheduling problem that addresses how to make use of the given raw materials, processing units, and storage in order to meet the LPG product deliveries. They did not investigate formulations related to product quality.

Goethe-Lundgren et al (2002) outline a discrete MILP model for a refinery production scheduling problem considering one distillation unit and two hydrotreatment units that can each operate in 5-10 modes. The model considers how to run the processing units in an optimal manner to minimize production and inventory costs. The model can also be used to evaluate the feasibility and the production cost for given product and crude oil shipping plans. To make the base schedule robust, Goethe-Lundgren et al (2002), implemented new constraints in the model that assure that enough end products are available if a tanker should arrive one day too early, and to assure enough storage capacity if a tanker is delayed one time period. They also report how the flexibility decreased (the cost increased) when a more robust schedule was offered.

Jia and Ierapetritou (2004) propose continuous time MILP formulations for specific crude oil, production and product scheduling problems. A lube-oil refinery is considered for the processing units parts. The study proposes a continuous time MILP formulation for the scheduling problem that takes into account material balance in tanks and production units, and capacity, allocation and sequence constraints, and demand constraints.

Due to the complexity of the problem, the current work proposed for the production scheduling relaxes most of the non-linear relations, and only simple refinery systems or subsystems of the refinery topology are considered. Future work in this area should focus on formulating models and finding corresponding solution approaches that enable companies to solve non-linear production scheduling models of real-world sizes in a reasonable time. In addition, new work that studies how the daily scheduling decisions might best be incorporated in the production planning and how uncertainty in the market data could be modeled in the scheduling problem would also benefit the gas and oil industry.

4 Product blending and recipe optimization

The product blending problem concerns the best way to mix different components and additives in order to meet quality and demand requirements of the final products. Several final products can be produced out of a number of combinations of components, but some properties of the final product do not show linear relationships, e.g. pour point of diesel. These relationships put requirements on the optimization model so that the non-linearity must be handled in some way.

The product blending problem is usually split into a long-term problem and a short–term problem. In the case of long-term, the problem is basically to determine optimal recipes that maximize profit given quality specifications and quantity requirements. In the short-term situation, detailed operational and temporal constraints come into play and the basic issue becomes that of scheduling.

Glismann and Gruhn (2001) claim that short-term scheduling of blending processes is more complicated than scheduling of most other processes because of the option of blending a product in many different ways. In the scheduling of blending, consideration of recipe optimization and short-term scheduling within an integrated approach becomes necessary. To address this Glismann and Gruhn develop an integrated approach to coordinate non-linear recipe optimization and short-term scheduling of blending processes. They propose a two-level optimization approach that sets up a large scale NLP model to determine product quantities and recipes. Given the result from the NLP model, a MILP model based on a resource-task-network is used for the scheduling problem to optimize resource and temporal aspects. Both models are discrete time models. Whereas the NLP model maximizes profit, the MILP model minimizes deviations from given tank volume goals. Glismann and Gruhn also present alternative strategies to handle situations where a given goal cannot be met. They advocate integrating the planning and scheduling by using an iterative approach so that if the goal at the scheduling level cannot be met (due to bottlenecks), then the new information will be brought back to the planning level and the modified NLP problem solved again. After this, the MILP problem would be reconsidered until a feasible or satisfying solution is found.

Jia and Ierapetriou (2004) consider scheduling of gasoline blending and distribution as one of three sub problems. The other two sub problems consider crude oil and processing units. They assume that the recipe of each product is fixed, in order to keep the model linear. The problem is modeled as a MILP-problem in continuous time and based on the state-task-network (STN) representation introduced by Kondili et al (1993). In Jia and Ierapetriou the objective function is formulated such that certain flows are as close as possible to a goal flow, but they also mention that other objective functions can be used.

Mendez et al (2006) point out that there are a number of mathematical programming approaches available to the short-term blending and scheduling problem. But in order to reduce problem difficulty, most of them rely on special assumptions that generally make the solution inefficient or unrealistic for real world cases. Some of the common simplifying assumptions are i) fixed recipes are predefined, ii) components and production flow rates are known and constant, iii) all product properties are assumed to be linear.

Mendez et al develop a novel iterative MILP formulation for the simultaneous optimization of blending and scheduling and formulate the problem both in discrete and continuous time. The components flow from the processing unit is stored in component tanks before the components are blended in blend headers and sent to product tanks. The resulting non-linear MINLP blending and shipment problem is modeled as a successive MILP problem. The objective function maximizes profit and is based on the assumption that the cost of components can be observed or determined.

Mendez et al also highlight the fact that the multi-period product blending and product shipping problem is a complex and highly constrained problem where feasible solutions may be difficult to find. To increase the speed of the solution procedure**,** preferred product recipes could be included in the problem to help find a feasible solution more quickly. To avoid infeasible solutions, Mendez et al propose to include penalty for deviation from preferred product recipe and penalties for deviations from specified product qualities. They also propose to allow purchase of components at a higher cost from a third-party to relax minimum inventory constraints.

Future work might focus on how to determine the component value and the preferred product receipt, in order to optimize the combined performance of the short-term blending and product shipments and how to coordinate the scheduling decisions with long-term planning decisions.

In the literature the values of the components are commonly presented as a known value, as in e.g. Mendez et al (2006). Often, however, the refinery's value of a certain component is unknown due one of two reasons; the component's value cannot be found from an external market or the value is not appropriate since lead times makes this option infeasible. A variety of methods, based on marginal values of components and properties and product values, can be used to determine the value of the components, and special attention should be made to the value that is used because different component values can give different optimal blends.

We know that the short-term blending decision is affected by two facts i) flexibility in the short-term is restricted, making it sometimes hard to stick to the recipe, which is considered optimal in the longer term, typically given by the planning model, and ii) the relative value of blending components at the blending point in time might be different from the value determined in the long-term optimization. Thus in the short-term, another recipe may be more profitable than the long-term optimal recipe, and the deviations from the long-term recipe may indicate that other blending recipes should be used. In the ideal world it would be possible to observe the values of components, and in order to more closely approximate the values of these components, there must be integration between short-term and long-term decision.

5 Discussion and further research

This report has analyzed papers that consider planning and scheduling problems in refineries. The papers consider planning and scheduling problems mainly for refinery subsystems and for refinery supply chains, in different forms and with different degrees of detail. It has been common to use commercial MILP and MINLP solvers to address the refinery model proposed. In addition, specialized algorithms have been proposed to solve specific industry sized problems in a reasonable time. Unfortunately, no general solution technique has so far been outlined that can solve real world problems in a satisfactory manner.

Due to the complexity of the refinery planning and scheduling problem, the works proposed to this date relax most of the non-linear relations. Future work should focus on formulating correct NLP that take into account all aspects of the refinery subsystems and on developing solution techniques that enable companies to solve non-linear scheduling models of real-world sizes in a reasonable time.

Better coordination of refinery activities can increase throughput, reduce quality give away and demurrage, and improve the refinery’s ability to evaluate special opportunities that may arise. Future research should consider how to coordinate the scheduling decisions with the long-term planning decisions.

Beyond from developing solution techniques and more advanced models, there is currently an increased focus on environmental impact from activities associated with refining of crude oil. Tougher environmental regulations on oil products set by authorities and an increased focus on reduction of CO_2 emissions put new constraints and requirements on decision making and adds more complexity to an already complex situation. Given contemporary consensus about the environment, more research focusing on environmental impact is needed.

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