# SNF Report No. 26/10

# Integrated planning of production, inventory and ship loading at refineries

**by**

**Jens Bengtsson**
**Patrik Flisberg**
**Mikael Rönnqvist**

**SNF Project No. 7985**
**Collaboration StatoilHydro**

The project is financed by Statoil ASA

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
BERGEN, DECEMBER 2010

ISBN 978-82-491-0741-4 Printed version
ISBN 978-82-491-0742-1 Online version
ISSN 0803-4036

# Contents

# 1 Introduction

Planning refinery activities is a complex task where a lot of considerations must be taken into account. Different refinery processes are tightly interconnected and the outcome of these will be dependent on crude oil mixes and the actual settings of the processes. As with other value chains, supply must match demand to stay profitable. However, any mismatch between supply and demand at a refinery will more quickly result in problems compared to many other value chains. There are several reasons for this. One reason is that the refinery process is a divergent process, which produces a basket of components and products and all must be taken care of. One second reason is that large amounts are produced and there are limited possibilities to put components and products in inventories.

The planning at a refinery often follows a hierarchical process. Disregarding strategic investment and maintenance, the plans covering the longest horizon consider crude oil purchases, and production and sales plans. These plans are looking one or several months into the future. They also coordinate the use of one or several refineries given market prices of crude oil, components and products, and freights in addition to operational status at the refineries. In general, these plans are a result from an iterative process between crude oil traders, product traders (including charters) and refinery planners. An important part is a delivery plan where product quality, quantity and expected delivery points in time are specified. Given a delivery plan, it is the refinery's task to plan operations to be able to deliver the right products with the right volumes. Integrating the refinery and logistics, where the latter is represented by arriving ships, in the same planning model could give that the following advantages are attained. First, the risk of running out of stock is reduced. Looking further into the future and explicitly dealing with time of arrival enables improved inventory management where inventory levels have been built up in an optimal way to handle demand. Second, the risks of too high inventory levels are reduced. The same reason as above but in this case production is planned and scheduled in such a way that critically high inventory levels are avoided.

A short term optimization model should include several parts of the refinery in addition to the delivery plan. However, due to complexity involved in the refinery supply chain, the refinery planning and scheduling problems are often separated into three different sub-problems. These parts are illustrated in Figure 1. The first sub-problem involves crude oil unloading from vessels or pipelines, its transfer to storage tanks and the charging schedule for each crude oil mixture into the crude distillation units (CDUs). The second sub-problem focuses on the refinery processes and particularly production planning and scheduling. The third sub-problem is related to planning and scheduling of blending, storage and lifting of final products.

The focus in this article is to develop a deterministic decision support to handle the storage, blending and lifting operation. However, ship arrivals are not known exactly in practice. Ships follow routes where a stop at the refinery is only one among many stops. The combination of

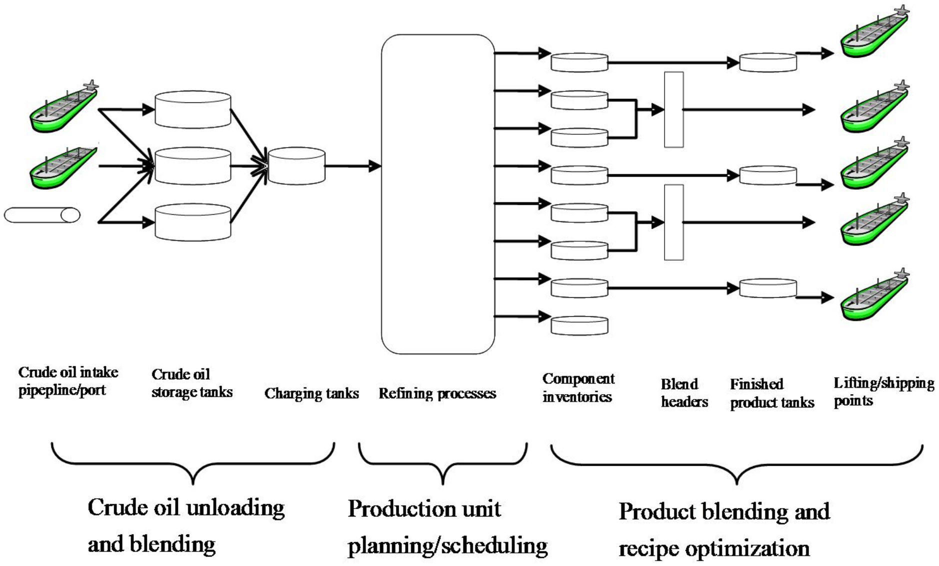

Figure 1: Description of the processes arising in the problem studied.

ship voyages, which are interconnected, and unexpected events along the voyages gives that the arrival times of ships are uncertain. An important way to handle deviations from expected arrival times comes from the fact that refineries typically are producing components instead of finished products. An advantage from producing components instead of products is that the number of inventories can be reduced, i.e. postponement, but another significant advantage is the so-called blending flexibility. Since finished products can be blended in several ways, and still meet required specifications, there are possibilities to find a substitute if one component runs out of stock, or consume more of a particular component if inventory levels are running high. However, this may result in so called give away in that customers are getting products of higher quality than originally asked for. This is a lower cost to pay, but not always possible, compared to reducing the capacity of the whole refinery or pay penalties, i.e demurrage, to charterers due to late deliveries. The inherent flexibility in a modern component producing refinery, in addition to common safety stock policies, is important to avoid or reduce delivery problems. However, information regarding expected time of arrivals is needed and thus logistic must be integrated in a planning and scheduling model. Integrating logistics in the model means in this case that one has to deal with uncertainty.

There are two main contributions of this paper. First, we propose a deterministic operational planning model, which integrates production and logistics operations. This model can be used to establish plans and to test various scenarios and to make sensitivity analysis.

Second, we apply simulations to analyze the deterministic approach when ship arrivals are uncertain. We compare the deterministic approach to an oracle approach, where the latter has full information regarding ship arrivals and thus represents a theoretical optimum. In that way, we get some information regarding value of information and potential profit gains from using information. Moreover, the overall integrated approach can be used as an important and practical decision support tool.

The outline of the paper is as follows. In Section 2, we describe the refinery operations in some more detail. This section also includes a review or related literature. The integrated model is developed and described in Section 3. The simulation study is described in Section 4. Section 5 gives the results and analysis. Finally, we make some concluding remarks in Section 6.

## 2 Problem formulation

### 2.1 Refinery operations

There are different types of refineries and the output from these will be dependent on the configurations of internal processes. An example of a stylized refinery, which also is used in the case study, is illustrated in Figure 2. This refinery consists of three different processes; a crude distillation unit (CDU), which performs atmospheric and vacuum distillation, a reformer and a cracker. In practice there will be other processes such as isomerization, hydrotreater and desulphurization but these are disregarded here in order to keep the model at an attractive level given the purpose of the article. Except from the configuration of the refinery the input, i.e. crude oil and other type of feedstock, will affect the output from the refinery since different inputs create different output from the the refinery processes, both in terms of quantity and quality.

The outputs from the CDU can in some cases be sold as finished product without further processing. In many other cases outputs must be further processed in e.g. the cracker or reformer in order to become saleable finished products or usable components. Components, which typically are not sold on a regular basis to customer outside the refinery, are used as an ingredient to blend finished products. In the refinery, which is used in our case study, finished products which are outputs from processes will be placed in inventories (see boxes named INV in Figure 2) and incoming ships are served from these inventories. In case of gasoline, jet fuel, AGO/HGO, and heavy fuel, blend headers are used in order to blend different components according to product specifications and this blending activity takes place directly onboard the ship. This implies that that there are no finished product inventory for gasoline, jet fuel, AGO/HGO, and heavy fuel.

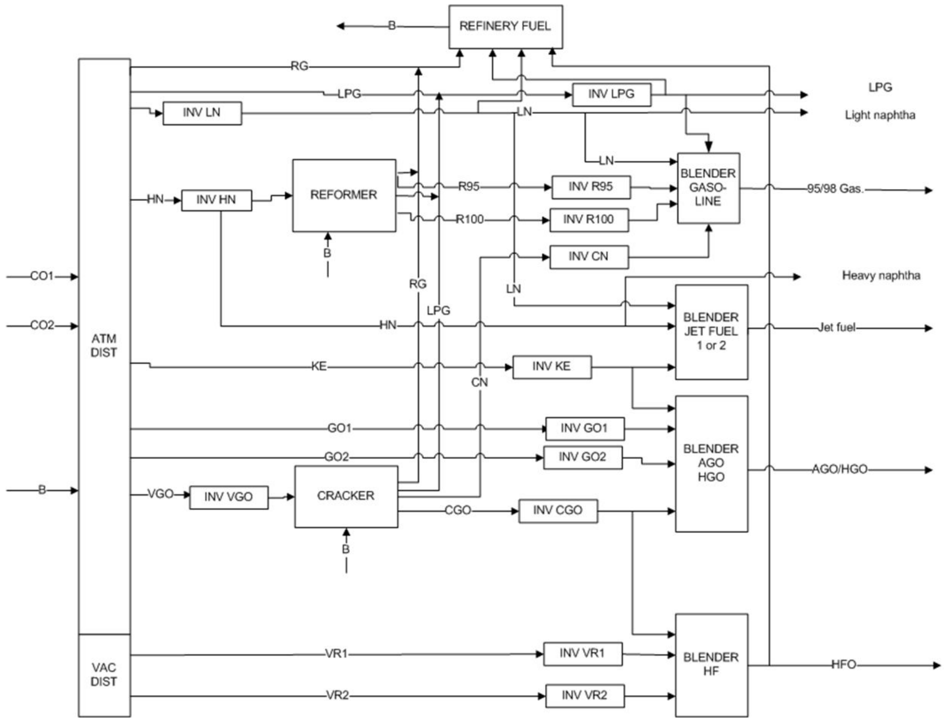

Figure 2: Flowchart of model refinery. Adapted from Coiffard (2001). Explanations of abbreviations are as follows. RG : Refinery gas, LPG: Liquefied petroleum gas, LN: Light naphtha, HN: Heavy naphtha, KE: Kerosene, GO1 : Gas oil 1 (originates from crude oil 1), GO2 : Gas oil 2 (originates from crude oil 2), VGO: Vacuum gas oil, VR1: Vacuum residue 1 (originates from crude oil 1), VR 2: Vacuum residue 2 (originates from crude oil 2), C4: Butane, ISOM: Isomerate, R95: Reformate 95, R100: Reformate 100, CN: Cracker naphtha, AGO: Automotive gas oil, HFO: Heavy fuel oil.

Seen from a planning and scheduling perspective the decision makers must make a number of decisions. Given demand, i.e. delivery plans, the decision makers must decide which crude oil mix to process, the utilization of CDU, cracker and reformer, recipes in order to blend finished products, and inventory build up of components and finished products. All this should be carried out with profit and customer satisfaction in mind. As illustrated before products and components are stored in inventory, i.e. large tanks. The inventory levels of these may vary considerably due to large withdrawals when ships are served and varying production rates of components and finished products. This aspect is illustrated in Figure 3, which shows inventory levels of six components over a period of 28 days.

Inventory management in refineries is a challenging task since refinery processes are interconnected and reducing the output of one component may increase the output of another. In a situation where the inventory level of a component tank is on its way to reach maximum level, some actions to avoid this may result in overfull inventory of other components. Thus, there is complex decision making and a decision support system would be very useful to plan-

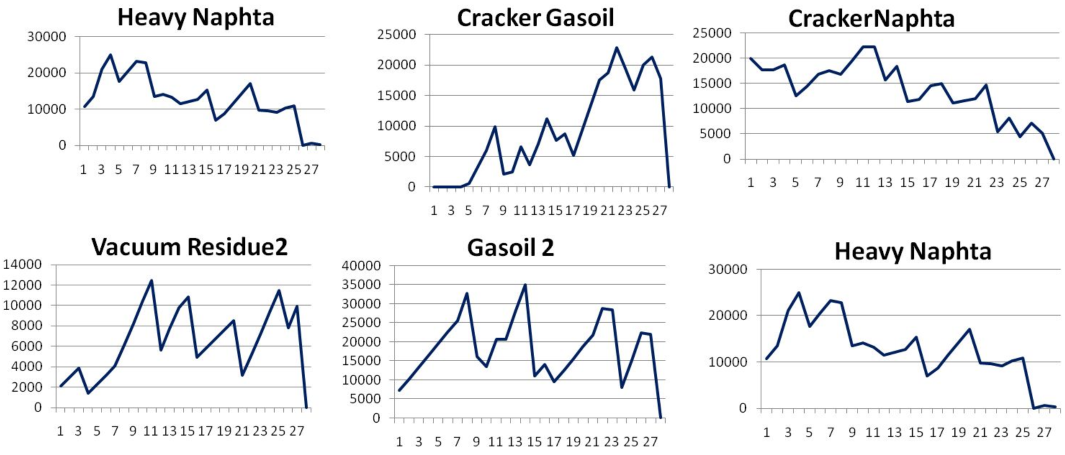

Figure 3: Inventory level of six components over 28 days.

ners in these situations. However, uncertainty in ship arrivals gives that the inventory levels are uncertain to some extent and Figure 4 illustrates this situation. In Figure 4 the planned inventory level for the next 28 days is illustrated. According to the plan the inventory will hit the maximum capacity at day 14 but an expected ship arrival, loading 20kt at day 14, will reduce the inventory level. If the ship is delayed one day giving that the 20kt loading is delayed there will be a situation where the inventory will be overfull and the refinery may have to change recipes, reduce capacity or even shut down the refinery temporarily.

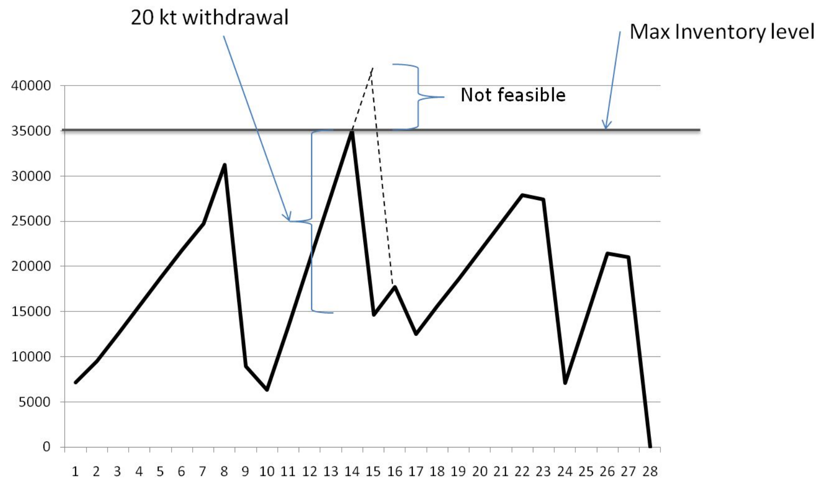

Figure 4: Illustration of the situation when the maximum inventory capacity reaches its maximum level.

## 2.2 Related published work

Previous literature on refinery planning can in several cases be placed in one of the three sub-problems described earlier in Figure 1. There have also been attempts to cover more than one of the sub-problems and a number of articles relevant to this paper is presented below. Neiro and Pinto [6] 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. The study outlines a large scale multi-period MINLP (Mixed-Integer-Non-Linear-Programming) planning model for the system addressing crude oil purchasing, production units processing, inventory management, logistics, and end product sales decisions. They 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. The supply chain includes four refineries connected with pipelines and storage tanks, each with different capacity and topology. Pitty *et al.* [7] and Koo *et al.* [3] 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.

Göthe-Lundgren *et al.* [1] outline a discrete MILP (Mixed-Integer-Linear-Programming) model for a refinery production scheduling problem considering one distillation unit and two hydro-treatment 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, Göthe-Lundgren *et al.*, 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 [2] 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 sub-systems of the refinery topology are considered.

Refinery planning and 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 determines 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.

Mendez *et al.* [5] focus on product blending, i.e. blend planning, and scheduling and point out that there are a number of mathematical programming approaches available to the short-term blending and scheduling problem. 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. In their model component flows from processing unit to component tanks are assumed to be constant, and components are blended in blend headers and sent to product tanks. 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. Kuo and Chang [4] also address the planning/scheduling 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.

From the literature review it is clear that there is a lack of decision support tool where integrated operational planning is studied and from this perspective, this paper contributes to fill such a gap.

# 3 Model

Before we state the model we define index sets and parameters necessary for the modelling.

| | |
|---|---|
| $P$ | set of processes (including CDU and mixing), index $p$ |
| $P^p$ | set of processes for components (not CDU and mixing) |
| $\underline{P}_p$, $\overline{P}_p$ | set of processes directly preceeding and directly following process $p$ |
| $I$ | set of oils, index $i$ |
| $K$ | set of products, index $k$ |
| $J$ | set of components, index $j$ |
| $J^c$ | set of components out from the CDU |
| $J^p_p$ | set of components in process $p$ |
| $J^k$ | set of components that can be mixed to products |
| $O^c$ | set of recipes at CDU, index $o$ |
| $O^p_p$ | set of recipes at process $p$ |
| $O^k$ | set of mixing possibilities (recipes) |
| $c^o_{p_1jt}$ | cost for delivering component $j$ demanded in time period $t$ one period later |
| $c^{lc}_{it}$ | cost for storage of oil $i$ after time period $t$ |
| $c^{lp}_{pjt}$ | cost for storage of components $j$ after time period $t$ at process $p$ |
| $c^{lk}_{kt}$ | cost for storage of product $k$ after time period $t$ |
| $c^{yc}_{ot}$ | cost to run recipe $o$ in the CDU in time period $t$ |
| $c^{yp}_{pot}$ | cost to run recipe $o$ in process $p$ in time period $t$ |
| $c^{yk}_{ot}$ | cost to mix recipe $o$ to products in time period $t$ |
| $c^{vc}_{it}$ | buying cost of oil $i$ in time period $t$ |
| $c^{vp}_{jt}$ | buying cost of component $j$ in time period $t$ |
| $b^{wp}_{jt}$ | selling value of component $j$ in time period $t$ |
| $b^{wk}_{kt}$ | selling value of product $k$ in time period $t$ |
| $\underline{f}^c_{oi}$ | use of oil $i$ when using recipe $o$ |
| $f^p_{oj}$ | use (-) or outcome (+) of component $j$ when using recipe $o$ |
| $\overline{f}^k_{ok}$ | outcome of product $k$ when using recipe $o$ |
| $\underline{s}^{yc}_t$ | min process volume at CDU in time period $t$ |
| $\underline{s}^{yp}_{pt}$ | min process volume of process $p$ in time period $t$ |
| $\overline{s}^{yc}_t$ | max process volume at CDU in time period $t$ |
| $\overline{s}^{yp}_{pt}$ | max process volume of proces $p$ in time period $t$ |
| $d^p_{jt}$ | demand of component $j$ in time period $t$ |
| $d^k_{kt}$ | demand of product $k$ in time period $t$ |

The decision variables used in the model (together with initial values and upper limits) are defined as follows.

| | |
|---|---|
| $l^c_{it}$ | storage of oil $i$ after time period $t$ (with given initial storage and upper bound) |
| $v^c_{it}$ | bought volume of oil $i$ in time period $t$ (with given upper bound) |
| $y^c_{ot}$ | volume in CDU of recipe $o$ in time period $t$ |
| $l^p_{pjt}$ | storage of component $j$ after time period $t$ at process $p$ (with given initial storage and upper bound) |
| $v^p_{pjt}$ | bought volume of component $j$ for process $p$ in time period $t$ (with given upper bound) |
| $y^p_{pot}$ | volume in process $p$ of recipe $o$ in time period $t$ |
| $w^p_{pjt}$ | sold volume of component $j$ in time period $t$ at process $p$ |
| $l^k_{kt}$ | storage of product $k$ after time period $t$ (with given initial storage and upper bound) |
| $y^k_{ot}$ | volume of mixture $o$ in time period $t$ |
| $w^k_{kt}$ | sold volume of product $k$ in time period $t$ |
| $x_{pp'jt}$ | volume of component $j$ from process $p$ to process $p'$ in time period $t$ |
| $x^o_{pp'jt}$ | volume of overdue component $j$ from process $p$ to process $p'$ in time period $t$ (fulfills demand in period $t$ from supply in period $t+1$) |

The objective function can be expressed as

$$
\begin{aligned}
\max \quad z = & \sum_{p\in P^p}\sum_{j\in J}\sum_{t\in T} b^{wp}_{jt} w^p_{pjt} + \sum_{k\in K}\sum_{t\in T} b^{wk}_{kt} w^k_{kt} - \sum_{p\in P}\sum_{p'\in \overline{P}_p}\sum_{j\in J_p}\sum_{t\in T} c^o_{p'jt} x^o_{pp'jt} - \sum_{i\in I}\sum_{t\in T} c^{lc}_{it} l^c_{it} \\
& - \sum_{p\in P^p}\sum_{j\in J_p}\sum_{t\in T} c^{lp}_{pjt} l^p_{pjt} - \sum_{k\in K}\sum_{t\in T} c^{lk}_{kt} l^k_{kt} - \sum_{o\in O^c}\sum_{t\in T} c^{yc}_{ot} y^c_{ot} - \sum_{p\in P^p}\sum_{o\in O^p_p}\sum_{t\in T} c^{yp}_{pot} y^p_{pot} \\
& - \sum_{o\in O^k}\sum_{t\in T} c^{yk}_{ot} y^k_{ot} - \sum_{i\in I}\sum_{t\in T} c^{vc}_{it} v^c_{it} - \sum_{p\in P^p}\sum_{j\in J}\sum_{t\in T} c^{vp}_{jt} v^p_{pjt}
\end{aligned}
$$

The objective is to maximize the income of sold components and products minus production costs. The cost components are: penalty for fulfilling demand one period later then required, inventory costs of oil, components and products, process costs at CDUs and processes, costs for mixing components to products and costs of buying oils and components.

The constraints are

$$
\begin{aligned}
l^c_{i(t-1)} + v^c_{it} - \sum_{o \in O^c} \underline{f}^c_{oi} y^c_{ot} &= l^c_{it}, && \forall\ i \in I, t \in T && (1)\\
\sum_{o \in O^c} f^p_{oj} y^c_{ot} - \sum_{p' \in \overline{P}^c} x_{pp'jt} &= 0, && \forall\ p = \text{'CDU'}, j \in J^c, t \in T && (2)\\
l^p_{pj(t-1)} + v^p_{pjt} + \sum_{o \in O^p_p} f^p_{oj} y^p_{pot} - \sum_{p' \in \overline{P}_p} x_{pp'jt} + & && && \\
\sum_{p' \in \underline{P}_p} x_{p'pjt} - \sum_{p' \in \overline{P}_p} x^o_{pp'j(t-1)} + \sum_{p' \in \underline{P}_p} x^o_{p'pjt} - w^p_{pjt} &= l^p_{pjt}, && \forall\ p \in P^p, j \in J^p_p, t \in T && (3)\\
\sum_{p' \in \underline{P}^k} (x_{p'pjt} + x^o_{p'pjt}) + \sum_{o \in O^k} f^p_{oj} y^k_{ot} &= 0, && \forall\ p = \text{'sale'}, j \in J^k, t \in T && (4)\\
l^k_{k(t-1)} + \sum_{o \in O^k} \overline{f}^k_{ok} y^k_{ot} - w^k_{kt} &= l^k_{kt}, && \forall\ k \in K, t \in T && (5)\\
\sum_{p \in P^p} w^p_{pjt} &= d^p_{jt}, && \forall\ j \in J, t \in T && (6)\\
w^k_{kt} &= d^k_{kt}, && \forall\ k \in K, t \in T && (7)\\
\sum_{o \in O^c} y^c_{ot} &\geq \underline{s}^{yc}_t, && \forall\ t \in T && (8)\\
\sum_{o \in O^c} y^c_{ot} &\leq \overline{s}^{yc}_t, && \forall\ t \in T && (9)\\
\sum_{o \in O_p} y^p_{pot} &\geq \underline{s}^{yp}_{pt}, && \forall\ p \in P^p, t \in T && (10)\\
\sum_{o \in O^p_p} y^p_{pot} &\leq \overline{s}^{yp}_{pt}, && \forall\ p \in P^p, t \in T && (11)\\
\text{all variables} &\geq 0. && && (12)
\end{aligned}
$$

Constraint sets (1) and (2) describe the node balance at the CDU for oils and components, respectively. Constraint set (3) describes the node balance at the other processes. Sets (4) and (5) describe the node balance for mixing of components and products, respectively. Sets (6) and (7) state the demand requirements of components and products, respectively. Sets (8) and (9) give lower and upper limit on production capacity at the CDU and sets (10) and (11) give lower and upper limit on production capacity at the other processes. Non-negative restrictions on variables are given in set (12). There is an initial storage level of oils, components and products and upper bounds on the storage levels are applied. There are also upper bounds on bought volumes of oils and components. The latter bounds are given explicit with the definition of decision variables. The model is a Linear Programming (LP) model and can be solved easily with standard LP solvers.

# 4 Case study

The refinery unit in our study consists of a CDU, a reformer, a cracker and blenders for gasoline, jet fuel, AGO/HGO and HFO. The CDU, reformer and cracker have different modes and the yields of these modes are presented in Tables 1, 2 and 3, respectively.

| Output | Crude oil 1 | Crude oil 2 |
|---|---|---|
| Refinery gas | 0.0013 | 0.0017 |
| LPG | 0.0298 | 0.01595 |
| Light naphtha | 0.1058 | 0.0618 |
| Heavy naphtha | 0.2626 | 0.1886 |
| Kerosene | 0.1160 | 0.1023 |
| Gas oil 1 | 0.1878 | 0.0805 |
| Gas oil 2 | 0.1062 | 0.2478 |
| Vacuum gas oil | 0.1491 | 0.2245 |
| Vacuum residue 1 | 0.0102 | 0.0044 |
| Vacuum residue 2 | 0.0311 | 0.0726 |

Table 1: Yields from crude distillation unit when fed with one unit of crude oil mix 1 and 2, respectively.

| Output | REF95 | REF100 |
|---|---|---|
| Refinery gas | 0.08 | 0.09 |
| LPG | 0.09 | 0.12 |
| Reformate 95 | 0.83 | – |
| Reformate 100 | – | 0.79 |

Table 2: Yields from reformer under REF95 and REF100 mode when fed with one unit of heavy naphtha

| Output | Naphtha mode | Gas oil mode |
|---|---|---|
| Refinery gas | 0.015 | 0.012 |
| LPG | 0.053 | 0.046 |
| Cracker naphtha | 0.436 | 0.381 |
| Cracker gas oil | 0.446 | 0.511 |

Table 3: Yields from cracker under naphtha and gas oil mode when fed with one unit of vacuum gas oil

For products which are blended directly onboard the ship it is important that recipes fulfill required specifications, e.g. octane number, vapour pressure, cetane number, sulphur content etc. In this case study a given number of recipes, which fulfill specifications are utilized, but it is possible to optimize the recipes as a part of the larger planning problem. The recipes utilized in this case study are presented in Tables 4, 5, 6 and 7, respectively.

| | Gasoline 95 | | | Gasoline 98 | |
|---|---|---|---|---|---|
| Input | Recipe 1 | Recipe 2 | Recipe 3 | Recipe 1 | Recipe 2 |
| LPG | 0.0509 | 0.03837 | 0.04 | 0.03733 | 0.04 |
| Light naphtha | – | – | 0.01 | – | – |
| Reformate 95 | – | 0.0662 | – | – | – |
| Reformate 100 | 0.29986 | 0.27521 | 0.32 | 0.72821 | 0.73 |
| Cracker naphtha | 0.64943 | 0.6202 | 0.63 | 0.23446 | 0.23 |

Table 4: Recipes for gasoline 95 and 98 describing inputs in order to make one unit of gasoline 95 and 98, respectively.

| | AGO/HGO | | |
|---|---|---|---|
| Input | Recipe 1 | Recipe 2 | Recipe 3 |
| Gas oil 1 | 0.39268 | 0.05044 | 0.10 |
| Gas oil 2 | 0.30248 | 0.57093 | 0.65 |
| Cracker gas oil | 0.30484 | 0.22128 | 0.25 |

Table 5: Recipes for AGO/HGO describing inputs in order to make one unit of AGO/HGO.

| | Heavy fuel | | |
|---|---|---|---|
| Input | Recipe 1 | Recipe 2 | Recipe 3 |
| Vacuum residue 1 | 0.13695 | 0.04366 | 0.02 |
| Vacuum residue 2 | 0.5761 | 0.65565 | 0.68 |
| Cracker gas oil | 0.28695 | 0.30069 | 0.3 |

Table 6: Recipes for heavy fuel describing inputs in order to make one unit of heavy fuel.

| | Jet fuel | |
|---|---|---|
| Input | Recipe 1 | Recipe 2 |
| Light naphtha | 0.05 | 0.035 |
| Heavy naphtha | 0.10 | 0.075 |
| Kerosene | 0.85 | 0.89 |

Table 7: Recipes for jet fuel describing inputs in order to make one unit of jet fuel.

The planning horizon is 28 days where each time period is one day. Over the planning horizon, 58 ships arrive with demand of some of the components and/or products. The size distribution of the ships arriving is given in Table 8.

| 1000's of tonnes | 5 | 10 | 12 | 15 | 20 | 25 |
|---|---|---|---|---|---|---|
| Number of ships | 10 | 26 | 2 | 9 | 4 | 7 |

Table 8: Size of the arriving ships.

Finally, to be able to maximize the profit the model need input data on crude oil prices, finished product prices and processing costs. In Table 9 crude oil and finished product prices are presented. Basically, we assume that the refinery can not export or import components. Hence, only crude oil and finished product prices are considered.

| Product | Crude oil 1 | Crude Oil 2 | Liquified petroleum gas | Light Naphtha |
|---|---|---|---|---|
| Price | 845 | 749 | 795 | 894 |
| Product | Gasoline 95 | Gasoline 98 | Heavy naphtha | Jet fuel |
| Price | 944 | 962 | 894 | 1139 |
| Product | Gas oil 1 | Gas oil 2 | Automotive gas oil | Heavy fuel |
| Price | 1087 | 1027 | 1057 | 444 |

Table 9: Prices of crude oils and finished products ($/tonne).

The reformer and the cracker have, as described earlier, two different processing modes and the costs of running each mode respectively, are presented in Table 10. It is worth to note that the prices and costs in Tables 9 and 10 are only for illustrative purposes in this paper.

| Process mode | Reformate 95 | Reformate 100 | Cracker naphtha | Cracker gas oil |
|---|---|---|---|---|
| Process cost \$/tonne | 5.4 | 6.4 | 6.0 | 6.0 |

Table 10: Processing costs of reformer and cracker (\$/tonne).

## 5 Computational experiments

The model and solution methods are implemented in the modeling language AMPL using the CPLEX version 11 solver. All runs have been done on a standard PC with a 2.67 GHz processor with 6 GB of internal memory.

In order to analyze the performance of the deterministic model, we simulate 100 full scenarios by randomly generating arriving times for the ships within given restrictions. In each simulation, we use a rolling horizon planning approach where the planning horizon is decreasing in length. We first find a solution for the first (current) period when the actual arrival times for the ships which were estimated to arrive in the first two time periods are known. The solution for the first period is then fixed and we find a solution for the second (new current)period. Now, the actual arrival times for the ships which were estimated to arrive in the third time period are known. This process is repeated until all 28 time periods are simulated. In the analysis, we are not considering activities and ship arrivals after day 28. In practice, expected ship arrivals after day 28 can be updated on a rolling basis, in order to find a solution for each days which covers a 28 days horizon. However, in order to perform our analysis this is not necessary and thereby we are considering a fixed planning horizon.

We test two different planning methods. The first method is a deterministic approach (solved with expected times of arrival for ships in future time periods) with safety stock levels. In this case, no consideration is taken to uncertainty in time of arrival. Each safety stock level will provide a different performance. The second method is called the oracle. In this method, we simply provide all information from start (i.e. the actual arrival times for all ships are assumed known from start) and solve one deterministic problem. This solution corresponds to the theoretical optimum that can be achieved and is used to measure the quality of the solutions for the deterministic method that can be used in practice. In our case, each ship has an estimated arrival time. However, the exact arrival time is randomly distributed. We analyze the case when the ships can be delayed at most one day and that at most one ship can be delayed each day. In order to analyze the performance, we study the operational decisions as well as differences in profit generation for all simulations.

## 5.1 Operational analysis

The refinery consists of a number of processes and in Figure 5 the utilization of the CDU is presented. As described earlier in the case study there are two different crude oils which can be processed in the CDU. In the figure there are two different diagrams showing the utilization for the deterministic and the oracle solution, and each diagram shows which crude oil that is processed each day during the 28 day horizon. As can be seen there are some major differences between the two solution approaches and an interesting observation can be seen in the deterministic case at day 12. It says that the CDU should be shut down that day and since this is costly it will of course affect the profit negatively.

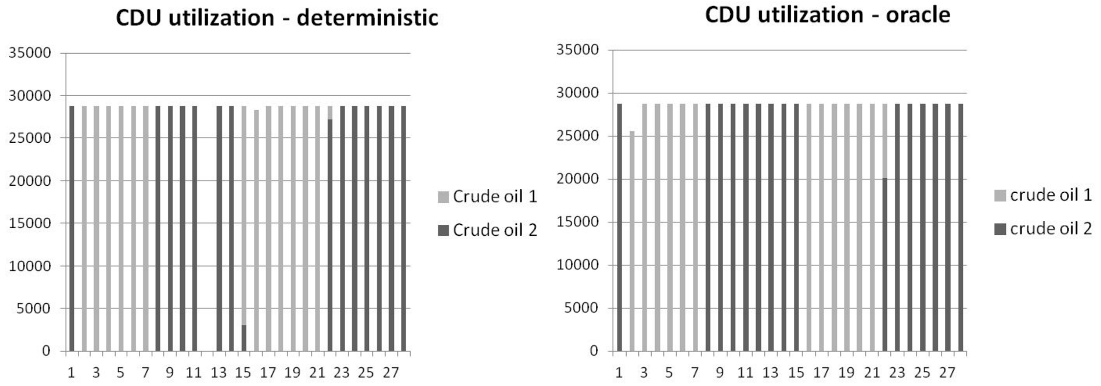

Figure 5: CDU utilization for deterministic and oracle solution, respectively

The reason for the shutdown can be seen in Figure 6 which shows the inventory level of diesel component gas oil 2. Diesel can be blended from several recipes but some recipes use more gas oil 2 than other. Considering the inventory levels for deterministic and oracle case in Figure 6 it can be seen that the inventory levels at day 9 differs. The reason is that the deterministic and oracle solution use different diesel recipes and if the CDU would not have been stopped in the deterministic case then the gas oil 2 inventory would have been overfilled. There are basically two reasons why the deterministic and oracle solution differ. The first reason is that the deterministic must do some adjustments in order to deal with late incoming ships, and the second reason is due to safety inventory where the deterministic solution must choose another action in order to not go below the safety inventory level.

Looking at the utilization of the cracker, see Figure 7, which can be switched between gas oil and naphtha mode, it can be observed that the production modes differ between the deterministic and the oracle solution. The most significant differences are that the cracker is shut down at day 12 and runs on reduced capacity at day 13 in the deterministic solution. In addition it runs in gas oil mode most of the time. There are several possible reasons for reducing utilization of the cracker and two of them are identical to those causing shut down of the CDU, i.e. adjusting to late incoming ship or safety stock. Another reason which

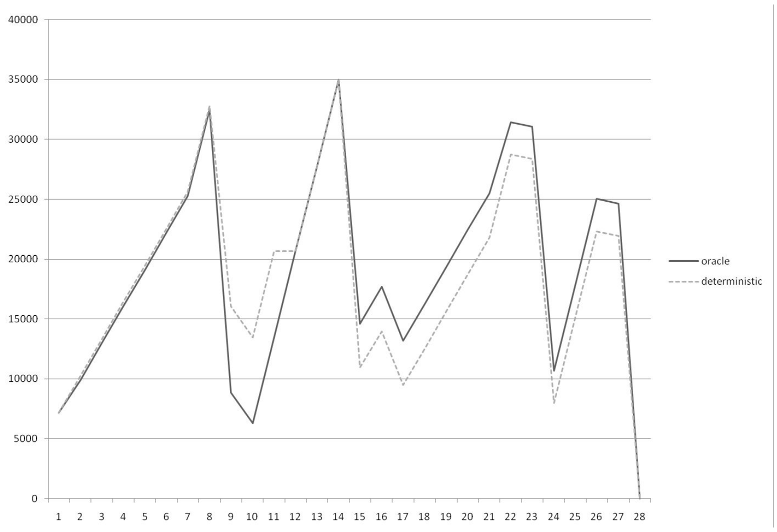

Figure 6: Inventory level of gas oil 2 for deterministic and oracle solution, respectively. Maximum inventory is 35 000.

may explain the reduction is that since the CDU is shut down, there is a lack of necessary components to blend products, and thus it is not profitable to run the cracker just to produce components which will end up lying unsold in inventory. Figure 8 and 9, which illustrate the inventory level of cracker naphtha and cracker gas oil, respectively, indicates that neither overfilled inventory nor safety inventory explains why there is a reduced cracker utilization and thus profitability consideration seems to be the reason.

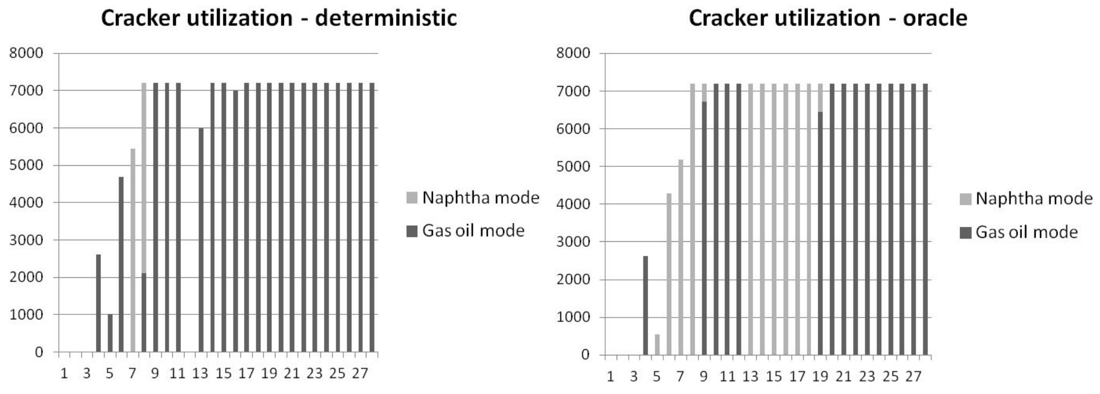

Figure 7: Cracker utilization for deterministic and oracle solution, respectively

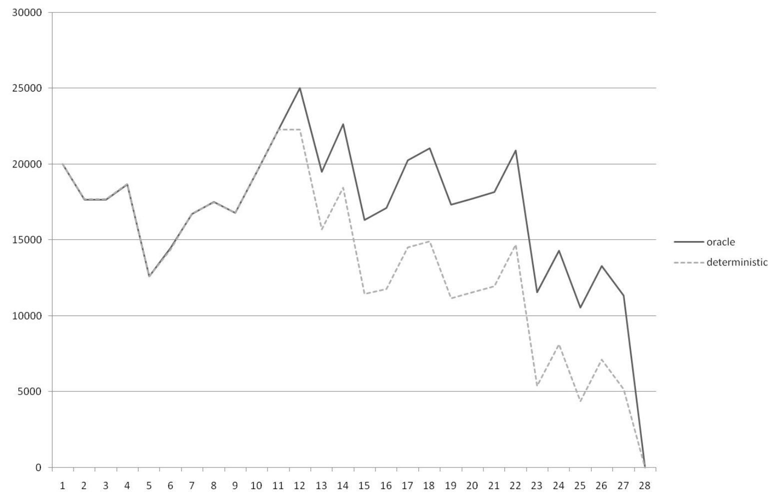

Figure 8: Inventory level of cracker naphtha for deterministic and oracle solution, respectively.

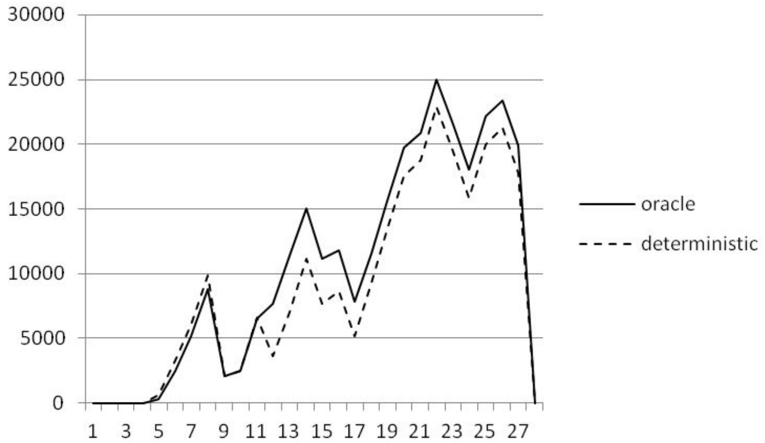

Figure 9: Inventory level of cracker gas oil for deterministic and oracle solution, respectively.

## 5.2 Analysis for all simulations

It is also of interest to analyze the profit for the two methods for all 100 scenarios; this is illustrated in Figure 10. All numbers in the figure are normalized such that the highest achieved profit in the oracle case is equal to 1. The oracle solution presents the highest profit as must be, both for each simulation run and on average. To establish good safety levels for the deterministic approach, we have solved one deterministic problem and then used a safety stock level corresponding to a certain percentage of the throughput (flow) for each component and product tank. We have tested several levels and selected the best in the results.

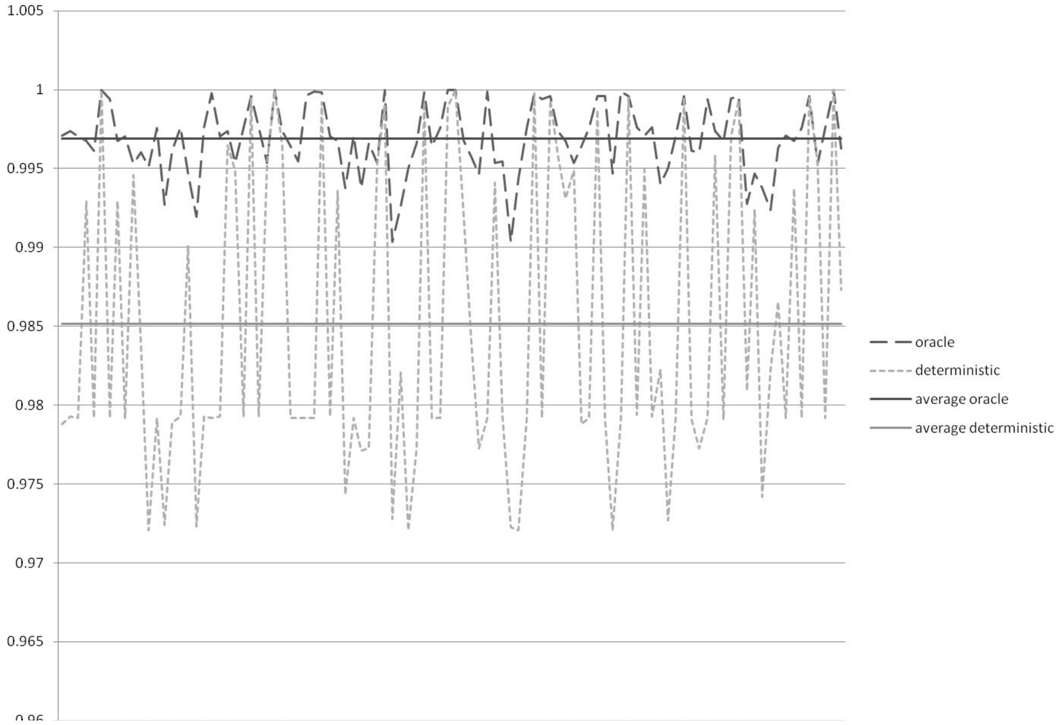

Figure 10: Result with normalized objective function values 100 simulations with max one ship delayed per day for deterministic and oracle solutions,respectively.

# 6 Concluding remarks

Integrated planning of refinery operations is difficult and there is a need for decision support tools. Various levels of integration have been proposed in several models in the research literature and in this paper we have proposed an deterministic LP model to integrate short term refinery operations including processes, inventory, blending and loading of ships. Many aspects of the overall process are uncertain but we choose to consider ship arrivals. The motivation is that this is one of the most complex to include in the plans. In order to analyze the performance of the deterministic model in an uncertain setting we set up a case study with ship arrivals. As a comparison to the deterministic model an oracle solution, where ship arrivals are known, is determined. From the simulation study it can be seen that the oracle solution differs significantly from the deterministic model in an uncertain setting, and this is both in terms of expected profit and how processes should be run. In the experiments, we find that the average difference is about 1.5%. In this paper safety stocks are used in order to handle uncertain ship arrivals. In this case uncertainty is not explicitly dealt with in the model and as can be seen from the analysis there are opportunities to increase profit if we could approach the results or the oracle. As such it is of interest to look more closely how we can incorporate uncertainty in the optimization methods. An interesting and promising approach is robust optimization where feasible solutions are guaranteed given a certain way of modeling the uncertainty. In future research we will use a robust approach which models interactions of uncertainty over several periods but where detailed statistical functions are not needed. We expect that the computation work will increase using the robust approach but since the subproblem is based on the deterministic model it should still be manageable. By using uncertainty information and a multi-period dynamic robust model we expect to end up with decisions that increase profit compared to the deterministic case presented in this model but it is also of interest to find out how close to the oracle solution we may come.

# References

[1] Göthe-Lundgren M, Lundgren JT, Persson JA (2002) An optimization model for refinery production scheduling. International Journal Production Economics 78:255-270

[2] Jia Z, Ierapetritou M (2004), Efficient short-term scheduling of refinery opertations based on continuous time formulation. Computers and Chemical Engineering 28:1001-1019

[3] Koo LK, Adhitya A, Srinivasan R, Karimi IA (2008), Decision support for integrated refinery supply chains - part 2. Design and operation. Computers and Chemical Engineering 32:2787-2800

[4] Kuo T-H, Chang C-T (2008) Application of a mathematic programming model for integrated planning and scheduling of petroleum supply networks. Industrial & Engineering Chemistry Research 47:1935-195

[5] Mendez CA, Grossmann IE, Harjunkoski I, Kaboré P (2006) A simulation optimization approach for off-line blending and scheduling of oil-refinery operations. Computers and Chemical Engineering 30:614-634

[6] Neiro S, Pinto, JM (2004). A general modeling framework for the operational planning of petroleum supply chains. Computers and Chemical Engineering 28:871-896.

[7] Pitty SS, Li W, Adhitya A, Srinivasan R, Karimi IA (2008) Decision support for integrated refinery supply chains - part 1. Dynamic simulation. Computers and Chemical Engineering 32:2767-2786