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Integrated multi-period planning of refinery operations, sales and supply

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Summary

Planning of a refinery supply chain is a complex task for several reasons. First, refinery processes are complex and yields from different processes are dependent on crude oil mix and process modes. Second, some products, e.g. gasoline do not have a unique composition and the most optimal way to blend the products may change over time and will depend on several external and internal factors. Third, prices of crude oils, freights, and products are rather volatile and to be able to make the most profitable decisions there is a need to constantly evaluating whether crude oils, components, or products should be bought, produced, or sold. In addition, the planner must take into account other constraints like tanker and inventory sizes.

In this report multi-period hierarchical planning and multi-period integrated planning are discussed in the context of proactive refinery supply chain planning, where the organization tries to take advantages from market opportunities, and the conclusion is that to a refinery an integrated model has some advantages over a hierarchical planning model. The integrated model does not have the same problems with infeasible plans as the hierarchical model, and in case of hierarchical planning model there is also a risk that effects from purchases or sales made today are not captured in plans which stretch a couple of weeks into the future. To reduce complexity of models and avoid an excessive use of details, which are known drawbacks of integrated models, the same approach as in Kanyalkar and Adil (2005) can be used. In Kanyalkar and Adil short time buckets are used in the beginning of the planning horizon and long time buckets towards the end of the horizon, thus reducing the need for a lot of detailed data for planning periods at the end of the planning horizon.

In order to perform some analysis on a planning framework similar to Kanyalkar and Adil, a number of stylized cases are analyzed. To do this a refinery model is formulated, optimization is performed, and effects from inventories, tanker sizes, increasing flexibility, limited market access, lack of feedstock are analyzed. The analysis illustrates that optimal sales, purchases, refinery process settings and recipes are affected, in some cases heavily, and that optimal plans may change a lot over time.

Keywords: Refinery planning, integrated planning, supply chain planning

1 Introduction

The supply chain of an integrated oil company stretches from the production of crude oil to small and large customer, which buys refined products such as petrochemical products or fuel for heating or transport. Integrated oil companies have several decisions to make along their supply chain where they amongst other must decide whether crude oil, components and products should be kept for internal use, stored, or sold to external customers. In the supply chain the refinery has a central position since it refines the crude oil to components and products. Refineries require large quantities of crude oil and will also produce large quantities of components and product, and this in turn require a well developed logistic function within the company. Typically, crude oils and products are transported either by pipeline or tankers.

The supply chain of an integrated oil company differs from many other types of supply chains. In a lot of other supply chains raw materials and components converge in order to create a product, and prices are relatively stable. Looking at a refinery the situation is different since, typically, a rather small number of crude materials end up in a large number of components and end products, and prices can be rather volatile.

The market for crude oil and products is a world-wide market. Crude oils and products can be produced and consumed in different continents and market places around the world connect buyers and sellers. Thus, prices are connected between countries and this gives that political issues, break downs of refineries, and sudden interruptions in supply in one country can result in price swings in other countries. As such the refiner is working in a market environment where costs and revenues are fluctuating. However, to a refiner the margins between products, and between products and crude are more important since these are giving information and directions of how refineries should be run and which products that should be sold.

Not all oil companies have their own fleet of crude oil and product tankers. This in turn gives that some companies that are dependent on the freight market where demand and supply of transport capacity results in fluctuating transportation costs. Transportation costs are important since these costs may have a significant impact on profitability. However, volatile prices may also open up for new market opportunities in that a product that was less profitable in the first place becomes more profitable and thus more preferable. In order to discover these opportunities the oil company must continuously be updated on prices of crude oil, product and transports.

In integrated oil companies the trading departments are typically responsible for buying and selling crude oils, components and products, in addition to arrange transports. In this way they can get an overview of the crude, product and freight markets, which to a large extent determines the profitability of the refinery. In addition to trading decisions, which involves physical delivery, trading departments also use the paper market to hedge and speculate.

Investing in a modern refinery requires a significant amount of capital and the revenues generated must cover high levels of fixed and variable costs for a long time. As such an efficient management of refinery resources is important in order to stay profitable and use the refinery in the best way subject to amongst other demand, prices, and availability of refinery resources. However, refineries consist of equipments, which are highly complex and these make it a challenge to determine how the refinery should be utilized.

Proactive management of refinery supply chains where the company tries to identify and take advantage of market opportunities put requirements on planning. both in terms of planning processes, frameworks and tools. This report takes a look at some of the requirements that proactive management puts on planning framework and the way planning is performed. These are then analyzed in order to suggest how refinery planning should be undertaken. Finally, a refinery model and optimization is used in combination with a number of stylized cases to show the suggested planning framework and how different settings affect sales, purchasing, process plans, and product recipes.

The rest of the report is structured in the following way. Chapter 2 gives a short background to production processes, products and planning. The chapter on planning is partly based on information from an oil company. Chapter 3 presents a literature review on refinery planning and on integration of short term and medium term planning. Chapter 4 consists of a problem analyses and chapter 5 presents the model based analysis. Chapter 6 concludes and present some ideas for further research.

2 Refinery processes, products and planning

2.1 Processes and products

The production planning and control environment in the refinery industries have some typical features that separate them from many other types of production. The refinery process is a continuous process where one or several different types of crude oils are split into different streams, components and products. Several different processes are connected in the refinery and once started it is not interrupted until crude materials have been processed to either chemical components or finished products. There are in general no or limited possibilities to store material between different processes in the refinery, which in turn implies a short lead time through the refinery, i.e. approximately 6-10 hours.

The refinery process produces a number of highly desired components and products, but in many cases it will also produce components or end products, which are not demanded for the moment. Some of the latter might even be considered as a bi-product where the refiner may have a small or even negative profitability. However, all components and products require storage spaces.

The components and products that come out from the refinery are classified according to their characteristics and the type of products is basically determined from the mixture of hydrocarbon molecules. The specifications, i.e. cut points on crude distillation unit, sulphur content, viscosity etc., of components and products may differ depending on crude oil types, refinery type and production modes. Some products are uniquely determined from a particular number of hydrocarbon molecules, like butane, but others, like e.g. gasoline, can be produced from a range of different mixtures of hydrocarbon molecules. As long as specifications, which might be given in the form of a range, are fulfilled different mixtures are allowed. Product specification often differs between countries, e.g. due to climate and environmental legislation, which also gives that e.g. gasoline is not a single product. There are still several ways to blend components and end up with the same product. From a planning and scheduling perspective a range of specifications gives flexibility since several recipes can be used to produce a product, but at the same time it will also complicate decision making in that it becomes harder and more complex to find the optimal production.

Nowadays, when ships are loaded at a refinery they are in many cases served from component inventories, where components are blended directly onboard the ship in the right amount and according to customer's specifications. An important advantage with this blend to order approach is that the required number of finished product inventories reduces since one can blend a lot of different products from a limited number of components, and where the number of components is significantly lower than the possible number of products. This reduces inventory holding costs, but with an intact or even better customer service level.

2.2 Refinery planning – a description partly based on a company case

2.2.1 Planning horizons

As seen in the previous section there are a number of decision that must be made along the supply chain where crude oil are refined to products. Table 1 below lists different planning categories together with their associated time horizon.

Planning	Plans	Time horizon
Long term	Location Capacity decision Product line Maintenance Logistical planning	Up to several years
Medium term	Crude oil purchase Sales planning Operations planning Logistical planning	2-6 months
Short term	Operations planning Crude oil planning Inventory planning Blending planning Ship planning	0-1 month

Table 1. Typical short, medium and long-term decision in refinery business

In this report the long term planning horizon will not be further dealt with since this report is not focusing in strategic decisions. Instead the focus will be on operational planning.

2.2.2 Medium term planning

At some refinery companies there are a routine to determine a plan for average monthly sales and production rates for the coming months. The plan is determined through an iterative process between sales (i.e. trading department), procurement (crude oil purchase) and operations. An important input to this process is the results from an optimisation model, which maximises profit given amongst other prices and refinery capacity. A lot of the conversation between involved divisions is based on the outcome from the optimization procedure both in terms of interpreting the outcome but also to analyze the sensitivity of the results.

A planning process may start approximately one month before the monthly production and sales plan is expected to be realized. One of the first decisions in this process is typically the crude oil procurement decision which concerns, quantity, type of crude oil, and delivery time. A reason for making this decision early in the process is due to rather long transportation lead times. In the crude oil selection process the optimization model helps a lot in order to find the a profitable crude oil mix, but it will at the same time give some directions to the sales department regarding which products that can be expected to be produced.

The monthly production plan is set approximately one week before the month where the plan starts to run. At this point in time, there exists information on promised deliveries a couple of weeks ahead since most of the products are sold. Quantities are known but the point in time is uncertain to some extent since there is a time window stated in the deals. However, the optimization models often used during this planning phase do not explicitly consider timing of demand since these are single period models and optimize in terms of aggregate average monthly figures. After the monthly plan is set it is updated during the month with new prices and other kinds of information that may cause changes in operation or sales. Every week there is a meeting to follow up performance of ongoing activities and during these meetings important information updates are included in the optimization model and analysed. The time horizon during these meetings is the same as the remaining time of the current month and as a consequence the time horizon gets shorter for every week. In parallel to this, the process starts to set up a new plan for the next month.

2.2.3 Short term planning

Short term planning includes planning of crude oil mix, inventory levels, blending to meet demand, ships, how the refinery should be run, see also Table 1. At this level the importance of inventory levels increases since these will have an effect on what is possible to achieve. A central input to short term planning is the lifting program which presents requested volumes, specifications, destinations, and time windows when ships are expected to be served at the loading port. The lifting program may stretch 2-3 weeks ahead but there are uncertainties associated with the lifting program in that ships arrive too late due to bad weather conditions etc. and sometimes the trading department at the oil company decides to change quantity, specifications or destination of a cargo.

If the refinery cannot serve incoming ships within the negotiated time window, the refiner has to pay a penalty, i.e. demurrage cost. In order to avoid demurrage cost there must be enough components, or products, in the inventories and there must be enough loading capacity at the ports. Typically, there will be a designated planner who monitor current and future inventory levels, and who has a frequent dialog with the ship planner. By monitoring the inventory levels, which are the result of previous, current and planned production and inventory withdrawals, the planner can forecast if there is a need to replan refinery activities in order to serve incoming ships, or to avoid overloaded inventories. A replanning of the refinery may incorporate crude oil mix, refinery processes and recipes and may also generate set up costs.

Another possibility to avoid stock outs or overloaded inventories is to use other recipes than those originally planned. However, using other recipes might result in so-called give away, i.e. the products ends up with better, and more expensive, specification than what is required by the customers. In case of overloaded inventories it is also possible to let the components pass through the refinery again, but if there is time to arrange a transport it is also possible to sell components to other refineries.

Since market prices fluctuates and profitability between products changes, trading departments are interested to sell those products that are the most profitable for the moment, even on rather short notice. In order to do this, ships might be swapped, or products or destinations are changed, but before any changes are done it is important to find out if the refinery is able to support the suggested change. The managers should also have in mind that the refinery gains from a stable production environment since set up costs are avoided and process yields are more predictable. In addition, in the short term it might be impossible to do any changes due to customer promises and difficulties to get necessary crude oils in place on such a short notice.

3 Literature review

3.1 Refinery planning

There are a lot of works done on refinery planning and scheduling in the literature but this review will focus on the latest references on operational and short term planning of refineries. Some references below also cover short term planning and scheduling but those which are only focusing on scheduling are left outside.

Moro et al (1998) 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 (Mixed Integer Non-Linear Problem) model is discussed for a diesel production planning problem and 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 (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. The study outlines a large scale single period MINLP planning model for the system addressing crude oil purchasing, production units processing, inventory management, logistics, and end product sales decisions. Neiro and Pinto 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.

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.

Mendez et al (2006) develop a novel iterative MILP (Mixed Integer Linear Problem) formulation for the simultaneous optimization of blending and scheduling and formulate the problem both in discrete and continuous time. Mendez et al focus on blending of components to product, and quantity and timing of movements from component tanks to product tanks in order to respond to demand. Thus, the scheduling of the production units is not considered and it is assumed that production of components take place at a constant rate. The resulting non-linear MINLP blending and shipment problem is modeled as a successive MILP problem where the objective function maximizes profit and is based on the assumption that the cost of components can be observed or determined.

Mendez et al 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 also propose to include penalty for deviation from preferred product recipe and penalties for deviations from specified product qualities, and allow purchase of components from a third-party to relax minimum inventory constraints.

Kuo and Chang (2008) have addressed the issue that if planning and scheduling is done sequentially, there is no guarantee that the production plan can give an operable schedule. They 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.

Pitty at al (2008) present a simulation based dynamic model of an integrated refinery supply chains which is used to analyze policies, refinery configuration, strategic plans and disruptions. Koo et al (2008) extends the work of Pitty et al to include optimization and present a simulation-optimization framework to provide a decision support for optimal supply chain design and operations.

Apart from just focusing on maximizing profit there is also a stream of research, which considers climate aspects such as greenhouse gas emissions and use of energy while meeting stringent product specifications. Szklo and Schaeffer (2007) address this problem whereas Holmgren and Sternhufvud (2008) discuss different possibilities for reduction of CO2 emissions. Other approaches to this problem have also been addressed. Pierru (2007), and Babusiaux and Pierru (2007) have proposed different methods for allocating the CO2 emissions among the different refinery products produced. 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. 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.

3.2 Integrating medium and short term planning

Basically the planning hierarchy are classified into three different planning levels: long-term, medium term and short term. Fleischmann et al (2005) choose to call the medium term and short term planning for operational planning and this is a concept that will be used in this report as well.

In many cases there are strong interdependencies between medium term planning and short term planning and in the literature there are approaches which connect these. An approach to integrate medium and short term planning is to use a monolithic formulation where both short term and medium term planning decision are modeled in the same model. A monolithic model may become large and complex and another possible implication of monolithic models is that due to the detailed level there is a need for a lot of data with high accuracy, which might be a challenging task especially when looking several months ahead.

Another approach which has received a lot of attention is the so called hierarchical production planning (HPP). The planning approach is called hierarchical if there for a level exists an upper level which is allowed to set the frame for decisions that will take place at lower planning levels. At each level decisions are assigned and separate models are formulated and in this way model size and complexity are reduced. For at least one level aggregation in terms of e.g. time, product and resources is made and this serves a purpose in that complexity is reduced since fewer details and fewer decisions reduce complexity.

A possible drawback with the hierarchical approach is that a plan that is feasible at a particular level in the planning hierarchy may be infeasible at a subordinated level. This drawback is often cited in the literature; see e.g. Schneeweiss (2003). Another drawback when several models are used, as in the case of hierarchical models, is that one may end up with suboptimal plans.

Hierarchical coordination concerns direction and feedback between planning levels and is central in order to deal with infeasibility problems. Directives set by an upper level can e.g. be a target inventory level at the end of the planning horizon of the lower level, or providing prices for utilization of resources. In turn, feedback to upper level regarding the fulfilment of targets is also important since these allow upper levels to revise plan, to better coordinate lower-level decisions and to enable lower levels to come up with feasible plans.

There is a lot of work done on hierarchical planning but in this report a number of references which focus on two and three level hierarchical planning are presented. A more exhaustive presentation of hierarchical planning of operations and supply chains can be found in Miller (2002). Katayama (1996) analyses a single plant, a lubricant manufacturer and a petrochemical company respectively, with two levels of decisions. Katayama aggregates over product and time and incorporates the coordination function between the production period and job-lot sequencing function. Tsubone and Sugawara (1987) study an electronic motor company and apply a three level hierarchical planning hierarchy. They use product aggregation to decide on the aggregate and family-level production plans and scheduling of finished goods on production line. Leong et al (1989) uses time and product aggregation in a three level hierarchical planning for a fibre-glass company. Carravilla and de Souza (1995) determine production planning for a shoe company using a three level hierarchical planning approach. In their paper they aggregate over product and capacity, and in the second level they also determine the layout of the plant.

Kanyalkar and Adil (2005) develops a formulation for a multi-plant, multi-selling location problem to generate plans at two levels in a single integrated model. In their model they use different time scales with short time buckets in the beginning of the planning horizon and longer time buckets during the rest of the planning horizon. Using different time buckets gives that a feasible short-term plan can be determined without an excessive computational burden, which could be the result if the whole planning horizon has the same short time grids. Kanyalkar and Adil (2007) extend the analysis and incorporate the procurement stage.

4 Problem analysis

4.1 Planning items – products vs. components

In some modern refineries components are produced, which then are blended to finished products when product tankers arrive at the refinery. However, most of the planning activities are carried out in terms of finished product. If one compare to other production environments, which are based on a finishing-to-order strategy, the way planning is conducted differs to some extent. In many cases these manufacturers, which use a finishing-to-order strategy perform their planning on component level and not on product level. The number of possible products is usually much higher than the number of components, since they can be combined in a number of ways. Thus, it is usually easier to get accurate forecasts on component level than on product level.

In refining there can be several reasons why planning is not carried out at a component level. One reason is that all components basically come from the same raw material, i.e. crude oil, and is produced in the same processes. An implication of this is that it might be impossible to produce certain amounts of components since the relationships between different components is, to a large extent, determined by the crude oil and the refinery set up. It is for example impossible to produce only one component used in e.g. gasoline blending. Another fact that speaks for planning at product levels is that products can be blended from different recipes. Thus the required amount of particular components could be different even though the final product is the same.

Compared to many other production sites, a refinery is also different in that, the inventories are often large, and due to limited space and high cost it is not economical to have many of these. Newly produced components will therefore be mixed with almost identical components already in place in the inventory and an implication of this is that the final quality, i.e. specification, of the component in the inventory will change over time as crude oil mixes and refinery modes changes. It cannot therefore be planned as if there was the identical component in the inventory over time and this also reduces the practicality of planning at component levels.

The planning of a refinery is complex and there are no obvious advantages from focusing on the component level. In addition, market prices of products change and can be observed whereas values of components are harder to determine. Thus, it should be harder for decision makers to identify the most profitable plan when planning is carried out on component level instead of product level.

The complexity of the planning task calls for decision support in forms of optimization models and tools, since it is hard to find out what consequences certain decisions cause. As such, optimization models and tools should have a central place in the decision process in order to find balance between demand and supply. It is in other words very important to both trading department and operations planners to have access to optimization models, collaborate, and to determine and analyze plans with different time horizons and different possibilities to make decisions.

4.2 Decisions and flexibility

The outline of a planning process and its framework will be affected by its purpose and differ between organization. If a refinery organisation is proactively managed or not will affect the need for communication between departments both in terms of frequency and content. To a refinery organization, not proactively managed, the use of a monthly plan and its production statements in terms of an average production and sales may work quite satisfactory. In this case the refinery organization is not searching for short term market opportunities, but sales are to a large extent determined by the monthly plan. In addition, if the trading department organizes sales and transport to be rather synchronized with the production rates there should be less need for replanning and rescheduling and a monthly plan should have the possibility to perform rather well. Under these circumstances the refinery should have a rather predictable environment with small deviations from the original plan mainly caused by logistical problems and disturbances in the refinery process.

A proactively managed organization, which strives to draw advantages from market opportunities, requires updated information and support tool in order to find out if a product is possible to produce and profitable. To be able to do this successfully, updated information from trading, process planning, crude oil planning and logistics is required and an iterative and co-operative process is also important in order to secure that the right buy-sell-make decisions are taken.

In order to be able to use and act upon updated information the refinery organization must also look at the real flexibility in the organization and along the supply chain. In the long term, there is a lot of flexibility, but in the short term it might be the fact that there is almost no flexibility. For a proactively managed refinery organization which constantly seeks for opportunities to increase profits, it must be possible to force decision through. An important part in the deals is logistics, which affect profitability, but which also affects whether a deal can be done or not. In the short term it can be hard to arrange a transport, even though the refinery could produce the products. Another situation could be that the refinery has to sell a minimum amount, or has to buy crude oils in amounts equal to the size of a VLCC or Afra-max tanker. These situations, which are given by logistical constraints, may have effect on the whole process since the size of the quantities give more wide-spread consequences.

The longer the time horizon, the more flexibility there is in general and in Table 2 below some central decisions and their associated time horizons are listed.

Flexibility	**Approximate time horizon**	**Uncertain parameters**	**Fixed parameters (to a large extent)**
Choose crude oil (incl. purchase) Freight options Which products to buy, make, sell and when to deliver Modes of refinery processes	1-3 months	Prices	Refinery capacity and set up
Buy-sell-make decisions Change crude oil mix (buy/sell) Modes of refinery processes Adjustments of blending recipes	2-4 weeks	Prices and arrival and departure times of ships	See above Crude oil availability Lifting programme
Buy-sell-make decisions Change crude oil mix (CDU feed) Modes of refinery processes Adjustments of blending recipes	0-2 weeks	Arrival and departure times of ships	See above Inventory levels

Table 2. Flexibility types available to decision makers, associated time horizons, uncertain and fixed parameters.

Several decisions concerning crude oil purchasing, products sales and logistics, which have effects 1-3 months into the future, will put a frame around future possibilities for trading.

After the frame is set there is room for the trading department, in collaboration with the production department, to find and take advantages of market opportunities by continuously evaluating buy-sell-make decisions. Some of these decisions concern:

i) selling products not planned to be produced in the first place, but which appear to be profitable
ii) buying products, either to store and sell later, or to release some refinery capacity and produce something else that appears to be more profitable
iii) buying crude oil not included in the original procurement plan
iv) changing cargoes by changing products and/or destinations
v) making products, store them and sell them by using the forward market

The capability to identify market opportunities will be dependent on the company's ability to, given current condition (prices, production decisions, available crude etc,) identify how buy, sell and make decisions should be undertaken. To do this, already booked and planned production must be considered together with futures and forecasted prices. Several of the alternatives listed above may require a replanning of the refinery and a deviation from the original monthly plan. This in turn may require a change in optimal recipes and other operational changes. This makes it complex to decide whether an alternative is profitable, or even feasible, or not in a larger perspective. To figure this out models with a short time horizon and many details must be used. E.g. to fully analyze the profitability and feasibility of a potential product sale it is required to take into considerations aspects such as available capacities along the supply chain, inventory levels, already promised deliveries in terms of quantity and delivery time, and prices of crude material, product and freights. This implies that more detailed information is required compared to what is needed in a typical average based monthly plan, but this is a necessity, together with more detailed models, in order to find optimal sales and trading strategies.

4.3 The importance of inventories

An important aspect which has a big impact on the possibility to perform buy-sell-make decision is the inventory. The inventories will affect planning both in terms of availability for storage spaces but also the possibility to separate procurement, production and consumption of crude, components and finished products over time. Larger inventories increases flexibility in that it allows to a greater extent to adjust and move production between different points in time. In similar fashion smaller inventories implies reduced flexibility since most of its capacity will be consumed when responding to demand. However, inventories gives the effect that decisions made today will affect the availability in the future and must therefore be considered in a planning model whose purpose amongst other is to find market opportunities. An example which can be used to illustrate this is if there is a possibility, announced on short notice, to buy a certain type of crude oil which is going to be delivered by a VLCC-tanker. To some refineries this amount is equal to one third of a monthly consumption of crude oil, and in order to perform an analysis of the profitability of such as purchase the refiner have to take into account that capital will be tied up in inventory, if there are place to store it, if the new crude oil will outperform the crude oil in place in short term or long term, and if the new oil will give new sale opportunities, and if these can be delivered given the existing lifting programme.

4.4 A planning model for proactive refinery management

In order to be profitable when performing proactive refinery management there will be a need for a planning model which supports decision makers. The model should be available to personnel with different planning tasks such that market opportunities are identified and necessary actions are analyzed and verified. To be successful there will be a need for a model, which handles both short term effects but also effects in the long term, and in order to take this into account there is a need for a multi-period model which allows for timing issues to be modeled. For example, to fully evaluate the attractiveness of the opportunity of buying a cargo with a certain type of crude oil with delivery in 14 days, planners must have the possibility to evaluate: i) what impact it will have on inventory levels and cost, ii) what should be done with the other tankers, which will arrive with crude oil, iii) how will this affect what products that is preferred from a refinery process point of view, iv) should the refinery switch to a new crude oil mix at the same time as it becomes available at the refinery. Since crude oil tankers in general do carry large quantities that could take e.g. 10 days to consume, a market opportunity like this may give effects for several weeks into the future and it can also be seen that several planners should be involved in evaluating such an opportunity. The necessary information exchange between planners, traders and optimization model can also be illustrated as in Figure 1.

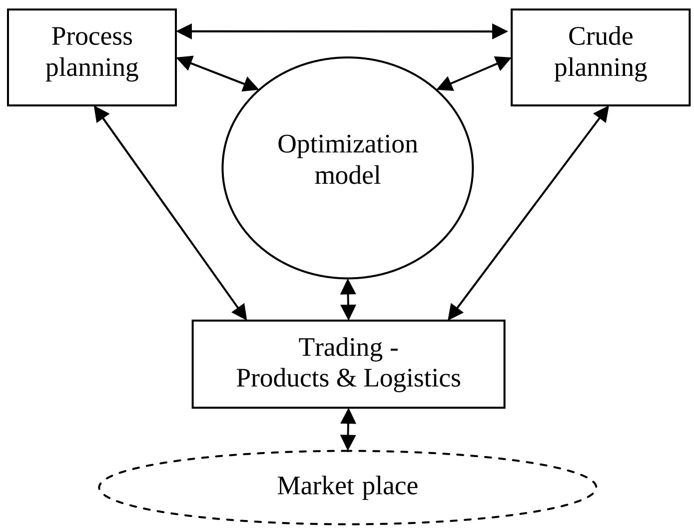

Figure 1. Overview of information exchange between planners, traders and optimization model

A multi period model is also important when an opportunity, which involves sale of a product in a rather short time, appears at the market. In such a case the following should be analyzed: i) is it possible to produce this product given current lifting program, ii) if not, is it possible to do trades at the market and end up with higher profit iii) should the refinery processes be adjusted in order to achieve a higher profit, iv) does it require component inventory build ups in order to be able to serve the customer at the delivery date. As can be seen here as well, several planners with different task should be involved, and timing is important in order to be able to perform the analysis. An overview of the information exchange in such a situation is presented in Figure 2, and it is central here that the same optimization model is used here as in Figure 1. A multi period model is not only preferable due to its advantages to analyze market opportunities like those mentioned above. Another situation where it could help is how the oil company should handle situations where unforeseen events like e.g. short supply or process breakdowns happen.

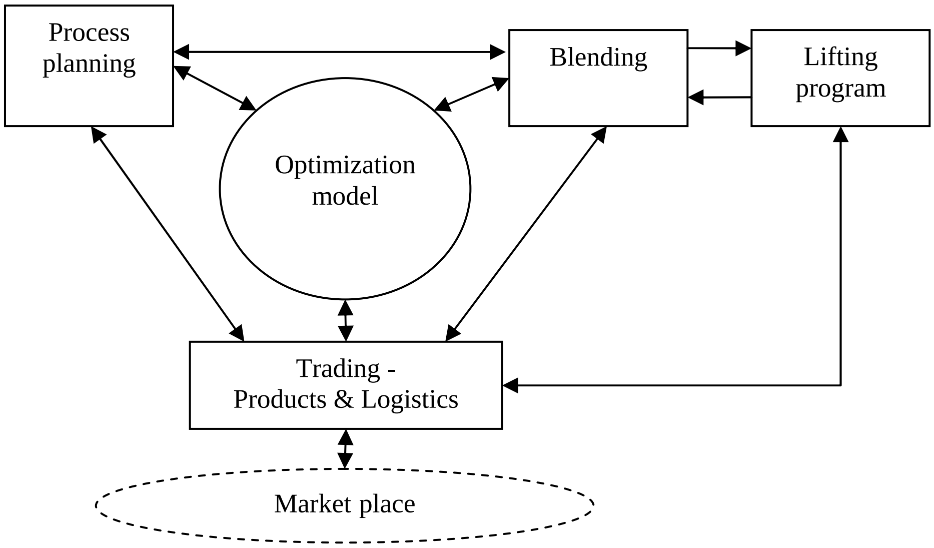

Figure 2. Overview of information exchange when a short term opportunity is analysed.

In the literature review on refinery planning several references were presented but seen from a proactive management view some important things are not dealt with in these. In Neiro and Pinto (2004) the whole supply chain is considered but is limited to a single period. Neiro and Mendez et al (2006) focus only on one part of the refinery, i.e. the blending and its associated scheduling activities. Pitty et al (2008) use simulation and Koo et al (2008)) use simulation-optimization and both assume that amongst other that prices and product demand are stochastic and exogenously given. Pitty et al and Koo et al does not explicitly consider the lifting program but assumes a statistical distribution for demand per day, thus not taking the information in a lifting program into account. Kuo and Chang (2008) formulate a model which integrates scheduling and planning but do not take into account that the market place can be used in order to fulfill customer promises, or increase profit.

Refinery planning with different planning horizons is often performed sequentially, mainly due to the complexity of the refinery sub-problems. If planning is done sequentially, there is no guarantee that the production plan is feasible, cf. the problem with hierarchical production planning, see also the literature review on production planning. Sequential planning could also risk that effects from purchase or sales today are not included in plans a couple of weeks into the future. Thus, a hierarchical approach, without any coordination between levels, should be of less interest to those companies trying to draw advantages of market opportunities.

An attractive approach, which also is mentioned in the literature review, is presented in Kanyalkar and Adil (2005). They use a multi period model where the whole planning problem is modeled in the same model, thus avoiding sequential and hierarchical planning and their associated drawbacks. However, they do not use the same time grid throughout the whole planning horizon and thus they avoid to some extent the need for detailed and accurate data for later time periods. The principles of this planning approach are illustrated in Figure 3.

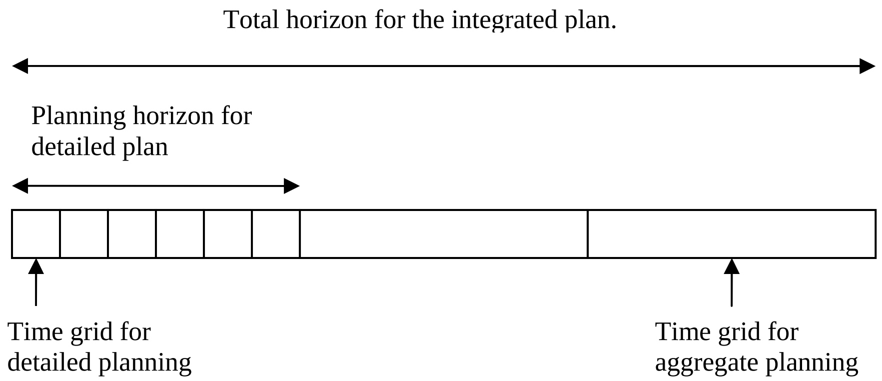

Figure 3. Illustration of time grids and horizons for integrating detailed and aggregate planning.

Using the approach by Kanyalkar and Adil gives that the planner can integrate short term planning, which requires more details, with the medium term planning which requires less. In addition to the advantages mentioned above Table 3 list some advantages of a multi period planning model.

Advantages
• More accurate plan which is fitted to actual demand. • Different prices at different point in time can be modelled • Availability and constraints of crude oil, processing capacity, and inventory at different points in time can be modelled • Flexibility increases over time and this can be modeled in a multi period model.

Table 3. Some advantages of a multi-period model.

A disadvantage with a multi period planning model is of course that the size and complexity of a planning model increases as the number of planning period increases, but the approach used in Kanyalkar and Adil (2005) is a way to reduce this problem.

In order to analyze how a multi period model could help and guide decision makers a model of a refinery in a multi period planning framework is formulated. Then a number of stylized cases are used to show how different situation will affect purchasing, process and sales plans.

4.5 Demarcation

In this paper the focus is not on technical modelling such as for example the cut points and yields from crude oil distillation units and fluid catalytic crackers. Such equipments are complex to model mainly due to non-linear properties and may increase the complexity of an optimization model significantly. The focus of this paper is on the planning framework and its layout and design in order to improve the way planning is carried out and decisions are made.

5 Model based analysis on stylized cases

5.1 Refinery model

The refinery model used in this report is based on a model from Coiffard et al (2001). However, the model in this report is extended by storing gasoline components instead of gasoline. The flow chart of the refinery can be seen in Figure 4 and the mathematical formulation of the model is presented in Appendix A – Model formulation. The abbreviations in the flow chart are explained in Appendix B – Parameter values, abbreviations and explanation. The optimization model is implemented in Microsoft Excel and solved with Frontline Premium Solver V 9.1.

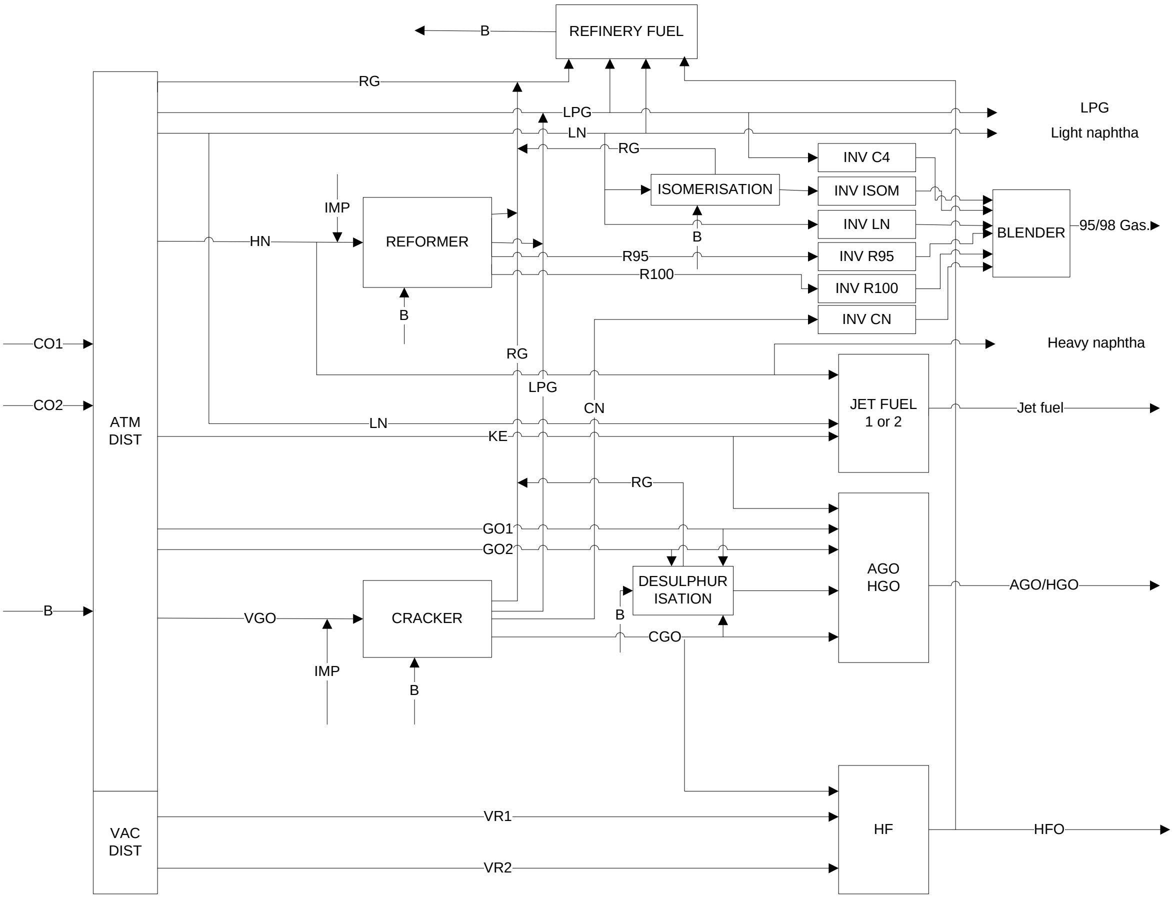

Figure 4. Flow chart of model refinery. Adapted from Coiffard (2001)

5.2 Settings, parameter values and cases

The parameters in the cases are set to reflect a potential situation in the refinery model. In this analysis the whole planning horizon is divided into five different periods in order to, amongst other, take into account the effects of increasing flexibility. The lengths of the periods are affected by how much flexibility there is during a certain period and operational constraints. For example, after a switch in crude material or in the production set up refinery processes need some time to find a steady state and therefore it might be pointless to have too short periods.

Throughout this chapter it is referred to a concept called the *long term optimal plan*. This plan maximizes cash flow when inventories are empty in the beginning of the planning horizon and there is full flexibility in terms of what to purchase, produce and sell. The reason for incorporating this plan is that it gives a point of reference since it says something about what should be purchased, produced, and sold, when there is full flexibility and when initial inventory levels and transportation lead times are not affecting the plan. The sales plan for each period given by the long term optimal plan is presented in Table 4.

Period	# of days	LG	HN	LN	G98	G95	JET	GO	HF
5	30	30,43	122,11	65,69	0,00	126,72	96,18	304,03	48,21
4	7	7,10	28,49	15,33	0,00	29,57	22,44	70,94	11,25
3	7	7,10	28,49	15,33	0,00	29,57	22,44	70,94	11,25
2	5	5,07	20,35	10,95	0,00	21,12	16,03	50,67	8,03
1	2	2,03	8,14	4,38	0,00	8,45	6,41	20,27	3,21

Table 4. Long term optimal plan – Sales in each period

Table 5 presents parameters for lower and upper bounds on sales, and scheduled crude oil deliveries, for each period. The planning horizon is divided into five different periods where the length of the periods are 2,5, 7, 7 and 30 days respectively. In Table 5 lower and upper bounds on sales are stated in terms of percent of *long term optimal plan.*

Period	**1**	**2**	**3**	**4**	**5**
Lower bound on sales (% of *long term optimal plan***)**	100%	100%	75%	75%	0%
Upper bound on sales (% of *long term optimal plan***)**	100%	100%	No limit	No limit	No limit
Scheduled crude oil deliveries (kilotonnes**):**					
Crude oil 2	180	180	0	0	0

Table 5. Sales bounds and expected crude oil deliveries

The purpose of the sales conditions in Table 5 is to illustrate the fact that in the short term all or most of the quantities are sold, transports are arranged, and there are no or small possibilities to change sales and to set -up new transports on short notice. However, in the medium term there is more flexibility since products and ships can be swapped and new transports can be bought in order to sell larger quantities. Table 5 also presents scheduled crude oil deliveries of crude oil 2. This exemplifies the case when the refinery has ordered crude oil earlier and due to transportation lead times these are expected in period 1 and 2.

In order to take into account the effect of inventory it is assumed that there are feedstocks, components and finished product available in the inventories. The planned inventory levels in the beginning of the planning horizon are presented in Table 6 inventory levels correspond to 20% of maximum inventory except for crude oil 1 and 2.

	CO1	**CO2**	**C4**	**LN**	**IS**	**R95**	**R100**	**CN**	**JP**	**GO**	**HN**	**VG**	**HF**
Maximum inventory	350	350	40	20	10	10	20	45	25	100	20	20	20
Inventory	100	100	8	4	2	2	4	9	5	20	4	4	4

Table 6 Maximum inventory levels and inventory levels in the beginning of the planning horizon. All figures in kilotonnes.

The analysis will focus on three different cases, which are presented in Table 7. The setting of each case depends on three different conditions. The first condition in Table 7 concerns if crude oil purchases must be done in multiples of 90 kilotonnes, or not. The purpose of the second condition is to reflect a situation where the current sales plan indicates larger quantities than those given by the *long-term optimal plan*. Finally, the purpose of the third condition is to capture the effect of having possibilities to import finished products, i.e. having the possibility to buy and swap products at the market and use the refinery in the most profitable way.

Case	A	B	C
Crude oil purchase in kilotonnes	No restrictions	Quantity equal to 90, 180, 270, 360, or 450	Quantity equal to 90, 180, 270, 360, or 450
Sales larger than quantities given by long -term optimal plan	No	Yes	Yes
Restrictions on product import (purchase)	Yes	Yes	No

Table 7. Conditions on crude oil purchases, sales and import for case A-C.

All other parameters like prices, process yields, product specifications etc, can be found in Appendix B – Parameter values, abbreviations and explanation.

5.3 Optimal actions and comparisons between cases

This chapter presents results from the optimization of each case. Optimal production figures will be presented in terms of daily rates in order to make it easier to compare between periods and cases. First, optimal production is presented and in this case this mean optimal crude oil mix which feeds the crude distillation unit, modes of reformer and catalytic cracker, isomerization activity, amount of gas oil sent to desulphurization, and jet fuel mode.

Process		CDU input (mix)		Reformer mode		Catalytic cracker mode		Isomerization	Desulphurization input			Jet fuel mode	
Period	# of days	Crude oil 1	Crude oil 2	REF 95	REF 100	Naphtha	Gas oil	Isom	Gas oil 1	Gas oil 2	Cracker gas oil	Jet fuel 1	Jet fuel 2
5	30	15,07	8,93	0,00	1,60	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
4	7	15,07	8,93	0,00	1,60	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
3	7	15,07	8,93	0,00	2,21	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
2	5	7,71	16,29	0,00	1,14	6,80	0,00	0,00	1,57	5,77	2,26	1,22	1,61
1	2	9,73	14,27	0,00	1,05	7,20	0,00	0,00	2,03	5,05	2,52	2,99	0,00

Table 8. Optimal daily production for case A

Process		CDU input (mix)		Reformer mode		Catalytic cracker mode		Isomerization	Desulphurization input			Jet fuel mode	
Period	# of days	Crude oil 1	Crude oil 2	REF 95	REF 100	Naphtha	Gas oil	Isom	Gas oil 1	Gas oil 2	Cracker gas oil	Jet fuel 1	Jet fuel 2
5	30	15,07	8,93	0,00	1,60	0,00	7,20	0,05	3,22	3,16	3,22	3,21	0,00
4	7	13,51	10,49	0,00	2,33	2,11	5,09	0,38	2,87	3,71	3,01	3,14	0,00
3	7	17,89	6,11	0,00	2,40	0,00	7,20	0,09	4,10	2,16	3,34	2,14	0,00
2	5	7,71	16,29	0,00	1,10	6,80	0,00	0,00	1,57	5,77	2,26	2,42	0,47
1	2	9,73	14,27	0,00	1,14	7,20	0,00	0,00	2,03	5,05	2,52	0,00	2,86

Table 9. Optimal daily production for case B

Process		CDU input (mix)		Reformer mode		Catalytic cracker mode		Isomerization	Desulphurization input			Jet fuel mode	
Period	# of days	Crude oil 1	Crude oil 2	REF 95	REF 100	Naphtha	Gas oil	Isom	Gas oil 1	Gas oil 2	Cracker gas oil	Jet fuel 1	Jet fuel 2
5	30	15,07	8,93	0,00	1,60	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
4	7	15,07	8,93	0,00	2,22	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
3	7	15,07	8,93	0,00	1,59	0,00	7,20	0,00	3,22	3,16	3,22	3,21	0,00
2	5	7,71	16,29	0,00	1,10	6,80	0,00	0,00	1,57	5,77	2,26	2,42	0,47
1	2	9,73	14,27	0,00	1,14	7,20	0,00	0,00	2,03	5,05	2,52	0,00	2,86

Table 10. Optimal daily production for case C

From Table 8 to Table 10 it can be seen that there are almost no differences between case A, B and C in the first, second and the fifth period. In the first and the second period there are almost no flexibility, since the lifting program and available crude oils are fixed during these periods in all three cases. In the fifth period there is also a lot of similarities between the cases, but this is due to the fact that inventory in the beginning of period 5 is basically zero, and no part of the lifting program and the crude oil purchase are fixed. Instead, there is a lot of flexibility and thus the processes converge towards the *long term optimal plan* and the figures for Period 5 in Table 8 and Table 10 is identical to *the long term optimal plan*Table 8. Optimal daily production for case A.

In Table 8 to Table 10 it can be seen that there is a significant shift in optimal crude oil consumption between the second and the third period. A reason for this is the fact that it is assumed that two ships with 180 kilotonnes each, will arrive in the first and the second period. In order to deal with the situation where it is a risk for overloaded crude oil 2 inventory, and where crude oil 1 cannot be delivered in period 1 a larger quantity of crude oil 2 must be consumed during the first and the second period.

The largest deviations from the *long term optimal plan* can be seen in Table 9 and it is affected by relatively large sales quantities of gas oil (GO) and gasoline (G95) in period 3 and 4 respectively. In order to be able to deliver these amounts the production plan must be changed compared to Table 8. To analyze the difference between the cases it is of interest to look at planned sales for period 3 and 4. The sales for case A and B are presented in Table 11 and Table 12 below.

Period	# of days	CO1	CO2	LG	HN	LN	G98	G95	JET	GO	HF
4	7	0,00	0,00	7,11	28,42	15,33	0,00	29,57	22,44	70,94	11,25
3	7	0,00	0,00	14,98	24,14	15,33	0,00	51,55	26,40	93,78	22,49

Table 11. Planned sales during period 3 and 4 for case A.

In Table 11 it can be seen that most sales figures are significantly higher in the third period than in the forth. The main reason for this is that it for the first time becomes possible to arrange new transports and sell all those components and products that are stored in inventory. Reduced inventories means reduced inventory holding costs so there is an incentive to reduce inventory as fast as possible. However, in case of heavy naphtha (HN) sales is lower in period 3 than in period 4, and the reason for this is that given inventory levels in the beginning of period 3 it is more profitable to increase HN to the reformer production and produce component R100, which in turn is used as a component in G95.

Period	# of days	CO1	CO2	LG	HN	LN	G98	G95	JET	GO	HF
4	7	0,00	0,00	5,87	21,37	11,50	0,00	70,00	22,00	70,44	12,69
3	7	0,00	0,00	16,95	27,23	17,25	0,00	22,18	18,94	100,00	19,89

Table 12. Planned sales during period 3 and 4 for case B.

In Table 12 there are two sales that are of particular interest. These are GO in period 3 and G95 in period 4, and to be able to deliver these the refinery must deviate from the *long term optimal plan*. From Table 12 it can be seen that 100 kilotonnes of GO is planned to be delivered in period 3, and one action that should be undertaken in order to do this in an optimal way is to reduce the planned sales of jet fuel (JET) in period 3. JET consists to a large extent of kerosene (KE), which also works as a diesel component, and under these circumstances, the KE is utilized in production of diesel. This can also be seen in Table 13 which shows the optimal diesel recipes for each period and it can be seen that KE is used as a diesel component in the third period. In the *long term optimal plan* KE is not an ingredient in diesel, but due to the quantity constraint here it has to bet. It is also of interest to note that since KE has rather high sulphur content the proportion of desulphurized gas oil 1 (DSG1) must be relatively high in the diesel recipe in order to meet sulphur quality specification of the final diesel product.

Period	# of days	KE	GO1	GO2	CGO	DSG1	DSG2	DSCG
5	30	0,00	0,08	0,00	0,00	0,31	0,30	0,30
4	7	0,00	0,07	0,00	0,00	0,28	0,36	0,29
3	7	0,09	0,06	0,00	0,00	0,36	0,19	0,29
2	5	0,00	0,05	0,00	0,00	0,16	0,57	0,22
1	2	0,00	0,06	0,00	0,00	0,20	0,50	0,24

Table 13. Optimal diesel recipes for case B. (Share of final product weight)

Regarding the 70 kilotonnes of G95 which is planned to be delivered in period 4 the production plan will also deviate from the *long term optimal plan*. As can be seen in Table 9 the activity in the reformer and isomerization processes are relatively high and the cracker will partly be run in a naphtha mode. Considering the inventory at the end of period 3, see Table 14, it can be seen that it is also optimal to build some inventory of gasoline components isomerate (IS), R100 and catalytic naphtha (CN) in order to deal with the demand in period 4.

Period	# of days	CO1	CO2	VG	HN	JP	GO	HF	LG	LN	IS	R95	R100	CN
4	7	2,18	233,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3	7	6,74	307,26	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,94	0,00	9,85	19,06

Table 14. Inventory from period 3 and 4 for case B.

Table 15 below shows the optimal recipes for G95 for case B, throughout the whole planning period. As can be seen the optimal recipes for G95 differs between the periods and in case of period 4 the biggest difference is that the relative proportion of IS is high whereas the relative proportion of CN is lower than usual.

Period	# of days	C4	LN	IS	R95	R100	CN
5	30	0,04	0,00	0,01	0,00	0,30	0,65
4	7	0,04	0,00	0,08	0,00	0,32	0,56
3	7	0,04	0,00	0,01	0,02	0,29	0,64
2	5	0,04	0,00	0,00	0,07	0,28	0,62
1	2	0,04	0,00	0,00	0,07	0,28	0,62

Table 15. Optimal recipes for G95 for case B. (Share of final product weight)

As can be seen in Table 8 and Table 10 there are only small differences in how the refinery processes should be run between case A and case C. However, between Table 9 and Table 10 there are large difference in the optimal process plan and the only fundamental difference between case B and C is that in case B the refinery is not allowed to buy product at the market to fulfill delivery promises. In case C where there are no restrictions in import quantities in period 3 to 5 it is optimal to buy some G95 and GO from the market, which can be seen in Table 16.

		Case A			Case B			Case C				
Period	# of days	CO1	CO2	VGO	CO1	CO2	VGO	CO1	CO2	VGO	G95	GO
5	30	452,18	42,80	98,87	450,00	90,00	98,87	450,00	90,00	98,87	0,00	0,00
4	7	105,51	0,00	23,07	90,00	0,00	21,01	90,00	0,00	23,07	11,06	0,00
3	7	63,51	0,00	20,20	90,00	0,00	23,92	90,00	0,00	20,20	0,00	6,22
2	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1	2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 16. Import decision for case A-C.

Table 16 also presents the optimal purchasing decisions for crude oil, i.e. CO1 and CO2, and vacuum gas oil (VGO), all used as feedstock. From the setting of the cases it is given that for case B and C crude oil quantities must be in multiples of 90 kilotonnes. Note that in this situation the differences are rather small between the case A, where there is no restrictions in purchasing quantities, and case B and C where crude oil has to be bought in multiples of 90. It is also worth to remember that in these cases the crude oil quantities are affected by crude oil inventories and already purchased quantities of crude oil. In Table 17, the crude oil inventories at the end of each period are presented. As can be observed there are no differences in the first and the second period and the inventory for CO2 is full at the end of period 2, since two 180 kilotonnes tankers will arrive during the first and the second period.

		Case A		Case B		Case C	
Period	# of days	CO1	CO2	CO1	CO2	CO1	CO2
5	30	0,00	0,00	0,00	56,00	8,80	47,20
4	7	0,00	225,02	2,18	233,82	10,98	225,02
3	7	0,00	287,51	6,74	307,26	26,49	287,51
2	5	42,00	350,00	42,00	350,00	42,00	350,00
1	2	80,53	251,47	80,53	251,47	80,53	251,47

Table 17. Crude oil and inventories for case A to C. All figures are in kilotonnes.

5.4 Interruption in VGO supply

As can be seen in Table 16 significant amounts of VGO should be imported in order to achieve optimal process utilization. As with any other components or products it might occur that the supply of VGO is limited during shorter or longer periods. Assume now that the refinery faces a situation identical to case C but without the opportunity to import VGO. What are the results of not being able to import VGO?

In Table 18 below the optimal average daily production plan is presented for each period when VGO cannot be imported. It can be seen that the production plan in period 3-5 is different compared to the same periods when it was possible to import VGO (see Table 10). One difference is that the cracker is not used to its full capacity. The cracker uses VGO as feedstock and when the option to import VGO is gone it is totally dependent on VGO that comes from the distillation unit and in this case it is not enough. It can also be seen that catalytic cracker switches mode from gas oil (GO) mode to naphtha (NA) mode, and that crude oil 2 (CO2) is the most preferred crude oil in all periods. Here it is worth to note that the VGO content in CO2 is much higher than in CO1, see also Appendix B – Parameter values, abbreviations and explanation, for CDU yields.

Process		**CDU input (mix)**		**Reformer mode**		**Catalytic cracker mode**		**Isomerization**	**Desulphurization input**			**Jet fuel mode**	
Period	# of days	Crude oil 1	Crude oil 2	REF 95	REF 100	Naphtha	Gas oil	Isom	Gas oil 1	Gas oil 2	Cracker gas oil	Jet fuel 1	Jet fuel 2
5	30	3,78	20,22	0,00	1,54	6,03	0,00	0,00	0,70	7,16	1,75	2,75	0,00
4	7	3,78	20,22	0,00	2,62	6,03	0,00	0,00	0,70	7,16	1,75	2,75	0,00
3	7	4,85	19,15	0,00	1,13	6,24	0,00	0,00	0,93	6,78	1,89	2,79	0,00
2	5	7,71	16,29	0,00	1,10	6,80	0,00	0,00	1,57	5,77	2,26	2,42	0,47
1	2	9,73	14,27	0,00	1,14	7,20	0,00	0,00	2,03	5,05	2,52	0,00	2,86

Table 18. Optimal daily production when VGO cannot be imported.

Table 19 presents the optimal purchasing decisions when VGO cannot be imported and this table should be considered at the same time as sales in Table 20. From earlier it is given that the activities during the first and the second period are frozen. During the third and the fourth period there is some flexibility but there are some minimum quantities that must be delivered.

Period	# of days	CO1	CO2	LG	HN	VG	LN	G98	G95	JET	GO	HF
5	30	90,00	540,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	7	90,00	0,00	0,00	14,38	0,00	4,72	0,00	12,35	0,00	0,00	0,00
3	7	0,00	0,00	0,00	2,63	0,00	3,91	0,00	0,00	0,00	9,47	0,00
2	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1	2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 19. Purchasing decisions in each period when VGO cannot be imported.

Table 20 presents the sales when VGO cannot be imported and it is of interest to note that planned sales quantities for LN and HN is identical to the lower bounds for period 1-4, given by the settings for case C. Table 19 also reveals that it is optimal to buy LN and HN from the market in period 3 and 4 to fulfill promised deliveries. In Table 19 one can also see that some quantities of GO in period 3, and G95 in period 4 should be bought from the market.

Period	# of days	CO1	CO2	LG	HN	LN	G98	G95	JET	GO	HF
5	30	0,00	0,00	18,40	62,46	29,05	0,00	121,47	82,51	288,63	92,81
4	7	0,00	0,00	5,33	21,37	11,50	0,00	70,00	19,25	67,35	21,66
3	7	0,00	0,00	11,48	21,37	11,50	0,00	22,18	23,51	100,00	31,91
2	5	0,00	0,00	5,07	20,35	10,95	0,00	21,12	16,03	50,67	8,03
1	2	0,00	0,00	2,03	8,14	4,38	0,00	8,45	6,41	20,27	3,21

Table 20. Sales in each period when VGO cannot be imported.

For purpose of comparison an almost identical problem was analyzed, i.e. case C an no import of VGO, but where it in addition was not possible to import anything but crude oils and heavy naphtha (HN) from the market. Under these circumstances it was not possible to find a feasible solution to the resulting optimization problem, and this also implies that delivery promises could not be met when the refinery could not buy products and components from the market.

6 Conclusions and further research

This report considers refinery planning and especially the planning framework. Refinery supply chains are complex and planners needs decision support like optimization models in order to be able to find how purchasing activities, process planning and sales are carried out in an optimal way. In this report it is argued for an integrated planning approach to be used, instead of a hierarchical planning approach. Integrated planning has several advantages in refinery settings: i) it connects short term and medium term planning without the risk of ending up with infeasible plans, ii) it enables analysis of how decisions made today will affect future plans, iii) it is possible to have different levels of details in different time periods if a multi-period planning model is used Different level of details in combination with different length of time periods allow for increased aggregation and longer time period at the end of the whole planning horizon. This will reduce the size and complexity of the optimization model.

To illustrate the integrated planning approach a stylized refinery example is implemented in an optimization model, and three different cases are analyzed. It is shown that inventories, current lifting program, incoming crude oil tankers, limited flexibility and import possibilities affect decision making in different directions. Some observations from the cases are:

i) Component and product inventories affects profit negatively, in absence of uncertainty, and should be reduced. This will affect optimal product recipes, and when inventory holding costs are taken into account recipes may be different between periods. If the first periods are freezed, then an optimization will also tell in what period the components should be used.

ii) The lifting program and logistics reduce flexibility during the first two periods. A lot of the transports have already been chartered and there are small possibilities to change these in the short term, and this will also give that there are a lot of similarities between the different cases.

iii) Taking into account that crude oil tankers deliver oil in discrete sizes (Afra-max, VLCC size etc.) may have an effect on how the refinery should be run. In one case, case B, the crude oil mix and process modes differ from the case when the tanker size is not considered. In case C, which requires discrete sizes, as in B, but where products can be bought at the market, the optimal crude oil mix and process modes are almost the same as for case A where there are no discrete size requirements.

iv) An interruption in VGO supply, which is used as a feedstock, affects the optimal purchasing, process and sales plan to a large extent.

In this report a linear optimization model of a refinery has been used in order to perform the analysis. There is a constant development of refinery models and a possible subject for further research is to do the same analysis using a more advanced model. Such a model could for example allow for non-linearity, more crude oil types, and more component inventories. Another interesting extension is to take uncertainty into account, both to do a simulation based analysis and to perform robust optimization. It is of interest to study both uncertainty in arrival times of tankers and price uncertainty, where the first has implications to short term planning and scheduling, and the latter have implications to revenues and costs.

Except from the pure modelling aspects there is also several issues connected to the planning process that are of interest to analyze further. An interesting issue is what the optimal length of the operational planning horizon is? Another important issue is what is the optimal frequency of replanning? Should planning be carried out on a predetermined regular basis, or should refineries replan when some certain event triggers it? In such a case, what triggers to use?

This report has not considered long term, or strategic, planning but it is of interest to perform analysis on refinery supply chain networks from a strategic point of view. In a refinery setting this includes to analyze refinery locations and capacities, inventory locations and sizes, long term supply, market strategies and logistical network.

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7 Appendix A – Model formulation

Sets

O_i	: Set of crude oils, index *i.*
F	: Set of outputs from CDU or processes, index *f.*
C	: Set of components, index *j*
C_j^{in}	: Input to components *j*, index *f.*
P	: Set of processes that generate output, index *p.*
Q	: Set of processes that receive input, index q.
K	: Set of products, index *k.*
S	: Set of outputs from all splits.
S_i	: Set of outputs from splits of oil or output *i*, index *s*.
M	: Set of specifications (qualities), index *m.*
T	: Set of time periods, index *t.*

Parameters data

Crude oil:

$\overline{S}_{it}, \underline{S}_{it}$	: Max and min supply of oil *i* during time period *t.*
S_{0i}	: Initial storage of oil *i.*
$S_{Max,i}$, $S_{Min,i}$	: Max and min storage of oil *i.*
$c_{it}^{O,imp}$	: Import (buy) price of oil *i* in time period *t.*
$c_{it}^{O,exp}$	: Export (sell) price of oil *i* in time period *t*
$c_i^{O,stor}$	: Storage cost of oil *i.*

CDU:

F_{if}^{frac}	: Fraction of output *f* given input *i* in CDU.
$\overline{C}_t^{cdu}$, $\underline{C}_t^{cdu}$	: Max and min volume (mass) generated in CDU in time period *t.*
c_t^{cdu}	: CDU operating cost in time period *t.*
$\overline{D}_{it}^{oil,cdu}$, $\underline{D}_{it}^{oil,cdu}$	: Min and max amount of crude oil *i*, consumed in CDU in time period *t.*

Processes:

c_{pt}^{proc}	: Process operating cost at process *p* in time period *t.*
$\overline{D}_{pt}^{proc}$, $\underline{D}_{pt}^{proc}$	: Lower and upper process capacity in process *p* in time period *t.*

Components:

C_{0j}	: Initial storage of component *j.*
$C_{Max,i}$	: Max storage of component *j.*

$c_j^{C,\,stor}$: Storage cost of component *j*.

Products:

$c_{k,0}^{K,}$: Initial storage of product *k*.

$\overline{D}_{kmt}^{M,prod}$, $\underline{D}_{kmt}^{M,prod}$: Max and min quality requirement of product *k* for quality *m* in time period *t*.

$\overline{D}_{kt}$, $\underline{D}_{kt}$: Max and min demand of product *k* in time period *t*.

$c_{kt}^{K,\,imp}$: Import product price of product *k* in time period *t*. (CIF)

$c_{kt}^{K,\,exp}$: Export product price of product *k* in time period *t*. (FOB)

$c_{kt}^{K,\,stor}$: Storage cost of product *k* in time period *t*

Variables

Crude oil

$x_{it}^{oil,imp}$: Amount of crude oil *i* imported (bought) in time period *t*.

$x_{it}^{oil,exp}$: Amount of crude oil *i* exported (sold) in time period *t*.

$x_{it}^{oil,cdu}$: Amount of crude oil *i* to CDU in time period *t*.

$x_{ipt}^{oil,proc}$: Amount of oil *i* to process *p* in time period *t*.

$x_{ijt}^{oil,comp}$: Amount of oil *i* to component *j* in time period *t*.

$v_{it}^{oil,\,stor}$: End storage of crude oil in *i* in time period *t*.

CDUs and processes

y_{ft}^{cdu} : Amount generated in CDU of output *f* in time period *t*.

z_{fpqt}^{in} : Amount of output *f* from process *p* to process *q* in time period *t*.

z_{fpt}^{out} : Amount from process *p* of output *f* in time period *t*.

z_{fqt}^{imp} : Amount of import of output *f* feeding process *q* in time period *t*.

z_{pjt}^{comp} : Amount of component *j* that comes from process *p* to the designated inventory (for component *j*) in time period *t*.

Components and products

z_{jkt}^{blend} : Amount blended from component *j* to product *k* in time period *t*.

$v_{kt}^{prod,imp}$: Amount of imported product *k* in time period *t*.

$v_{kt}^{prod,exp}$: Amount of exported (sold) product *k* in time period *t*.

$v_{jt}^{comp,stor}$: End storage of component *j* in time period *t*.

$v_{kt}^{prod,stor}$: End storage of product *k* in time period *t*.

$u_{kmt}^{M,comp}$: Quality concentration in product *k* and quality *m* in time period *t*.

Objective function

$\max z = z_1 - z_2$

$$z_1 = \sum_{k\in K}\sum_{t\in T} c_{kt}^{K,exp} v_{kt}^{prod,exp} + \sum_{i\in O}\sum_{t\in T} c_{it}^{O,exp} x_{it}^{oil,exp}$$

$$z_2 = \sum_{k\in K}\sum_{t\in T} c_{kt}^{K,imp} v_{kt}^{prod,imp} + \sum_{i\in O}\sum_{t\in T} c_{it}^{O,imp} x_{it}^{oil,imp} + \sum_{t\in T}\left(c_{it}^{cdu} * \sum_{i\in O} x_{it}^{oil,cdu} \right) + \sum_{t\in T}\sum_{p\in P} c_{pt}^{proc} z_{pt}^{in}$$

$$+\sum_{i\in O}\sum_{t\in T} c_i^{O,stor} v_{it}^{oil,stor} + \sum_{j\in C}\sum_{t\in T} c_j^{C,stor} v_{jt}^{com,stor} + \sum_{k\in K}\sum_{t\in T} c_k^{C,stor} v_{kt}^{prod,stor}$$

Constraints

Crude oil and CDU

$$y_{ft}^{cdu} - \sum_{i\in O} F_{if}^{frac} x_{it}^{oil,cdu} = 0, \quad \forall f,t$$
Amount of component f from CDU

$$v_{it}^{oil,stor} - x_{it}^{oil,imp} + x_{it}^{oil,exp} + x_{it}^{oil,cdu} - v_{i,t-1}^{oil,stor} = 0, \quad \forall i,t$$
Crude oil inventory

$$v_{i,0}^{oil,stor} - S0_i = 0, \quad \forall i$$

Process

$$z_{fpt}^{out} + z_{fqt}^{imp} - \sum_{q\in Q} z_{fpqt}^{in} - \sum_{q=j} z_{pjt}^{comp} = 0, \quad \forall f,p,t$$
Flowbalance

$$h_{fqt}^{split} \times \sum_{p\in P} z_{fpqt}^{in} - \sum_{f\in F} z_{fqt}^{out} = 0, \quad \forall q,t$$
Balance in splitter-processes

$$\sum_{f\in F}\sum_{p\in P} z_{fpqt}^{in} - z_{f'qt}^{out} = 0, \quad \forall q,t$$
Balance in blending processes

Components

$$v_{j,0}^{comp,stor} - C0_j = 0, \quad \forall j$$

$$v_{jt}^{comp,stor} - v_{jt}^{comp,imp} + v_{jt}^{comp,exp} + \sum_{p} z_{pjt}^{comp} - v_{j,t-1}^{comp,stor} = 0, \quad \forall j,t$$
Component inventory

Products

$$v_{k,0}^{prod,stor} - c_{k,0}^{K,} = 0, \quad \forall k$$

$$v_{kt}^{prod,stor} - v_{kt}^{prod,imp} + v_{kt}^{prod,exp} + \sum_{j\in C} z_{jkt}^{blend} - v_{k,t-1}^{prod,stor} = 0 ,$$ $\forall\ k,t$
Product inventory

Crude oils

$$\underline{S}_{it} \le x_{it}^{oil,cdu} \le \overline{S}_{it}$$ $\forall\ i,t$
Lower and upper limit of consumption of crude oil i

$$S_{Min,i} \le v_{it}^{oil,stor} \le S_{Max,i}$$ $\forall\ i,t$
Lower and upper limit on crude oil i storage

CDU

$$\underline{C}_t^{cdu} \le \sum_{f\in delmengd} y_{ft}^{cdu} \le \overline{C}_t^{cdu}$$ $\forall\ t$
Lower and upper limit of CDU capacity utilization

$$\underline{D}_{it}^{oil,cdu} \le x_{it}^{oil,cdu} \le \overline{D}_{it}^{oil,cdu}$$ $\forall\ i,t$
Lower and upper limit on amount of crude oil i into CDU

Process

$$\underline{D}_{pt}^{out,proc} \le \sum_{f\in delmengd} z_{pft}^{out} \le \overline{D}_{pt}^{out,proc}$$ $\forall\ p,t$
Lower and upper limit of process p capacity utilization

$$\underline{D}_{pft}^{out,proc} \le z_{pft}^{out} \le \overline{D}_{pft}^{out,proc}$$ $\forall\ i,t$
Lower and upper limit on amount of output f from process p

Components

$$\underline{D}_{jt}^{comp,stor} \le v_{jt}^{comp,stor} \le \overline{D}_{jt}^{comp,stor}$$ $\forall\ j,t$
Lower and upper limit stored amount of component j

Products

$$\underline{D}_{jkt}^{blend} \le z_{jkt}^{blend} \le \overline{D}_{jkt}^{blend}$$ $\forall\ j,k,t$
Lower and upper limit of component j in product k

$$\underline{D}_{kt}^{prod} \le v_{kt}^{prod,exp} \le \overline{D}_{kt}^{prod}$$ $\forall\ k,t$
Lower and upper limit of demand for product k

8 Appendix B – Parameter values, abbreviations and explanation

Abbreviations
RG – Refiney gas
LPG – Liquified petroleum gas (propane or butane or a mix of these)
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
HFO – Heavy fuel oil
DSGO1 – Desulphurizes gas oil 1.

Prices

	FOB prices $/tonne (export from refinery	CIF prices $/tonne (import to refinery)
Crude oil 1 (CO1)	845	835
Crude oil 2 (CO2)	749	740
Heavy naphtha	894	909
Light naphtha	894	909
LPG	795	820
Gasoline 98	962	977
Gasoline 95	944	959
Jet fuel	1139	1151
Gas oil	1057	1077
Heavy fuel	444	460
Vacuum gas oil		732

Inventory holding cost: 1 $/tonne/period

Process yields:

Process: CDU	Max capacity : 1000 tonne/h	
	Input	
Yield in weight %	Crude oil 1	Crude oil 2
Refinery gas	0,1	0,2
LPG	4,01	0,56
Light naphtha	13,89	2,87
Heavy naphtha	31,82	13,3
Kerosene	12,63	9,2
Gas oil	26,83	35,4
Vacuum gas oil	9,26	28,1
Vacuum residue	1,46	10,37

Process: Reformer	Max capacity: 200 tonne/h	
	Input: Heavy naphtha	
Yield in weight %	Mode 1: Reformer 95	Mode 2: Reformer 100
Refinery gas	8	9
LPG	9	12
Reformer 95	83	
Reformer 100		79

Process: Cracker	Max capacity: 300 tonne/h	
	Input: Vacuum gas oil	
Yield in weight %	Mode 1: Naphtha	Mode 2: Gas oil
Refinery gas	1,5	1,2
LPG	5,3	4,6
Cracker naphtha	43,6	38,1
Cracker gas oil	44,6	51,1

Process: Isomerisation	
Yield in weight %	Input: Light naphtha
Refinery gas	3
Isomerate	97

Process: Desulphurization	Max capacity 400 tonne/hour		
	Input:		
Yield in weight %	Gas oil 1	Gas oil 2	Cracker gas oil
Refinery gas	2	3	4
Desulphurized gas oil	98	97	96

Capacity constraints inventories

Product/ component	**Max inventory (kilotonnes)**
CO1	350
CO2	350
C4	40
LN	20
IS	10
R95	10
R100	20
CN	45
JET	25
GO	100
HN	20
VGO	30
HF	20