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Short-term Scheduling for Refinery Process: Bridging the Gap between Theory and Applications

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Abstract- **It is a great challenge to find efficient tools for short-term scheduling of oil refinery processes. Although some, theoretical advancement has been made in this field, a gap between theory and applications exists. In practice, the short-term scheduling job of oil refinery processes is still done manually by planners, because of the lack of such tools. This paper briefly introduces the production processes in a general oil refinery. Then, a short-term scheduling problem for such processes and requirements are presented. A brief review of the theoretic research advancement in this field is made. It shows that although progress in research in this field has been made, the techniques obtained are not applicable in the practice. Thus, the future research trends in this field should focus on methods that can bridges the gap between theory and applications. Based on the review, it is pointed out that it may be helpful if the problem is studied in a viewpoint of control theory and hence, solved by combining enumeration and heuristic instead of using mathematical programming formulations.**

***Index Terms*—Refinery process, Short-term scheduling, Process industry**

1. INTRODUCTION

In recent years, the technology for process industry has attracted more and more research interest. Oil refinery is one type of such processes. There are three levels in operating a plant of refinery: production planning, production scheduling, and process control. When the plant is well operated it may increase profit by $10 per ton of product or more [34]. Thus, attention has been paid to the development of effective techniques for the operation of refinery. Up to now, at the process control level, advanced control systems have been installed for unit control to optimize production objectives in most oil refineries. The implementation of advanced control systems has allowed significant productivity gains in the plant units. However, the optimization of the production units does not achieve the global economic optimization of the plant. Usually the objectives of the individual units are conflicting and thus lead to a suboptimal and often infeasible overall operation.

At the planning level, the potential benefits of optimization for process operations in oil refineries have long been observed, and linear programming has been applied in crude oil blending and product pooling [52]. Oil refineries are increasingly concerned with improving the planning of their operations. Faced with global market competition, companies should assess the potential impact of dynamical changes such as demands for final product specifications, prices, and crude oil compositions [29]. For this purpose, Coxhead [9] identifies several applications of planning models in the refining and oil industry, including crude selection, crude allocation for multi-refinery situations, and operations planning. With the availability of LP-based commercial software for refinery production planning, such as PIMS [Process Industry Modeling System - 3], general production plans of the whole refinery can be found. As pointed out by Pelham and Pharris [38], the planning technology can be considered well developed and its drastic progress should not be expected. Additional advances in this area may be based on model refinement through the use of nonlinear programming.

Short-term scheduling is at the middle level. As pointed by Shobrys and White [49], to effectively operate a process plant, the three levels should work together. In fact, the need for integration has been a frequent topic since the 1960s [2, 4, 21, 33]. Thus, with the will-development of techniques for planning and process control, it is crucial to develop effective techniques for short-term scheduling.

There are mainly two types of industries: discrete manufacturing industry and process industry. It is believed that scheduling discrete manufacturing operations is well-established [1]. There is a large body of literature on this field. Because of the NP complexity in nature for the general scheduling problem, usually heuristics and search algorithms, such as simulated annealing algorithms, genetic algorithms, and tabu algorithms, are applied [6, 10, 30, 44, 47, 56].

Process industry can be further divided into two categories: batch process and continuous process. In batch process industry, the materials are processed in batches. These discrete batches can be thought of as jobs as in the discrete manufacturing systems. Nevertheless, the materials are transferred between devices continuously as fluid, and hence, they are characterized as continuous variables. Great effort has been made in scheduling of batch process by using rule-based algorithms [26, 50], search algorithms [25, 36], and mixed integer programming [19, 24, 31-32, 37, 41, 45]. When mathematical models are used as in [19, 24, 31-32, 37, 41, 45], often state task network [24] or resource task network [37] is used to describe the configuration of the processes for the formulation of a mixed integer programming. However, it lacks effective techniques and software tools for continuous process industry to which the oil refinery industry belongs. This paper introduces the short-term

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scheduling problem for refinery processes, presents the current situation, and discusses the possible future trends of research.

In the next section we describe the oil refinery processes in fair details. Based on the description of the processes, short-term schedule is defined and the requirements are provided in Section 3. Section 4 briefly reviews the advancement made in the literature and points out the gap between theory and applications. A discussion is made in Section 5 and we point out the possible research trends in this field. Section 6 presents the conclusions.

2. THE REFINERY PROCESS

Roughly, a refinery process can be divided into three parts: crude oil operations, production, and product blending as shown in Fig. 2.1, where CO_i, PC_i, and P_i denote crude oil type i, product component i, and product i, respectively. In crude oil operations, a variety of crude oil is handled so that they can be fed into production devices for refining. In the production process, crude oil is decompounded into different product components. The components then are blended into numerous products. Because blending can be done at the planning level, we present the processes for crude oil operations and production in detail below.

2.1 Crude Oil Operations

The subprocess of crude oil operations of a general refinery is shown in Fig. 2.2. Crude oil is carried to a port near the plant by crude oil tankers, where crude oil is unloaded into storage tanks by the port. The crude oil in the storage tanks is then transported to charging tanks in the refinery plant through a pipeline. From the charging tanks, oil is fed into distillers for distillation.

In a refinery, various types of crude oil are processed. The components of different types of crude oil are different. In crude oil unloading, crude oil can only be unloaded into an empty tank unless the same type of crude oil is in the tank. After the end of filling a tank, the crude oil must be stored in the tank for a certain amount of time to separate the brine, and can then be transported to the refinery plant. We call this requirement residency time (RT) constraint.

When crude oil is transferred through the pipeline to the charging tanks in the plant, some different types of crude oil may be mixed to obtain suitable components for distillation. A mixture of crude oil from two or more types of crude oil can be seen as another type of crude oil. Usually, pipeline takes tens of kilometers long with capacity of tens of thousand cubic meters, and the pipeline is full of crude oil all the time and cannot be completely emptied. The crude oil in the pipeline should be taken as inventory and cannot be neglected. The crude oil in the pipeline may be divided into a number of segments with each segment containing different type of crude oil (mixed or not). Although crude oil can stay in the pipeline and be kept motionless, the crude oil in the pipeline must be kept flowing if there are some types of crude oil with high fusion point in it. Otherwise such oil may become solid and thus block the pipeline. This must be avoided in practice.

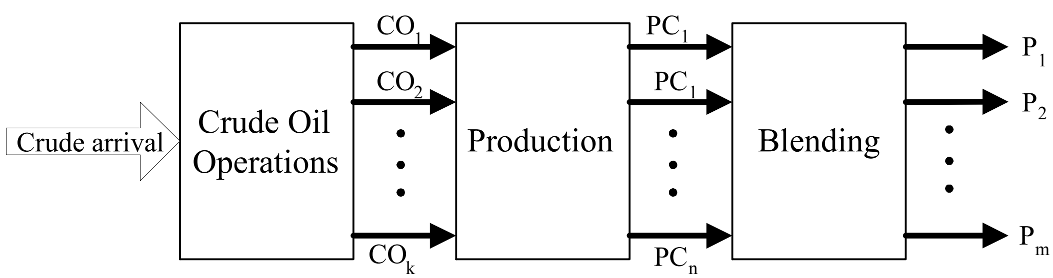

Fig. 2.1. The three subprocesses of refinery process.

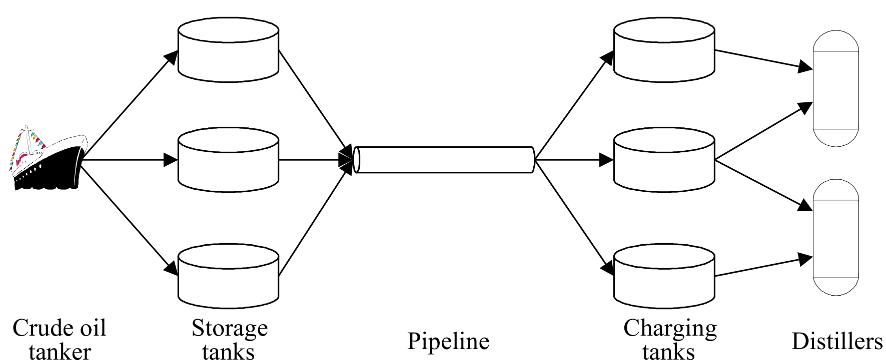

Fig. 2.2. Process of crude oil operations.

When crude oil in the pipeline fills into charging tanks in the plant, each charging tank can hold one type of crude oil at a time. After filling, the crude oil must stay in the charging tank for some amount of time before it can be charged into distillers. In other words, RT constraints apply to charging tanks as well. Although the pipeline can receive oil from multiple tanks simultaneously for crude oil mixing according to a prescribed process planning, it usually feeds to one charging tank at a time. There is also operational requirement constraint for both storage and charging tanks that a tank cannot receive and send oil at the same time. Crude oil can also be mixed when it is charged into distillers, i.e., a distiller can be charged by more than one tank.

Some operational requirement is imposed in feeding crude oil into distillers. When a tank is feeding a distiller, it needs to switch to another tank to feed the distiller when the oil in the tank is used up. However, in practice, the successor tank should be in duty before the oil in the predecessor tank is used up. This process can be described as follows. Assume that tank #1 is just feeding distiller #1 and the oil in tank #1 for distiller #1 can last to time t, and the successor of tank #1 to feed distiller #1 is tank #2, then at time $t_1 < t$ tank #2 must start to feed distiller #1 so that during a time interval $[t_1, t]$ tanks #1 and #2 feed distiller #1 simultaneously until the oil in tank #1 for distiller #1 is used up. We call this process distiller feeding switching (DFS). Often, this time interval between t_1 and t lasts for several hours.

2.2 Production Process

The production process of a refinery is very complex and a sketch of the material flow is shown in Fig. 2.3. In this process, there are various devices including distillers, catalytic crackers, hydrocrackers, devices for reforming, and devices for hytrotreating.

A distiller transforms crude oil into gases, naphtha, gasoline, distillates, and bitumen. Different types of crude oil have different rates for some key components, such as sulfur, paraffin, and asphalt. This leads to different physical and/or chemical properties such as flash point, fusion point, density and/or viscosity, and causticity. Thus, a distiller is suitable for processing only some types of crude oil and often there are a number of distillers so that different types of crude oil can be processed. The output products of a distiller from one type of crude oil have different rates of components. For example, the distillates from crude oil with high rate of paraffin are much different from the ones that from crude oil with low rate of paraffin. Hence, the output products of distillation from different types of crude oil may be required to be stored in different tanks.

By distillation of one type of crude oil, different types of distillates can be obtained, and also distillates obtained from different crude oil are different. Hence, there are a large number of types of distillates. Some types of distillates can be used as raw materials for lube oil making, but others are not. A type of distillate can be mixed with bitumen obtained from some type of crude oil for catalytic cracking that transforms distillates or mixture of distillate and bitumen to middle products. After hydrotreating, these products are transformed into different components for gasoline. A catalytic cracker can process a number of types of distillates or mixture obtained from some distillate and bitumen. Often there are a number of catalytic crackers, so that all types of distillates can be covered. In production, a catalytic cracker can process one type of distillate or mixture, and changeover is required from one type to another. Some types of distillates need to be processed by hydrocracker that transforms distillates mainly into gases, naphtha, and gasoline. Also, switches are made from one type to another so that different types

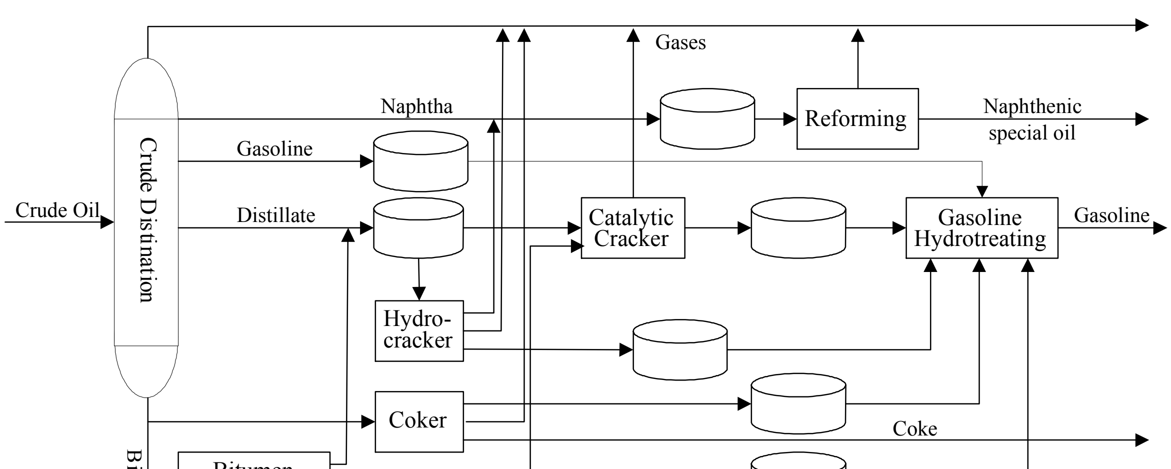

Fig. 2.3 Schematic material flow for production process of a refinery.

can be processed. Although a type of distillate cannot be processed on all the crackers, often one type of distillate can be processed by more than one device. Thus, in scheduling the system, decisions should be made to determine which type of distillate should be processed on which catalytic cracker, or hydrocracker, and when switch should be made.

Just like distillates, there are different types of naphtha obtained from different crude oil. While some types of naphtha can be used as raw material for plastic making, others are to be transformed into various types of naphthenic oil by reforming. Often there is more than one naphtha reforming device with each one able to process a number of types of naphtha. Similar to the production process of distillate processing, in scheduling the system, decision should be made to determine which type of naphtha should be processed on which device and when switch should be made.

Beside it can be used to mix with distillates for catalytic cracking, bitumen can go to different production processes depending on its type and market demands. Some types of bitumen can be further cracked through bitumen hydrocracking to produce more distillates and gasoline. Some of it goes to a coker so as to produce coke and some is used to produce asphalt.

It should be noticed that there are many choices in scheduling the system. Depending on the dynamic market demands for products and price, different choice results in different profit. Because of the large number of types of middle products, there are thousands of tanks for storing the products. It is very difficult to manage the dynamic inventory in scheduling such systems.

3. THE SHORT-TERM SCHEDULING PROBLEM

With the production processes of oil refinery given above, now we can present the short-term scheduling problem for the processes. Although short-term scheduling of crude oil operations is different from that of a production process, they must share some properties. Furthermore, the processes of crude oil operations form the main differences between oil refinery industry and other continuous process industry. Thus, here we present the short-term scheduling problem just based on crude oil operations.

3.1 The Scheduling Problem

The crude oil operation process is composed of a series of operations. The question is when an operation should take place, what should be done, and how it should be done. For each operation to take place, decisions should be made to answer these questions. To describe a short-term schedule, we first define an operation decision.

Definition 3.1: OD = (OT, V, S, D, INT = [a, b]) is defined as an operation decision, where OT = crude oil type; V = volume of crude oil to be delivered; S = the source from where the crude oil is to be delivered; D = the destination where the crude oil is to be delivered to; INT is a time interval, a is the start time point of the operation and b is the end time point.

Theoretically, the flow rate in delivering crude oil in the interval [a, b] can be variable. However, to ease the operations, in reality, the flow rate for a single operation is kept as a constant. Thus, given volume V and time interval [a, b] in an OD, the flow rate $f = V \div (b-a)$ is determined.

There are three types of ODs: unloading, transportation, and feeding, denoted by OD_{unload}, OD_{trans}, and OD_{feed}, respectively. For OD_{unload}, S is a tanker and D is a storage tank, for OD_{trans}, S is a storage tank, D is a charging tank, and the transportation must be implemented through a pipeline, for OD_{feed}, S is a charging tank and D is a distiller. Let $T = [t_1, t_2]$ be the schedule horizon. Often it lasts for a week or ten days. Given the system state, such as the inventory of crude oil and the production state of all the devices, and information of tanker arrival, the short-term scheduling problem is to find a series of ODs described as follows.

$$SCHD = \{OD_1, OD_2, \ldots, OD_n\} \quad (3.1)$$
$$\text{where } OD_i = (OT_i, V_i, S_i, D_i, INT_i = [a_i, b_i])$$

Subjected to

$$T \subseteq [a_1, b_1] \cup [a_2, b_2] \cup \ldots \cup [a_n, b_n] \quad (3.2)$$
$$(G_q)^{min} \le g_q \le (G_q)^{max}, \text{ for } \forall q \in Q \quad (3.3)$$
$$F^{min} \le f \le F^{max} \quad (3.4)$$
$$(H_k)^{min} \le h_k \le (H_k)^{max}, \text{ for } \forall k \in K \quad (3.5)$$
$$\nu_j(\tau) \le C_j, \text{ for } \forall j \in J \text{ and } \tau \in \Gamma \quad (3.6)$$
$$(x_{ji\tau})\times(y_{jd\tau}) = 0 \quad (3.7)$$
$$(z_{ji\tau})\times(z_{jw\tau}) = 0, \text{ for } i \neq w \quad (3.8)$$

In the above formulation, Q, K, and J denote the sets of tankers, distillers, and tanks including storage and charging tanks, respectively. $(G_q)^{min}$ and $(G_q)^{max}$ denote the minimal and maximal flow rate for tanker q, F^{min} and F^{max} the minimal and maximal flow rate for the pipeline, $(H_k)^{min}$ and $(H_k)^{max}$ the minimal and maximal feeding rate for distiller k. Variables g, f, and h denote flow rates for a tanker, pipeline, and distiller decided by OD_i, respectively. C_j denotes the capacity of tank j, and $\nu_j(\tau)$ is the volume in tank j at time τ. $x_{ji\tau} = 1$ if OD_i requires that tank j be charged at time τ, otherwise $X_{ji\tau} = 0$. Similarly, $y_{ji\tau} = 1$ if OD_i requires that tank j be discharged at time τ, otherwise $y_{ji\tau} = 0$. $z_{ji\tau} = 1$ if there is crude oil type i in tank j at time τ, otherwise $z_{ji\tau} = 0$. Constraint 3.2 requires that the schedule should cover the entire scheduling horizon. Constraints 3.3 through 3.5 enforce the flow rates to be in a given range. Capacity constraint is given by 3.6. Constraint 3.7

guarantees that when a tank is being charged it cannot be discharging at the same time, and Constraint 3.8 enforces that each tank can hold one type of crude oil.

3.2 Schedule Feasibility

When a discrete manufacturing system, such as a job shop, is to be scheduled, often any schedule that satisfies the operation precedence constraint is feasible. The difference between different schedules is their completion time. However, a schedule for oil refinery may not be feasible. To show this, consider the situation shown in Fig. 3.1. Assume that there are one distiller and two charging tanks with the same capacity, and initially at time t_1 tank #1 is full and tank #2 is empty. This system can be scheduled such that at time t_1 it starts to feed the distiller by tank #1 with feeding rate f and at the same time it starts to charge tank #2 through the pipeline with charging rate f that is equal to the feeding rate. At time t_2, tank #1 is emptied and tank #2 is full, and tank #2 is used to feed the distiller and it starts to charge tank #1 both with same rate f. It can be sure that at time $t_3 = t_2 + (t_2 - t_1)$ tank #2 will be emptied and tank #1 will be full. Thus, this process can be repeated until the end of the scheduling horizon if there is enough crude oil in the storage tanks. Surely, this forms a short-term schedule for this simple system.

It seems that such a schedule is feasible, but in fact it is not due to the RT constraint on tank #2. At t_2, when tank #1 is emptied and tank #2 is full, the crude oil in tank #2 cannot be fed into the distiller immediately, but certain delay time units is required. It implies that during the time interval $[t_2, t_2 + a]$ there is no crude oil to be fed into the distiller. This is not acceptable for oil refinery for a production device cannot be interrupted unless maintenance is necessary. This means that the schedule is infeasible. To make the schedule feasible requires one to change the initial condition: at t_1 tank #1 is full and tank #2 is empty.

There are several factors that affect schedule feasibility. These factors are:

1) *Multiple types of crude oil processed in the plant*. A distiller can process only limited types of crude oil, but not all types. Similarly, a type of crude oil can be processed by only some distillers. An earlier inappropriate crude oil type assignment to the distillers may cause a later lack of suitable crude oil types for some distillers, leading to an infeasible schedule.
2) *The RT and DFS constraints*. Because of these constraints and the limited number of charging tanks in a plant, the scheduling problem becomes very complicated. Often these constraints are not considered in scheduling the system in the literature, leading to an often infeasible solution.
3) *High fusion point crude oil transportation*. As pointed out in the last section, if a type of crude oil with high fusion point is fed into the pipeline, the oil in the pipeline should be kept in moving. However, if the system is not properly scheduled so that while there is crude oil with high fusion point in the pipeline there is no enough charging tank capacity to hold the oil that should come out from the pipeline, a forbidden state occurs. In other words, this is an infeasible schedule.

3.3 Schedule Optimization

Because of the ever intensive market competition, great attention has been paid to schedule optimization. The objectives include:

1) *Profit gain increase*. To increase profit, the objective is to schedule the system so that it can produce as much as possible.
2) *Cost reduction from inventory control*. Schedule the system so that the inventory is minimized and the tanks used are as few as possible.
3) *Cost reduction from distiller feeding switches*. Schedule the system so that the number of switches in feeding the distillers is minimized.
4) *Cost reduction from assigning appropriate crude oil types to appropriate distillers for distillation.* Although one type of crude oil can be processed in more than one distiller and one distiller can process more than one type of crude oil, some type of oil is more appropriate to be processed by some distiller than the others. Thus, different assignments create different cost.

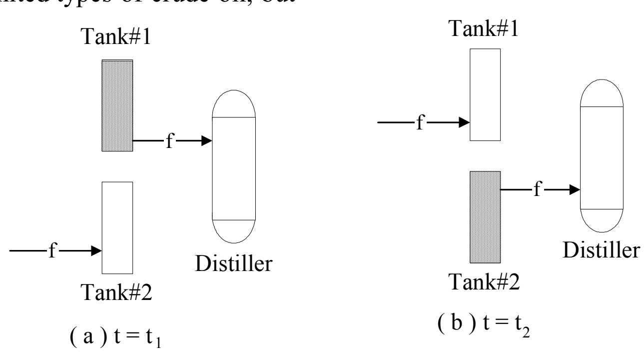

Fig. 3.1. The illustration of an infeasible schedule.

5) *Cost reduction from oil degradation*. When a tank is discharged it cannot be fully emptied. Instead there is some oil remaining called heal. Thus, if a tank is filled with one type of crude oil and after discharged another type of crude oil is charged into this tank, the heal is mixed with the newly filled oil, thereby leading to oil type degradation or cost increase. To reduce such cost, it is better to fill the same type of crude oil, or the type of crude oil with less difference in components. Oil degradation also exists when there is a switch from one type of crude oil to another in crude oil transportation through the pipeline. Thus, reducing the number of switches and the type difference between the two types of oil in each switch can reduce this kind of cost.

6) *Energy saving in crude oil transportation*. In crude oil operations, much energy is consumed by crude oil transportation. Furthermore, the cost is nonlinear function with respect to the transportation flow rate. For example, in an oil refinery, the pipeline can be driven by one, two, or three sets of pumps. The flow rate can vary between 10,000 tons and 33,000 tons per day with rate of 20,000 tons per day being the most economical one. Thus, it is meaningful to schedule the system to minimize the cost per unit of crude oil to transport.

   Another types of operations in crude oil transportation that consume much energy are the transportation of crude oil with high fusion point. To prevent the crude oil with high fusion point from solidifying in the pipeline, the entire pipeline should be heated to a certain temperature. Thus, it is meaningful in energy saving if the time to heat the pipeline is minimized.

7) *Crude oil unloading penalty reduction*. When a tanker arrives, it requires that the crude oil in the tanker be emptied in a given time and often such a time is very short. If it is done before the given time it does not charge for the crude oil unloading. However, failing to do so causes severe penalty. Physically, the maximal unloading flow rate is fast enough to guarantee that this can be done in time. The problem is how to schedule the system so that there will be enough storage tank spaces to hold the crude oil without having different types of crude oil mixed in such a short time because of the limit of tank capacity.

It should be noticed that the scheduling problem with each of the objectives above is a very complex optimization problem, and these objectives may conflict each other. Thus, It is a great challenge to optimize a short-term schedule.

3.4 Push and Pull Schedules

Like scheduling discrete manufacturing systems, a schedule of an oil refinery process can be push or pull. Often a push schedule is generated to maximize the production of a system based on its initial state and tanker arrival information. However, such a schedule may lead to high inventory and cannot meet varying market demands.

Because of the global market competition, companies are required to dynamically respond to market changes including final product demand and price changes. Thus, a short-term schedule should be generated based on dynamic product demand and price changes. By minimizing the inventory and maximizing the profit at the planning level, it can be found when, what and how much should be produced. In this way, a target schedule can be obtained. The problem is if such a target schedule can be realized and if so how it will be realized by a short-term schedule. Such a schedule is a pull schedule. In practice, short-term scheduling is often done manually in this way. A ten-day target schedule for crude oil distillation is illustrated in Figure 3.2 in a refinery company with three distillers.

3.5 Complexity

Consider the crude oil transportation problem. Assume that there are k transportation jobs (each corresponds to an OD) through the pipeline during the schedule horizon. The scheduling problem is to sequence the k jobs. Notice that different job may transport different type of crude oil. Thus, different job sequence results in different crude oil degradation, or the problem is sequence dependent. Then there are k! solutions, and it is an NP problem.

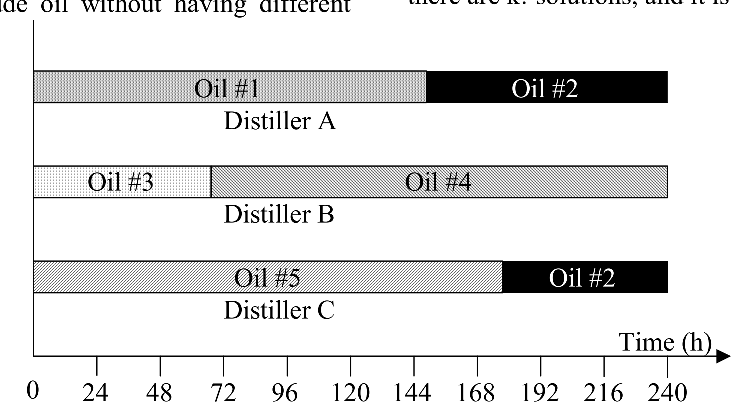

Fig. 3.2. The illustration of a target schedule in a company.

The crude oil from the pipeline for job i can be charged into one of n charging tanks. Because the capacity for different charging tank is different and the types of oil remaining for different charging tanks are different, different charging tank assignment results in different cost. This problem is similar to scheduling problem with parallel machines in discrete manufacturing systems, which is also an NP problem.

The processes of crude oil unloading from tankers and crude oil feeding to distillers are similar. Moreover, the processes of crude oil unloading, crude oil transportation, and crude oil feeding are coupled together, we need to determine the batch size for each OD, the sequences of the ODs, and the flow rate for each OD so that the oil unloading penalty and cost for energy consumption are minimized. It is certain that the problem is much more complicated than the one in scheduling discrete manufacturing systems.

4. CURRENT SITUATIONS

The scheduling literature presents very few formulations to schedule continuous multiproduct plants, as opposed to the large amount of work in batch plants [41, 45]. Because of the continuous nature of oil refinery processes, the key issue in short-term scheduling concerns the time representation. All the existing scheduling formulations can be classified into two categories: discrete-time and continuous-time models as shown in Fig. 4.1. In the discrete-time representation as shown in Fig. 4.1(a), the scheduling horizon is divided into a number of time intervals with uniform time durations. An event, such as the beginning and ending of an operation, should happen at the boundary of a time interval. As shown in Fig. 4.1(b), contrary to discrete-time representation, events are potentially allowed to take place at any time point in the continuous-time representation.

The work in [28, 38, 47] belongs to the discrete-time representation domain. Mixed integer linear programming (MILP) models with different objectives are developed in [28, 48] for the short-term scheduling problem of crude oil operations based on a configuration shown in Fig. 4.2. With this configuration, different types of crude oil are allowed to be transported concurrently from storage tanks to charging tanks. However, this is not possible if the configuration shown in Fig. 2.2 is considered. Furthermore, they ignore the RT and DFS constraints. Also, in this method, the objective is to minimize tank heals.

The main drawback with such models is that the uniform time interval must be small enough so as to obtain acceptable accuracy. This leads to a large number of binary variables and makes the problem very difficult to solve. As pointed out in [43] that if the horizon is 112 hours and time slot duration is 15 minutes, an MILP model with 21,504 binary variables will be generated for a problem with pipeline receiving three parcels of oil, six charging tanks, one distiller, and three types of crude oil.

By using discrete-time representation in [43] mixed integer programming (MIP) models with large number of discrete variables are proposed for scheduling of production and distribution, fuel oil/asphalt production, and liquefied petroleum gas production.

A case problem shown in Fig. 4.3 is considered in [39] and an MILP model is developed. Inventory detail for individual tanks and materials is not taken into account. By defining neighborhood, tabu search is used to solve the problem.

To reduce the number of discrete variables, a continuous-time representation is adopted by some researchers. Based on the formulations for batch and general continuous processes in [19-20], continuous time MIP models for oil refinery are proposed in [22-23]. In their works, a model for crude oil operations is developed and it also presents a model for lube-oil production. The configuration for crude oil operation is similar to that shown in Fig. 4.2 with RT and DFS constraints ignored. Although, with these models, the number of discrete variables is reduced significantly, there are nonlinear constraints in it, which makes the problem difficult to solve. Furthermore, these models are developed based on event points and it assumes that the number of events is known in advance. Unfortunately, this is not true in practice.

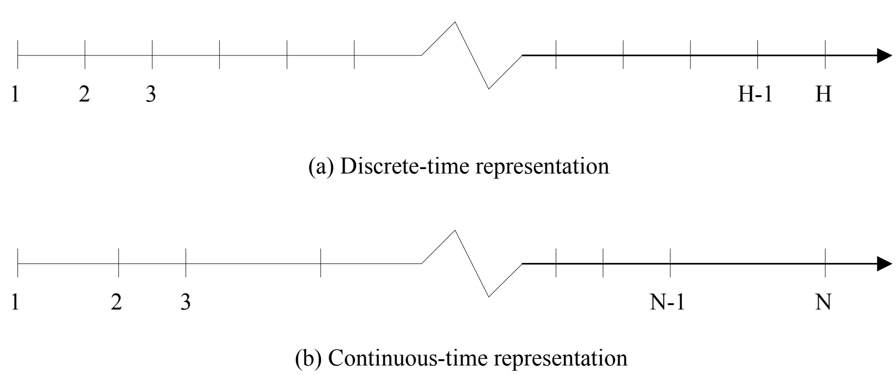

Fig. 4.1. Two representations of time (a) Discrete and (b) Continuous.

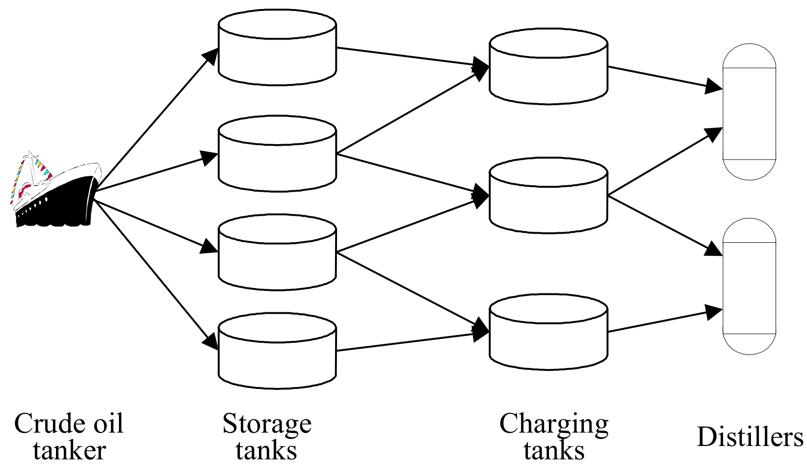

Fig. 4.2. A configuration of process for crude oil operations.

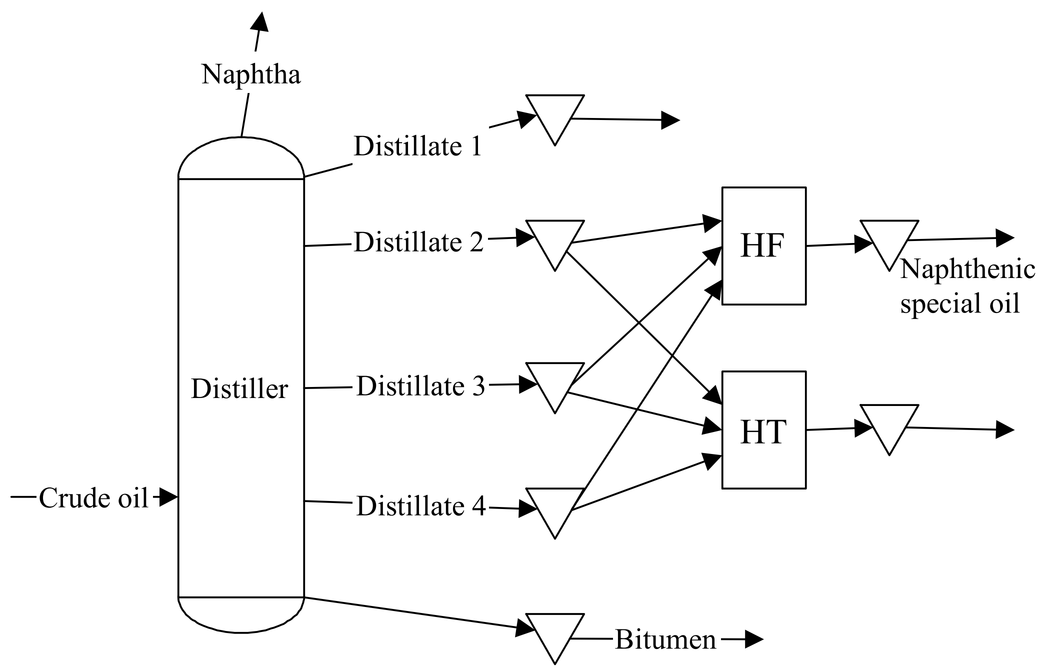

Fig. 4.3. The system configuration considered in [Persson et al. 2004].

To overcome the drawbacks of both discrete-time and continuous-time approaches, a MIP model for crude oil operation is proposed in [35, 43] by using so called variable-length time slots. The problem considered in fact is the downstream part of the problem handled in [48]. It assumes that the number of parcels to go through the pipeline, the volume of each parcel, and the starting and ending time of each parcel are known. Thus, it sets the starting and ending times for the crude parcels as fixed event points, and the other event points will be determined by the model just as a continuous-time approach does. The number of event points must be given to model the system. By this approach, the number of discrete variables is reduced from 21504 to 912 for the same problem mentioned above [43]. In this sense, it is a significant improvement. However, it is based on the assumption that the events scheduled for the pipeline and the number of events is known in advance. This is rare in reality and hence it can be applied to some special cases. Furthermore, the formulation contains nonlinear constraints, usually leading to a complex solution methodology.

In summary, while discrete-time formulations generate a large number of discrete variables, continuous-time models result in very complex models. Moreover, all the models ignore some critically important constraints or make some unrealistic assumptions. As a consequence, the obtained solution is operationally infeasible as pointed out in [18]. Also, only a limited number of the objectives discussed above are considered. All the considered objectives are modeled as linear functions only, which is usually not true in practice.

5. DISCUSSION

As discussed above, although there is a theoretically significant advancement in short-term scheduling for oil refinery, there is still a large gap between theory and applications, and there is lack of efficient tools for applications. In fact, the short-term scheduling job for oil refinery processes is still done by planners manually. Thus, significant research and development should be conducted to bridge such a gap.

It should be noticed that in all the approaches mathematical programming models are used to formulate the problems. Based on the models attempts are made to find optimal solution in an exact way. Due to the inherently combinatorial nature of the problem, this may not be reasonable. In the community of discrete manufacturing system scheduling, it is commonly recognized that it is unwise to model a practical scheduling problem by mathematical formulations and find an optimal solution in an exact way, instead people use dispatching rules, heuristics, genetic algorithms, etc. for a suboptimal solution. Thus, with this in mind, it may be helpful to study other ways for the short-term scheduling problem of oil refinery processes instead of using those proposed mathematical models.

5.1 Schedulability

First of all, feasibility is the essential requirement for a short-term schedule to be applicable. However, as discussed in the last section, to make the problem solvable in the problem formulation for an MIP model some operational requirements are ignored, which leads to an infeasible solution just as shown in Fig. 3.1. In fact, without changing the initial condition of the problem in Fig. 3.1, it would not be schedulable. By taking the RT into consideration, to guarantee that there is oil to feed to the distiller at t_2, it should stop to charge tank #2 before t_2. This implies that tank #2 cannot be full. However, there would be no crude oil to feed the distiller for certain time. In other words, from a viewpoint of control theory, the initial state shown in Fig. 3.1 is an unsafe state.

With MIP models, if all the detailed constraints are taken into account, the models would be too complex to solve. On the other hand, with all the constraints considered, the feasible solution space should become smaller. Thus, it may become easier to solve by heuristic search related methods. Notice that each OD in a short-term schedule given in (3.1) can be seen as a control action. With such action, the system is transferred from one state to another. From the viewpoint of control theory, to guarantee the correctness of a control action, the system should be transferred from a safe state to another after the action is taken. Therefore, schedulabilty analysis should be done to reveal the characteristics of the problem. With schedulabilty analysis, some hints may be obtained for a better solution, thereby making the problem easier to solve than the existing approaches. Thus, it may be helpful to study this problem from the control theoretic viewpoint. However, up to now there is no such research report.

5.2 System Modeling

In order to obtain a feasible schedule in discrete manufacturing systems where conflicts and deadlock exist, Petri nets are used to model the system so that the system remains in safe states [7, 27, 55]. In analog to the discrete manufacturing system scheduling, modeling techniques should be developed to model the oil refinery processes so as to do the schedubility analysis.

Process industry belongs to a type of hybrid systems. Suitable models are necessary to be developed. Two categories of process industry can be identified: continuous and batch processes. There is a large body of literature for the modeling of batch processes, such as those in [5, 13-14, 16-17, 53]. Hybrid Petri net models are also developed for continuous processes [8, 11-12, 15, 50]. However, as pointed out in [54], these hybrid PN models can describe continuous process well, but they cannot be directly applied to the crude oil refinery processes because of the special constraints and requirements discussed above. Thus, it is meaningful to develop hybrid models for analysis, simulation, and control suitable for oil refinery processes.

5.3 Scheduling for Just-In-time (JIT) Production

JIT scheduling is widely applied in discrete manufacturing systems, and as pointed out in Section 3 the oil refinery processes should be scheduled in the same way. Up to now, all existing approaches for short-term scheduling generate a push schedule. Thus, it is meaningful to make it clear what a JIT scheduling problem is for oil refinery. Like scheduling discrete manufacturing systems, it is a great challenge to search for approaches that can generate a JIT short-term schedule for oil refinery processes.

5.4 Enumeration + Heuristic for Optimization

As pointed out by Honkomp et al. [18], the devil is in the details in scheduling chemical processes. On one hand, a mathematical programming model with a reasonable size cannot describe every detail of the system, leading to infeasible solutions. On the other hand, with purely heuristic methods it is likely that opportunities will be lost by not searching more exhaustively for high quality solutions. Thus, it may be helpful to combine both enumeration and heuristic. Take the case of energy saving in crude oil transportation given in Section 3 as an example. Although transportation flow rate can be any number between 10,000 tons per day and 33,000 tons per day, it can be shown that the cost will be minimized if the flow rate is appropriately switched among 20,000, 30,000, and 33,000 tons per day. Based on this kind of rules, the search can be carried out to obtain a fairly satisfied solution by using some off-the-shelf search algorithms.

6. CONCLUSIONS

It is a great challenge to search for efficient tools for short-term scheduling of oil refinery processes that can be applied in the practice. Although, theoretically, significant advancement has been made in this field, a gap between theory and applications exists. In practice, the short-term scheduling job is manually done by planners because of the lack of such tools.

In scheduling oil refinery processes, feasibility is the essential requirement for a short-term schedule obtained. Up to now, in the literature, people use mathematical programming to model the processes and attempt to find an optimal solution in an exact way. Because a mathematical programming model with reasonable size cannot describe the very detail, often a solution obtained is not operationally feasible, so it is not applicable.

Based on this observation, we think that it may be helpful if the problem is studied in the viewpoint of control theory so that the system can always be kept in a safe state space. In this way, the feasibility requirement can be met. To do that, modeling techniques should be developed to do schedulability analysis. With feasibility requirement satisfied, the solution may be improved through enumeration plus heuristic methods. This represents the research trends in this field.

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