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Refinery Operations Optimization Research Based on Units Processing Characteristics

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Abstract

The operational stability and continuity are key production characteristics of actual refinery processing units, which plays important role to safe and efficient production. While few literatures have given a sufficient and comprehensive expression of such characteristics. In view of the problem, this paper discussed refinery operations optimization based on operational stability and continuity. The production characteristics were described by logic proposition though logic rules and expert experiences, and the optimization problem of refinery operations was formulated as a logic programming model with object of maximizing production profit. Finally, the proposed model was used to optimize operations of a actual refinery. Numerical results illustrate the model's feasibility and efficiency.

Keywords*: operations optimization, refinery, processing characteristics, logic programming*

1. Introduction

Refinery industry is mainstay of the national economy and acts very important role. Improved quality and efficiency of operating activities can be realized through operations scheduling optimization. Nowadays, the scheduling problem is still a hot issue and most challenging problem due to the complexity of refinery operations.

Establishing scheduling models is the key to realize scheduling optimization. Mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) are two major modeling approaches in common use. Pinto [1] proposed the general scheduling model framework of refinery process and gave a foundation of refinery scheduling problem, but exact models were not mentioned in his paper. Luo and Rong [2] presented a MILP optimization model based on discrete time representation to decide optimal operations of processing units. Karuppiah, Furman and Grossmann [3] used MINLP approach to model the scheduling problem of crude oil movement at the front-end of a petroleum refinery. Cao and Gu [4] formulated a MINLP scheduling model to deal with the refinery blending problem. The crude oil unloading, and mixing and product blending and delivery have characteristics of batch process, while the operation of processing units that is the middle refinery process has its own distinguishing features such as operational stability and continuity, which play important role in refinery production and receives significant attentions in schedulers' practical work. However, most presented refinery scheduling models are transformed and developed from models of batch plant [5-7]. Schemes obtained from such models are hard to utilize directly, so it is need to study on the representation of refinery production characteristics and the corresponding scheduling problem, which is the focus of this work.

In view of the above problems, the refinery production characteristics of operational stability and continuity were represented, and a new operations optimization model was built based on the logic programming approach proposed by the formal work [8]. In this paper, section 2 gives an outline of a refinery process and describes the operations optimization problem in detail. The expressions of production characteristics are given, and a new scheduling optimization model and its solution method is presented. Numerical results of case study are shown in section 3 to illustrate the model's feasibility and efficiency. Finally, Section 4 gives the concluding remarks.

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2. Research Method

2.1. Problem Statement

The main work of a refinery is to convert kinds of crude oils into valuable final products such as gasoline, diesel and jet fuel, etc. The refinery process is usually divided into three parts in researches of refinery scheduling. The first part contains the crude oil unloading, and mixing, the second part involves the operation scheduling of processing units, and the third part consists of the product blending and delivery. The refinery process referred in this paper involves processing units operation process as well as product blending as shown in Figure 1 in which the storage tanks are not drawn for brevity.

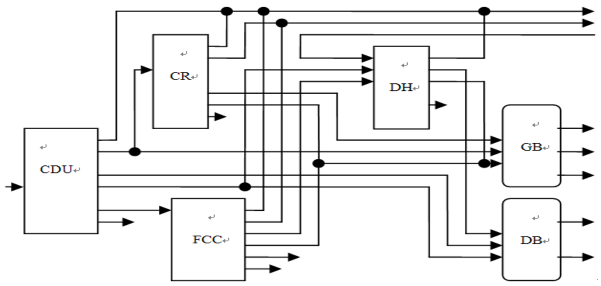

Figure 1. Simplified Flow Sheet of A Refinery

The flow sheet in Figure 1 is derived from the practical production process of Shengli refinery in eastern china. The crude distillation unit (CDU) is the head processing unit of the refinery, by which the crude oils are transformed into a wide variety of distillates. Afterward, the distillates are converted into semi-manufactures and final products by the following processing unit which are fluid catalytic cracking unit (FCC), continuous reforming unit (CR), diesel hydrotreating unit (DH), gasoline blending unit (GB) and diesel blending unit (DB).

In refineries, processing units are closed connected. Units processing characteristics have major impact on refinery production. The startup/shutdown, and big throughput fluctuating of processing units may cause interrupt of production logistics and quality decline of products. If the operational stability and continuity are not guaranteed, the operation cost is very high. So, the schedulers' work in practice is to ensure production profit at the condition of satisfying requirements of operational stability and continuity to make product safely and efficiently. Effective operational scheduling optimization is key to improve profit and production performance.

2.2. Proposed Operations Optimization Model

The object of refinery operations optimization is to maximize production profit at the condition of ensuring operational stability and continuity. In actual production process, there include lots of logic rules and expert experiences which can be expressed as logic propositions. It makes represent the production characteristics easily and conveniently. Based on the logic programming approach proposed by the formal work [8], a heuristic rules-integrated mixed integer programming scheduling model was formulated relies on discrete-time representation. The nomenclature is as follows:

Indices:

i: units
j: raw materials, intermediates or final products
t: time periods
r: material properties

Sets:

SU: set of processing units
BU: set of blending units
WL: set of materials
SWL: set of inventoriable materials
NWL: set of noninventoriable materials

RWL: set of raw materials
DWL: set of final products
T: set of time periods
XZ(j): set of properties of material *j*
CI(j): set of units consuming material *j*
CH(j): set of units producing material *j*
CL(i): set of materials consumed by unit *i*
CO(i): set of materials produced by unit *i*

Parameters:
N: amount of time periods
CS_i: required minimum amount of continuous run time periods of processing unit *i*
CS_{i0}: initial continuous run time periods of processing unit *i*
P_i^U: maximum process capacity of unit *i*
P_i^L: minimum process capacity of unit *i*
KC_j^U: maximum storage of material *j*
KC_j^L: minimum storage of material *j*
B_{jt}^U: maximum purchase amount of raw material *j* limited by market during time period *t*
B_{jt}^L: minimum purchase amount of raw material *j* available in market during time period *t*
M_{jt}^U: maximum sale amount of final product *j* limited by market during time period *t*
M_{jt}^L: minimum sale amount of final product *j* available in market during time period *t*
λ_i: allowed startup/shutdown number of processing unit *i*
w_i: allowed maximum throughput fluctuating of processing unit *i*
β_{ji}: output ratio of material *j* in unit *i*
α_{jr}: property *e* of material *j*
δ_{jt}: price of final product *j* during time period *t*
ρ_{jt}: price of raw material *j* during time period *t*
γ_j: storage cost of material *j*

Variables:
S_{it}: boolean variables denoting whether processing unit *i* runs during time period *t*
s_{it}: binary variables corresponding to R_{it}
QD_{it}: boolean variables denoting whether processing unit *i* starts up in time period *t*
TZ_{it}: boolean variables denoting whether processing unit *i* shuts down in time period *t*
qd_{it}: binary variables corresponding to QD_{it}
tz_{it}: binary variables corresponding to tz_{it}
tp_{it}: throughput of unit *i* during time period *t*
ti_{ijt}: amount of material *j* consumed by unit *i* during time period *t*
to_{ijt}: amount of material *j* produced by unit *i* during time period *t*
KC_{jt}: storage of material *j* at the end of time period *t*
B_t: amount of raw material *j* purchased during time period *t*
M_{jt}: amount of final product *j* sold during time period *t*

2.2.1. Expression of Operational Stability

Operation states of processing units reflect prodution characteristics directly. The less startup and shutdown, and tiny throughput fluctuating of processing units, the better stability the production process obtained.

Logic proposition (1)-(3) describe the operational stability requirement of startup and shutdown.

$$\neg S_{i(t-1)} \wedge S_{it} \Leftrightarrow QD_{it},\ i \in SU, t \in T \qquad (1)$$

$$\neg S_{it} \wedge S_{i(t-1)} \Leftrightarrow TZ_{it},\ i \in SU, t \in T \qquad (2)$$

$$\sum_{t\in T} tz_{it} + \sum_{t\in T} qd_{it} \le \lambda_i,\ i \in SU \qquad (3)$$

If processing unit *i* stops in time period *t*-1 and operates in time period *t*, it indicates a startup as expression (1) shows. Likewise, the operating state of shutdown is denoted by expression (2), where S_{i0} indicates the initial operating state of unit *i*. Constraint (3) makes unit operating satisfies the stability requirement, which prevents frequent startup and shutdown.

$$S_{i(t-1)} \wedge S_{it} \Leftrightarrow L_{it},\ i \in SU, t \in T \quad (4)$$

$$L_{it} \Rightarrow \left[-w_i \le tp_{it} - tp_{i(t-1)} \le w_i\right],\ i \in SU, t \in T \quad (5)$$

The operational stability requirement of throughput fluctuating is described by logic proposition (4) and (5). Expression (4) denotes the continous run state of unit i during time period *t*-1 and *t* as boolean variable L_{it} indicates. If L_{it} is true, then the throughput fluctuating of processing unit *i* must be in the allowed maximum range, as shown by expression (4).

2.2.2. Expression of Operational Continuity

In the production and schedulers' work, to make the refining process operate in continuous state, there have operating requirements of minimum continuous runtime of processing units. Literature [9] use constraint (6)-(8) to describe the operational continuity requirement.

$$CR_{it} = (CR_{i(t-1)} + 1) \cdot s_{it},\ i \in SU,\ t \in T \quad (6)$$

$$pd_{it} = \begin{cases} 1, & 0 < CR_{i(t-1)} < CS_i \\ 0, & \text{else} \end{cases},\ i \in SU, t \in T \quad (7)$$

$$s_{it} - PD_{it} \cdot s_{i(t-1)} \ge 0,\ i \in SU, t \in T \quad (8)$$

Constraint (6) calculates the continuous runtime of unit *i*. Piecewise function (7) determines whether the unit continuous runtime satisfies the operational continuity requirement. If the requirement is not satisfied, then unit i must run in the following time period, as constraint (8) shows. While constraints (6)-(8) are nonlinear functions which makes model complex and hard to solve, and the operational continuity requirement of different scheduling period is not represented. It is difficult to get global optimization solution.

For the problem mentioned above, the scheduling horizon is divided into three stages, and operational continuity requirement of different stages is represented by logic propositions (9)-(10). The logic expressions can be converted into linear algebra expressions (see section 3.5) which are easy to solve. The solution efficiency is improved.

$$PD_{i0} \Rightarrow \wedge S_{it},\ \ i \in SU, 1 \le t \le CS_i - CS_{i0} \quad (9)$$

$$QD_{it} \Rightarrow \wedge S_{it'},\ \ i \in SU, 1 \le t \le N - CS_i, t+1 \le t' \le t + CS_i - 1 \quad (10)$$

$$QD_{it} \Rightarrow \wedge S_{it'},\ i \in SU, N - CS_i + 1 \le t \le N-1, t+1 \le t' \le N \quad (11)$$

Logic proposition (9) makes unit *i* run during time period [1, CS_i -CS_{i0}], if the minimum run time CS_i is not satisfied at initial time, where PD_{i0} is the boolean variable corresponding to pd_{i0}. If unit *i* start up in time period [1, $N - CS_i$], it must run in time period [t+1, t+CS_i -1], as expression (10) shows. If processing unit *i* starts up during time period *t*, $t \in [N–CS_i +1, N-1]$, then it must keep on running to the end of the scheduling horizon (i.e. time period t=N), the continuity will be guaranteed at the beginning of the next scheduling by constraint (9), as expressed by logic proposition (11).

2.2.3. Constraints of Units and Materials

The operation of processing units are discribed by constraint (12)-(15). Constraint (12) limits the throughput of processing units between production capacity P_i^L and P_i^U. Constraint

(13) makes the throughput equal to the consumed volume to_{ijt}. The output of processing units is computed by constraint (14). Constraint (15) calculates the throughput of unit *i*.

$$s_{it} \cdot P_i^L \le tp_{it} \le s_{it} \cdot P_i^U,\ i \in SU, t \in T \quad (12)$$

$$tp_{it} = \sum_{j \in CO(i)} to_{ijt},\ i \in SU, t \in T \quad (13)$$

$$to_{ijt} = \beta_{ji} \cdot tp_{it},\ i \in SU, j \in CL(i), t \in T \quad (14)$$

$$tp_{it} = \sum_{j \in CL(i)} ti_{ijt},\ i \in SU, t \in T \quad (15)$$

Constraint (16) and (17) state operations of blending unit. Because there is no chemical reaction or separation in blending process which is just a mixing process, blending units are different from processing units. In refineries, the blending capability is usually large enough to satisfy production requirement. Therefore, the blending capability limitation is not considered in the model. The material balance is expressed by Constraint (16). Constraint (17) forces the properties α_{jr} of products to meet specification, where function *f* is to make the property change of mixing process be in the linear form [10].

$$\sum_{j \in CL(i)} ti_{ijt} = \sum_{j \in CO(i)} to_{ijt},\ i \in BU, t \in T \quad (16)$$

$$\sum_{j \in CL(i)} f_i(\alpha_{jr}) \cdot ti_{ijt} = \sum_{j \in CO(i)} f_i(\alpha_{jr}) \cdot to_{ijt},\ i \in BU, r \in XZ(j), t \in T \quad (17)$$

According to storability of refinery materials, materials can be divided into two kinds: non-inventoriable materials and inventoriable materials. The production and purchase amount of non-inventoriable materials, such as dry natural gas and hydrogen, must equal to the amount of consumption and sales, as shown by constraint (18).

$$\sum_{i \in CH(j)} to_{ijt} + B_{jt} = \sum_{i \in CI(j)} ti_{ijt} + M_{jt},\ j \in NML, t \in T \quad (18)$$

Constraint (19) calculates materials inventory at the end of time period *t*. Constraint (20) gives the storage upper and lower bounds of inventoriable material *j*.

$$KC_{jt} = KC_{j(t-1)} + \sum_{i \in CH(j)} to_{ijt} + B_{jt} - \sum_{i \in CI(j)} ti_{ijt} - M_{jt},\ j \in WL, t \in T \quad (19)$$

$$KC_j^L \le KC_{jt} \le KC_j^U,\ j \in WL, t \in T \quad (20)$$

Constraint (21) and (22) presents the limitation of material purchase and sale amount.

$$B_{jt}^L \le B_{jt} \le B_{jt}^U,\ j \in RWL, t \in T \quad (21)$$

$$M_{jt}^L \le M_{jt} \le M_{jt}^U,\ j \in DWL, t \in T\ . \quad (22)$$

2.2.4. Object Function

The objective of the optimization model is to maximize production profit as expression (23) shows. The terms in the objective function calculate sale income, purchase cost, inventory cost, respectively.

$$\max Z = \sum_t \sum_j \delta_{jt} \cdot M_{jt} - \sum_t \sum_j \rho_{jt} \cdot B_{jt} - \sum_t \sum_j \gamma_j \cdot KC_{jt}\ . \quad (23)$$

2.3. Model Solution

The logic rules and expert experiences can be expressed as logic propositions conveniently, which makes the proposed model easy to understand. In order to use software Lingo9.0 to solve the operations optimization model in this paper, the logic propositions should be converted into equivalent algebra expressions, which lets the model programming and solution efficiently.

2.3.1. Logic Propositions with Boolean Variables only

There are two kinds of logic propositions in the proposed model. Logic proposition (24) can be converted to algebra expression (25) equivalently. Logic proposition (26) is equivalent to algebra expression (25) and (27).

$$Y \Rightarrow \wedge_k^n Y_k \tag{24}$$

$$y_k - y \ge 0,\ k \in K \tag{25}$$

$$Y \Leftrightarrow \wedge_k^n Y_k \tag{26}$$

$$n - 1 + y - \sum_{k=1}^{n} y_k \ge 0 \tag{27}$$

Where Y and Y_k, $k \in K$, $K=\{1,2 \ldots n\}$ is boolean variable, y and y_k, $k \in K$ is binary variable corresponding to Y and Y_k.

2.3.2. Logic Propositions with Function

The equivalent algebra expressions of Logic proposition (28) are expression (29) and (30) where ε_k^1 and ε_k^2 $k \in K$ are positive real number, vector **v** is the set of continuous real variables, g_k, $k \in K$ is the linear function of vector **v**.

$$Y_k \Rightarrow \left[-\varepsilon_{1k} \le g_k(\mathbf{v}) \le \varepsilon_{2k}\right],\ k \in K \tag{28}$$

$$g_k(\mathbf{v}) \le y_k \cdot \varepsilon_{2k},\ k \in K \tag{29}$$

$$-g_k(\mathbf{v}) \le y_k \cdot \varepsilon_{1k},\ k \in K \tag{30}$$

If there exists logic relation "not" in the above expressions, such as $\neg Y_k$, it is only need to replace y_k into $1-y_k$ by which the equivalent algebra expressions can be got。

Based on the above equivalent transformation approach, the proposed logic programming model can be converted into equivalent MILP model which is able to be solved by software Lingo9.0 conveniently and efficiently.

3. Results and Analysis

3.1. Case Study

Table 1. Operation Parameters of Processing Units

Unit	Process capacity (10^4 ton/annual)	Initial continuous run time periods	Required minimum continuous run time periods	Maximum startup and shutdown number	Maximum throughput fluctuating amount (10^4 ton)	Planned unit maintenance time period amount
CDU	450	10	9	1	3	2
FCC	270	10	6	2	2	1
CR	70	3	3	2	0.2	-
DH	90	0	3	3	0.5	-

An operational scheduling problem is presented to evaluate the proposed model in this section. The problem is derived from the practical production procedures at Shengli refinery as illustrated in Figure 1. The operation parameters of processing units are shown in Table 1. Table 2 gives the output ratios of produced materials. Table 3 shows the properties of blending materials and product specification.

Table 2. Output Ratios of Processing Units (%)

Material	CDU	FCC	CR	DH
Reforming material	16	-	-	-
Diesel	20	-	-	-
Catalyzing material	58	-	-	-
Kerosene	5	-	-	-
Gasoline	-	48	70	2
Light diesel	-	20	-	-
LPG	-	12	3	-
Refinery coke	-	15	-	-
Over head oil	-	-	24	-
Refining diesel	-	-	-	96
Dry natural gas	0.7	4.5	2	1
Lost	0.3	0.5	1	1

Table 3. Properties of Blending Materials and Product Specification

GB	Octane number	DB	Freezing point factor
Reforming material	66	Diesel	0.473
Over head oil	80	Light diesel	1.6075
Gasoline	90.2	Refining diesel	1.2075
Alcohol	117	-10 # diesel	1.2069
90 # gasoline	90	0 # diesel	1.6059
93 # gasoline	93		
97 # gasoline	97		

In view of the scheduling problem, two scheduling models were built. Scheduling model 1 is the units processing characteristics based operations optimization model with expressions (1)-(5) and (9)-(23). Scheduling model 2 was developed by expression (12)-(23) without considering production characteristics, which is the general form of most related publications. The case study has a 100 days scheduling horizon which is divided into 10 time periods equally. The formulated two model was implemented in LINGO 9.0, and the obtained optimal schemes are presented in Figure 2 and Figure 3.

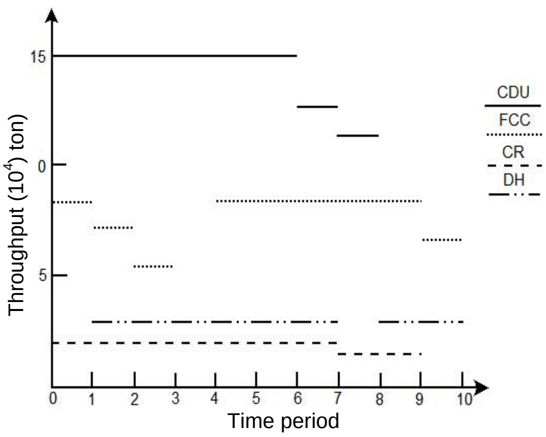

Figure 2. Gantt Chart for Optimal Schedule 1 of Model 1

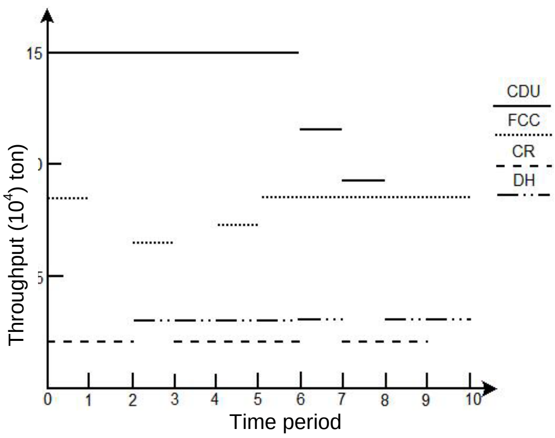

Figure 3. Gantt Chart for Optimal Schedule 2 of Model 2

3.2. Disscution

As the simulation results shown in case study, due to the expression of operational stability and continuity, schedule of scheduling model 1 can met actual production requirements and improve production performance, while such production requirements cannot be satisfied by the common scheduling model 2.

According to unit continuous runtime requirement and initial operating state, based on the operational continuity expressions of model 1, eleven boolean/ binary decision variables S_{it}/s_{it} can be determined during solution, which makes the combination state amount of S_{it}/s_{it} decrease from 2^{40} to 2^{29}. The model solution space is greatly reduced, which can improve solution efficiency, and global optimization solution can be got. The object value of model 1 is 18720.87. Although it is less than the object value of model 2 that is 19887.15, but better production performance is obtained.

As stated above, the startup/shutdown and big throughput fluctuating of processing units can cause product quality decline and high operation cost, and the production performance cannot be ensured. Compared to the case without considering production characteristics, schedule obtained from the scheduling model based on operational stability and continuity can reduce operation cost significantly, satisfy actual operating requirements and improve production performance, which is more feasible and practical. Calculated results show that the proposed model is effective.

4. Conclusion

The refinery operations optimization problem based on operational stability and continuity is studied in this work. A logic programming scheduling model is proposed. The model represents production characteristic by logic rules and expert experiences using logic proposition, which ensures operating performance of stability and continuity, and more feasible and practical schedule can be obtained. Numerical results shows that the proposed formulation is effective.

In this work, only two aspects of units processing characteristics are considered in scheduling optimization. Other processing characteristics (i.e. safety) and the synthesized evaluation criterion are worthy to be studied in the future.

References

[1] Pinto JM, Joly M, Moro LFL. Planning and Scheduling Models for Refinery Operations. *Computers and Chemical Engineering*. 2000; 24(9-10): 2259- 2276.

[2] Luo C, Rong G. Hierarchical approach for short-term scheduling in refineries. *Industrial Engineering and Chemical Research*. 2007; 46(11): 3656–3668.

[3] Karuppiah R, Furman KC, Grossmann IE. Global optimization for scheduling refinery crude oil operations. *Computers and Chemical Engineering*. 2008; 32(11): 2745–2766.

[4] Cao Cuiwen, Gu Xingsheng, Xin Zhong. A Data-Driven Rolling-Horizon Online Scheduling Model for Diesel Production of a Real-World Refinery. *AIChE Journal*. 2013; 59(4): 1160-1174.

[5] Mockus L, Reklaitis GV. Continuous Time Representation Approach to Batch and Continuous Processes Scheduling.1.MINLP Formulation. *Industrial and Engineering Chemistry Research*. 1999; 38(1): 197-203.

[6] Lee K, Park HI, Lee I. A novel nonuniform discrete time formulation for short-term scheduling of batch and continuous processes. *Industrial and Engineering Chemistry Research*. 2001; 40(22): 4902-4911.

[7] Shaik MA, Floudas CA, Josef K, Pitz HJ. Production scheduling of a large-scale industrial continuous plant: Short-term and medium-term scheduling. *Computers and Chemical Engineering*. 2009; 33(3): 670-686.

[8] Ming Li, Qiqiang Li, Qingqiang Guo. A heuristic rules-integrated mixed integer programming scheduling model. *Chinese High Technology Letters*. 2010; 20(9): 971-977.

[9] Qiqiang Li, Ran Ding, Qingqiang Guo, Ming Li. Process industry scheduing optimization methods. Beijing: Science Press. 2010.

[10] Zhang BJ, Hua B, Lu ML. Multiperiod integration optimization for production planning and utility system in refinery industries. *ACTA Petrolei Sinica*. 2006; 22(2): 56-68.