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Cyclic Scheduling of No Backup Cracking Furnace System Considering Real World Operational Characteristics ⋆

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Abstract: Ethylene cracking furnace system is the heart of ethylene production. It can process different raw materials in the pipe group of each furnace and can produce the main chemical products like ethylene, propylene and ethane. In the real world ethylene plant, there are two operation modes in the furnace system, one has a backup furnace in the system and the other is with all the furnaces available online. Compared with the mode which has a backup furnace, the operation mode with all the furnace online has more benefits in prolonging the batch processing time and saving the operational cost. Considering some of the operational characteristics like shutting down for decoking and varying running capacity with the processing cost and product values, the scheduling scheme is optimized to achieve the best economic performance of the cracking furnace system. In this paper, an improved MINLP model considering some real world operational characteristics under the no backup furnace operation mode is developed and solved by a new heuristic iterative solving method. The feasibility and the efficiency of the model is demonstrated through a numerical case study from a real world plant.

1. INTRODUCTION

In chemical production, ethylene is one of the major products in the petrochemical industry and it is a very reactive intermediate to produce materials like plastics, resins and fibers (Berreni and Wang [2011]). The most important facility in the ethylene plant is the cracking furnace system. The yields of major product and intermediate in the ethylene plant are mainly determined by the pyrolysis operation in the cracking furnace (Zhao et al. [2011]). In the duration of the cracking operation in furnaces, the coke will be formed and then accumulated on the reaction coils, resulting lower energy transfer efficiency and the decaying performance of product yield. Thus, the furnace cracking operation is a semi-continuous process and must be shutdown for decoking every 20-90 days. Nowadays the fierce and competitive markets have forced petrochemical plants to use various feedstocks, from liquefied gas to heavy liquid hydrocarbons. These materials are usually composed of naphtha, light diesel, heavy diesel, liquefied petroleum gas, ethane etc. The characteristics of these materials could directly impact the yield of the final products, such as ethylene, propylene, ethane, C4 fraction, methane etc. Thus, during the scheduling horizon, it is necessary to decide the feeds type and exact running mode of each furnace to meet the demand under specific supply capacity.

Usually there are two kinds of operation mode in the cracking furnace system, furnace system with one furnace used as backup furnace (backup furnace running mode) and furnace system with all the furnace online (no backup furnace running mode). In the first mode, all of the furnaces will be running at their maximum designed capacity. If one of the furnaces is shutdown, the backup furnace will be setup for cracking operation to make up for the total product amount decrease of the furnace system. While in the no backup furnace mode, all of the furnaces are simultaneously running online at 70%-85% of the designed maximum capacity. For the first mode, the yield of the furnace will decline drastically which means furnace has to be shutdown more often and leading to a shorter batch life cycle. While in the no backup furnace mode, the furnace can have a longer operation sub-cycle. However, it remains a much more difficult scheduling problem of how to arrange the furnace feeding material in the each pipe group and set the best starting and end time to avoid simultaneous cracking and achieve dynamic running capacity when one furnace is under decoking.

Few works of the ethylene plant production scheduling and cracking furnace operation can be found in literature. Jain and Grossmann [1998] studied the problem of assigning multiple feeds on parallel units, and proposed a MINLP model representing the decaying performance of the yield. Schulz et al. [2000] firstly considered the recycled ethane and analysis the interactions between the plant operation and furnace performance. Then they also extended the work to a entire plant at each time interval to meet varying demands and developed an MINLP model based on the research to increase the net profit (Schulz et al. [2006]). In the work of Lim et al. [2006], they solved the decoking scheduling problem of multiple tube system with the constraint of a constant total throughput. In the later work, they used a proactive decoking strategy and applied to a multiple furnace simulation system to prove the

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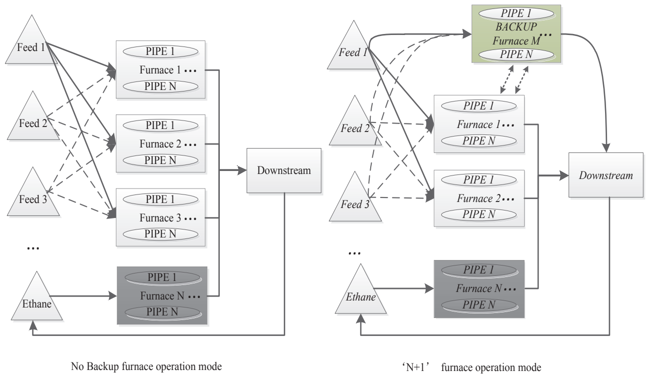

Fig. 1. Basic operation structure of furnace cracking system

efficiency in risk management (Lim et al. [2009]). However, in Lim's work multiple feeds is still not considered. Based on the former analysis, a new MINLP model is proposed by Zhao et al. [2010] considering the multiple feeds and secondary ethane cracking. After that, they extended the model into a rescheduling frame to deal with dynamic information (Zhao et al. [2011]). Nevertheless, some of the aforementioned operational characteristics like co-cracking different materials in the same furnace are still not considered. And the operational behaviour like varying running capacity of furnace should also be introduced into practice since the fluctuation caused by the cleanup switch may incur safety problems to the downstream production. In this paper, we introduce these operational characters and build a new MINLP model considering pipe groups as the minimum operation unit. This complex model is efficiently solved with a new solving method. Compared with the one backup furnace operation system, a case study with the new scheduling system demonstrates the efficacy of the proposed model.

2. PROBLEM STATEMENT

As we have discussed above, the furnace system is usually composed of several furnaces consuming different raw materials and cracking in the pipe groups as the basic operation unit. The basic structure of the furnace operation system is illustrated in Fig. 1. The cyclic scheduling problem in the cracking furnace should determine the best total cycle time, the starting and end time of each batch slot, the time for decoking, feeding material for each pipe groups etc. For easy understanding, Fig.2 shows the concepts of the scheduling result of ethylene yield in the no backup furnace mode. The batch processing time is usually depending on the cracking severity(Zhao et al. [2010]), and the yield curve in Fig. 2 represents the dynamically decreasing characteristic caused by the coking and pyrolysis reaction kinetics. Cleanup operation time is between the two adjacent batches. In a SRT type furnace, there are 4-6 pipe groups in each furnace. Co-cracking operation can happen when one furnace is consuming different raw materials but cracked separately in the specific pipe groups. As shown in Fig. 2, there are three pipe groups cracking material A in the first batch of furnace one while only one pipe group is cracking material B. Besides, nonsimultaneous cleanup operation is a critical issue in maintaining the stable production of the furnace system. It means that the decoking operation between different furnaces cannot be overlapped. Since the furnace sytem is not running at its maximum designed capacity in the no backup furnace mode, it will increase the running capacity around 10%-15% to make up for the total product amount loss when one furnace is shutdown for decoking.

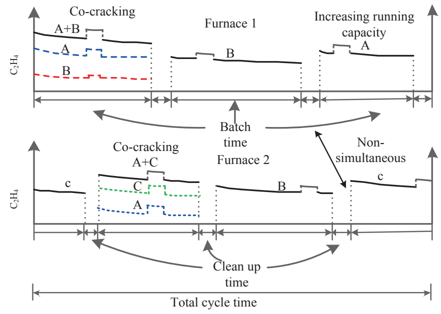

Fig. 2. An illustrative example for a furnace cyclic scheduling problem of no-backup furnace operation

3. SCHEDULING MODEL

In this section, a newly developed MINLP model which incorporates some real world operational characteristics of the no backup furnace model is introduced. Based on the above characteristics, the new developed model still needs some assumptions: a) There is enough feedstock supply under specific average flow rate range; b) The generated yield model used for each pipe groups in the furnace are accurate and has the same characteristics in the same furnace; c) The recycled ethane is fully reused for the secondary cracking; d) The increased running capacity during the decoking operation will not affect the original decaying trend of the furnace production yield.

3.1 Production Mass balance

The input and output flow of the material balance in the cracking furnace is presented in (1) and (4). In these equations, the operation mode $i, i \in I_j^s$ represents that all of the pipe groups in the same furnace is cracking the same material and mode $i, i \in I_j^c$ represents the co-cracking operation. In (1), $FL_{l',i,j}^{in}$ represents the feeding flow rate of material l' of the operation mode i in furnace j. As pointed out in the work of Jain and Grossmann [1998], the item $c_{l,l',j} + a_{l,l',j} e^{b_{l,l',j} t}$ is used to describe the dynamic changing trend of the product l's yield when cracking the material l' in furnace j. Then integral function calculates the total production amount of product l produced by furnace j in batch n in the first item of (1) and the total consumed feeds is calculated by the flow rate $FL_{l',i,j}^{in}$ multiply the time duration $t_{i,j,n}$ in (2). From (3)-(4), the item is calculated similarly with the co-cracking mode m which represents the proportion of the mixed feeding materials decided by the number of the total the pipe groups in SRT furnace. For example, if there are 4 pipe groups in the each furnace and the co-cracking materials are A and B, it is reasonable to assume that we have three modes: the feed A comes into one, two or three pipe groups while the feed B goes to the left. In these equations, the second item on the right side is the increased running capacity which will be explained in the later section.

$$SC_{l,i,j,n} = FL^{in}_{l,i,j}t_{i,j,n}+p_jFL^{in}_{l,i,j}Tad_{i,j,n}, \quad \forall i \in I^s_j, j \in J, n \in N, l \in L^i_F \tag{1}$$

$$SP_{l,i,j,n} = \int_0^{t_{i,j,n}} FL^{in}_{l',i,j}(c_{l,l',j} + a_{l,l',j}e^{b_{l,l',j}t})dt + p_jFL^{in}_{l',i,j}yst_{l,l',j}Tad_{i,j,n}, \quad \forall i \in I^s_j, j \in J, n \in N, l' \in L^i_F, l \in L^i_P \tag{2}$$

$$SC_{l,i,j,n}=\sum_{m\in M}FLG^{in}_{l,i,j,m}tg_{i,j,m,n}+p_jFL^{in}_{l,i,j,m}Tadm_{i,j,m,n}, \quad \forall i \in I^c_j, l \in L^i_F, j \in J, n \in N \tag{3}$$

$$SP_{l,i,j,n}=\sum_{l'\in L^i_F, m\in M}\int_0^{tg_{i,j,m,n}} FLG^{in}_{l',i,j,m}(c_{l,l',j}+a_{l,l',j}e^{b_{l,l',j}t})dt + \sum_{l'\in L^i_F, m\in M} p_jFLG^{in}_{l',i,j,m}yst_{l,l',j}Tadm_{i,j,m,n} \quad \forall i \in I^c_j, l \in L^i_P, j \in J, n \in N \tag{4}$$

The mass balance of input and output flow is explained in (5). Equation (6) is used to prevent the recycled ethane from the products accumulate within the system. Equation (7) illustrates the average feeding flow rate of material l should be within the estimated supply capacity.

$$\sum_{l\in L_p} SP_{l,i',j',n}=\sum_{l\in L^i_F} SC_{l,i,j,n}, \forall i \in I_j, j \in J, n \in N \tag{5}$$

$$\sum_{i'\in I}\sum_{j'\in J}\sum_{n\in N} SP_{l,i,j',n} \le FL^{in}_{l',i,j}\sum_{n\in N} t_{i,j,n}, \quad \forall i \in I^s_j, j \in J, j = J^{ET}, l \in L^i_P, l' \in L^i_F \tag{6}$$

$$H \cdot FLa^l_l \le \sum_{i\in I_j}\sum_{j\in J}\sum_{n\in N} SC_{l,i,j,n} \le H \cdot FLa^u_l, l \in L^i_F \tag{7}$$

3.2 Logical assignments

In (8), the binary variable $wv_{i,j,n}$ is used to assign different operation mode i to the furnaces j during batch n. The logical constraints of the batch utilization of the furnace is presented in (9)-(11). Equation (9) explains that one batch slot could only be used for one cracking mode at most. And the equation (10) suggests that the first batch should always be used for cracking. The equation (11) is an supplement constraints means every single operation mode will be used at least once during the total cycle time.

$$\sum_{l\in L_p} SP_{l,i,j,n} \le H\times CAP^{up}_j \times wv_{i,j,n}, \forall i \in I_j, j \in J, n \in N \tag{8}$$

$$\sum_{i\in I_j} wv_{i,j,n} \le 1, \forall j \in J, n \in N, n > 1 \tag{9}$$

$$\sum_{i\in I_j} wv_{i,j,n} = 1, \forall j \in J, , n \in N, n = 1 \tag{10}$$

$$\sum_{j\in J}\sum_{n\in N} wv_{i,j,n} \ge 1, \forall i \in I^s_j \tag{11}$$

If one the furnace is under co-cracking mode $i, i \in I^c_j$, one mixed combination type m has to be decided aligning with the mode i. These logical and time constraints are explained from (12)-(14).

$$\sum_{m\in M} wvg_{i,j,m,n} = wv_{i,j,n}, i \in I^c_j, j \in J, n \in N \tag{12}$$

$$TH^l_{i,j}wvg_{i,j,m,n} \le tg_{i,j,m,n} \le TH^u_{i,j}wvg_{i,j,m,n}, \quad \forall i \in I^c_j, j \in J, m \in M, n \in N \tag{13}$$

$$\sum_m tg_{i,j,m,n} = t_{i,j,n}, i \in I^c_j, j \in J, n \in N \tag{14}$$

The non-simultaneous cracking logical constraints can be referred to the work of Zhao et al. [2010] which is not explained here due to the page limits. A binary variable $x_{j,n,j',n'}$ is used to control the cleanup sequence of different operation batch of different furnaces. If it has the value of 1, which means the nth cleanup in furnace j is no-overlap behind the n'th cleanup in furnace j'; if it is designated as 0, the nth cleanup in furnace j is no-overlap ahead of the nth cleanup in furnace j'.

3.3 Time constraints

In the cyclic scheduling model, the first batch can start from the previous cycle or from the current cycle. A binary variable θ_j is introduced to determine the difference. This constraint is realized by big-M method in (15). According to the information of θ_j, in (16)-(17) we are able to formulate the equation which explain the relationship of the cleanup time $\beta_{i,j}$ between the two adjacent batches. The time duration $t_{i,j,n}$ for each batch and the total length constraints is calculated in (18)-(21).

$$-\theta_jM \le Tf_{i,j,1} - Ts_{i,j,1} \le (1-\theta_j)M, \forall i\in I_j, j\in J \tag{15}$$

$$Ts_{i,j,n} = Tf_{i,j,n'} + \sum_{i\in I_j} \beta_{i,j}wv_{i,j,n'} - (1-\theta_j)H, \quad \forall j \in J, n, n' \in N, n = 1, n' = N \tag{16}$$

$$Ts_{i,j,n}=Tf_{i,j,n-1}+\sum_{i\in I_j}\beta_{i,j}wv_{i,j,n-1}, \forall j\in J, n\in N, n>1 \tag{17}$$

$$Tf_{i,j,1} = Ts_{i,j,1} + \sum_{i\in I_j} t_{i,j,1} - H \cdot \theta_j, \forall j \in J \tag{18}$$

$$Tf_{i,j,n} = Ts_{i,j,n} + \sum_{i\in I_j} t_{i,j,n}, \forall j \in J, n \in N, n > 1 \tag{19}$$

$$\sum_{i\in I_j}\sum_{n\in N} (t_{i,j,n} + \beta_{i,j}wv_{i,j,n}) = H, \forall j \in J \tag{20}$$

$$TLH_{i,j}wv_{i,j,n} \le t_{i,j,n} \le TUH_{i,j}wv_{i,j,n}, \forall i\in I_j, j\in J, n\in N \tag{21}$$

3.4 Increased running capacity

As we have mentioned before, when one furnace shuts down for decoking in the no backup furnace mode, the current running capacity of the rest furnaces would rise by 10%-20% to make up for the loss of the product amount. Then the information of the total time when the running capacity is increased during one batch should be gathered. Here, a binary variable $yv_{j,n,j',n'}$ is introduced to represent this information. If $yv_{j,n,j',n'}$ is designated as 1, which means the time window of n'th cleanup of furnace j' is within the processing time window of furnace j in batch

n, otherwise the variable $yv_{j,n,j',n'} = 0$. The value of the binary variable $yv_{j,n,j',n'}$ can be deduced from $x_{j,n,j',n'}$ in nonsimulataneous cracking constraints. For example, if the nth cleanup of furnace j is within the processing time window of furnace j' in batch slot n', $j < j'$ then the $n'-1$th cleanup of furnace j' is ahead of the nth cleanup of furnace j, otherwise $n'+1$th cleanup of furnace j' is behind the nth cleanup of furnace j. This concept can be written in mathematical forms in (22)-(29).

$$yv_{j,n,j',n'} \leq x_{j,n,j',n'}, \forall j,j' \in J, j<j', n,n' \in N \tag{22}$$

$$yv_{j',n',j,n} \leq x_{j,n,j',n'-1}, \forall j,j' \in J, j<j', n,n' \in N \tag{23}$$

$$yv_{j,n,j',n'} \leq 1 - x_{j,n-1,j',n'}, \forall j,j' \in J, j<j', n,n' \in N \tag{24}$$

$$yv_{j',n',j,n} \leq 1 - x_{j,n,j',n'}, \forall j,j' \in J, j<j', n,n' \in N \tag{25}$$

$$yv_{j,n,j',n'} \geq x_{j,n,j',n'} - x_{j,n-1,j',n'}, \forall j,j' \in J, j<j', n,n' \in N \tag{26}$$

$$yv_{j',n',j,n} \geq x_{j,n,j',n'-1} - x_{j,n,j',n'}, \forall j,j' \in J, j<j', n,n' \in N \tag{27}$$

$$yv_{j,n,j',n'} = 1 - x_{j,n'',j',n'} + x_{j,n,j',n'},$$
$$\forall j,j' \in J, j<j', n,n',n'' \in N, n=1, n''=N \tag{28}$$

$$yv_{j',n',j,n} = 1 - x_{j,n,j',n'} + x_{j,n,j',n''},$$
$$\forall j,j' \in J, j<j', n,n',n'' \in N, n'=1, n''=N \tag{29}$$

However, in some furnaces the last used batch slot might not be the maximum batch number N. Thus the binary variable $yv_{j,n,j',n'}$ cannot give the right information and should be rectified in (30)-(33) and return the true status information with a positive continuous variable $zv_{j,n,j',n'}$.

$$zv_{j,n,j',n'} \leq yv_{j,n,j',n'}, \forall j,j' \in J, n,n' \in N \tag{30}$$

$$zv_{j,n,j',n'} \geq yv_{j,n,j',n'} + \sum_{i \in I_i} wv_{i,j',n'} - 1, \forall j,j' \in J, n,n' \in N \tag{31}$$

$$zv_{j,n,j',n'} \leq \sum_{i \in I_{j'}} wv_{i,j',n'}, \forall j,j' \in J, n,n' \in N \tag{32}$$

$$zv_{j,n,j',n'} \leq \sum_{i \in I_j} wv_{i,j,n}, \forall j,j' \in J, n,n' \in N \tag{33}$$

With the variable $zv_{j,n,j',n'}$, the information of total time length for the increased running capacity are presented by $Tad_{i,j,n}$ with single feed and $Tadm_{i,j,n,m}$ with multiple feeds in (34)-(42).

$$Tcl_{j,n,j',n'} \leq \sum_{i \in I_{j'}} \beta_{i,j'} wv_{i,j',n'}, \forall j,j' \in J, n,n' \in N \tag{34}$$

$$Tcl_{j,n,j',n'} \leq Th^c zv_{j,n,j',n'}, \forall j,j' \in J, n,n' \in N \tag{35}$$

$$Tcl_{j,n,j',n'} \geq \beta_{i,j'} \Big(\sum_{i \in I_{j'}} wv_{i,j',n'} + yv_{j,n,j',n'} - 1 \Big),$$
$$\forall j,j' \in J, n,n' \in N \tag{36}$$

$$Tad_{i,j,n} \leq \sum_{j' \in J} \sum_{n' \in N} Tcl_{j,n,j',n'} + H(1 - wv_{i,j,n}),$$
$$\forall i \in I_j^s, j \in J, n \in N \tag{37}$$

$$Tad_{i,j,n} \geq \sum_{j' \in J} \sum_{n' \in N} Tcl_{j,n,j',n'} - H(1 - wv_{i,j,n}),$$
$$\forall i \in I_j^s, j \in J, n \in N \tag{38}$$

$$Tad_{i,j,n} \leq t_{i,j,n}, \forall i \in I_j^s, j \in J, n \in N \tag{39}$$

$$Tadm_{i,j,m,n} \geq \sum_{j',n'} Tcl_{j,n,j',n'} - H(1 - wvg_{i,j,m,n}),$$
$$\forall i \in I_j^c, j \in J, m \in M, n \in N \tag{40}$$

$$Tadm_{i,j,m,n} \leq \sum_{j',n'} Tcl_{j,n,j',n'} + H(1 - wvg_{i,j,m,n}),$$
$$\forall i \in I_j^c, j \in J, m \in M, n \in N \tag{41}$$

$$Tadm_{i,j,m,n} \leq tg_{i,j,m,n}, \forall i \in I_j^c, j \in J, m \in M, n \in N \tag{42}$$

Based on the length of time window for the increased running capacity, the dynamic part of the input and output flow is added as the second item in the mass balance equation from (1)-(4). The item $p_j FL_{l,i,j}^{in} yst_{l,l',j} Tad_{i,j,n}$ represents the increased amount of product l when furnace j is running in the single-material cracking mode i of batch n with feeds l' in (1). And the item $p_j FL_{l,i,j}^{in} Tad_{i,j,n}$ represents the increasing part of the consumed material in (2). The variable p_j represents the increased percentage of running capacity. And parameter $yst_{l,l',j}$ is a constant value to prevent the equation become much more complex, since the total time duration only takes a small proportion of the total subcycle time and the running capacity is controllable in the system. Similarly, if the furnaces is co-cracking different materials, this information is also added in (3) and (4).

Objective function. As shown in (43), the objective of the production in ethylene furnace system is to maximize the average daily profit over a long cycle period H. The first term in the equation is the total profit may earned from the cracking products, the second term is the cost of raw materials and the third term represents the operational cost. The last two terms are the extra operational cost which represents the running burden of different furnaces when they dynamically increased their running capacity.

$$\max Profit \times H = \sum_{l \in L_p, i \in I_j, j, n} ax_l SP_{l,i,j,n} - \sum_{l \in L_F^i, i \in I_j, j, n} bx_l SC_{l,i,j,n}$$
$$- \sum_{i \in I_j, j, n} cx_{i,j} wv_{i,j,n} - \sum_{i \in I_j^s, j, n} d_{i,j} Tad_{i,j,n}$$
$$- \sum_{i \in I_j^c, j, n} d_{i,j} \sum_{m \in M} Tadm_{i,j,m,n} \tag{43}$$

3.5 Solution Method

The proposed cyclic scheduling formulation of ethylene furnace is a challenging MINLP model that integrates nonlinear yield constraints and some 3 dimensional and 4 dimensional integer variables which make this problem heard to solve, let alone get the optimal solutions. To over this problem, we propose an iterative heuristic solution strategy with integer cut to improve the solution performance when applying DICOPT solver in the GAMS. The scheduling model is divided into two stage sub-problems. The first stage is the normal cyclic scheduling problem without varying running capacity which is solved by the DICOPT solver in GAMS with CONOPT to handle the NLP subproblem and CPLEX to handle the MIP subproblem. The integer variables like $wv_{i,j,n}$ in the first stage is used as the initial starting point of the next stage's problem. In the second stage, heuristic searching rules are employed as additional constraints to cut a significant branches in the searching path to save the calculation time. For example, i) The maximum batch slot number $|FN|_j$ can be added and affect the batch duration time for each furnace processing operation thus the solver is able to jump out of the local optimal solution and choose the best subcycle. ii) The cleanup operation with longer time duration should be better within the time window when the system have a higher ethylene production yield.

After each heuristic search, if the result of second stage is not better than the first stage or the previous full space problem's solution, integer cut is set to exclude the former tested solutions. This iterative solution repeats until the possible solution is not getting better after the preset iterative steps. The mathematical expression is in (44), in which PI=$\{(i,j,n)|wv'_{i,j,n}=1\}$, NI=$\{(i,j,n)|wv'_{i,j,n}=0\}$, PG=$\{(i,j,m,n)|wvg'_{i,j,m,n}=1\}$, NG=$\{(i,j,m,n)|wvg'_{i,j,m,n}=0\}$, and $wv'_{i,j,n}$, $wvg'_{i,j,m,n}$ are integer solutions from the previous iterative step.

$$\sum_{(i,j,n)\in PI} wv_{i,j,n} - \sum_{(i,j,n)\in NI} wv_{i,j,n} + \sum_{(i,j,m,n)\in PG} wvg_{i,j,m,n} - \sum_{(i,j,m,n)\in NG} wvg_{i,j,m,n} \le |PI|+|NI|+|PG|+|NG| \qquad (44)$$

4. CASE STUDY

A case study from a real world ethylene unit which has six cracking furnaces is presented in this paper. Each furnace has four pipe groups and is running online at its 70%-80% designed capacity under the no backup furnace mode, and one furnace is especially assigned for cracking ethane. The feeding material is composed of liquefied petroleum gas(LPG), naphtha(NP), light diesel(LD), ethane(ETH). The final product is mainly composed of ethylene, propylene, ethane, C4 fraction, methane, hydrogen etc. The product yield data comes from the industrial regression data, in which ethane and LPG has the highest ethylene yield, and each furnace has different performance according to the feeds type and operation mode.

The MINLP scheduling model is implemented in GAMS 24.1 and is solved by the heuristic iterative solution method. The model has 726 discrete variables and 4636 continuous variables and is also solved with other solver like DICOPT or SBB/BARON to prove its solution quality, which is represented in Table 1. The final results of the proposed method have a total cycle time of 256 days and have a net profit of 322111.73$ per day. Compared to the other solvers, the proposed method provides better solution performance and higher average profit gain. The final scheduling result is presented in Fig. 3.

Table 1. Solution performance of different solver

Solver	Result	Time
DICOPT:NLP-SNOPT	313180.55	11.425s
DICOPT:NLP-IPOPT	312980.55	14.685s
SBB	No Solution	≈1h
BARON	309791.7	≈24h
DICOPT with HEURISTIC	322111.73	60s

According to the final result, there are four batches in the furnace 1 and furnace 3 and three batches in the other four furnaces. This is because the ethylene yield decline more rapidly in furnace 1 and 3 than the other four furnaces when cracking naphtha. Co-cracking operation occurs in the first batch slot of furnace 3 and the second batch slot of furnace 2. In furnace 3 one pipe group is cracking light diesel and the other three are cracking naphtha. In furnace 2 the liquefied petroleum gas goes to three pipe groups while only one pipe group is consuming naphtha. Most of the batches in the first four furnaces are consuming naphtha since naphtha is the main supply feedstock for the ethylene plant. In furnace 5, three batches are arranged with liquefied petroleum gas which has the highest ethylene yield. And the ethane furnace has three batches in the total cycle time. The information of the time length of dynamic running capacity for each batch and exact scheduling time is illustrated in Table (2).

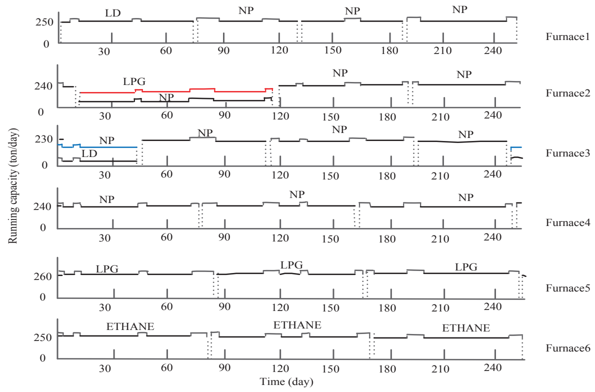

Fig. 3. Scheduling result of cracking furnace production

Table 2. Detailed results for furnace production

furnace	starting time/day	end time/day	duration time/day	Running capacity change time/day
1	190.7	0	65.3	15
	2	75.2	73.2	4
	78.2	132.5	54.2	13
	134.5	188.7	54.3	7
2	192.7	14.9	78.2	15
	16.9	116.9	100	15
	119.9	190.7	70.8	11
3	249	46.7	53.7	11
	48.7	113.9	65.2	10
	116.9	192.7	75.8	16
	195.7	246	50.3	0
4	251	78.2	83.2	14
	80.2	163.6	83.4	13
	165.6	249	83.4	15
5	253	83.2	86.2	17
	85.2	165.9	80.7	10
	167.9	251	83.1	15
6	256	80.2	80.2	11
	83.2	167.9	84.7	14
	170.9	253	82.1	14

The scheduling result is also compared to the backup furnace mode with related industrial test data. The furnace system is running at its maximum designed capacity, and furnace five is used as the backup furnace when the system is under decoking. The related mathematical model is similar with the no backup furnace mode and the detailed scheduling results will not be explained here. We compare the flow rate information which characterize the average flow rate and fluctuation level in Fig (4)-(7). The best cycle time in '5+1'backup furnace mode is 207 days with an average profit of 268628.78\$. The average flow rate of ethylene is 501.2 ton/day in the backup furnace mode and 571.1 ton/day in the another mode, while the average flow rate of propylene is 133.2 ton/day in the backup furnace mode and 146.5 ton/day without the backup furnace. Based on the final result, it is clear that the no backup scheduling mode can prolong the total length of batch processing time and have a higher profit with increased ethylene and propylene products. Besides, the product flow rate variation is more steady in the proposed model.

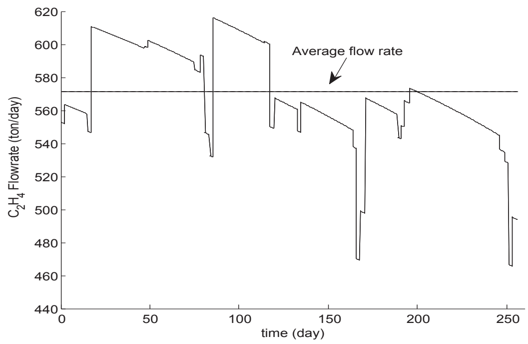

Fig. 4. Ethylene flow rate of No back-up furnace mode

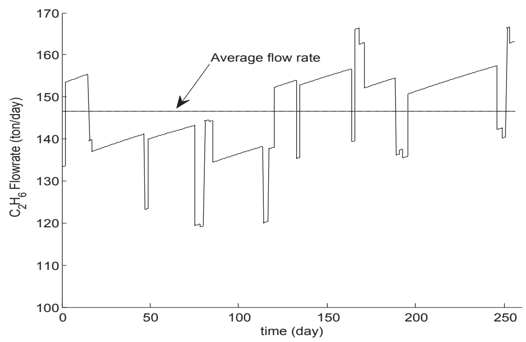

Fig. 5. Propylene flow rate of No back-up furnace mode

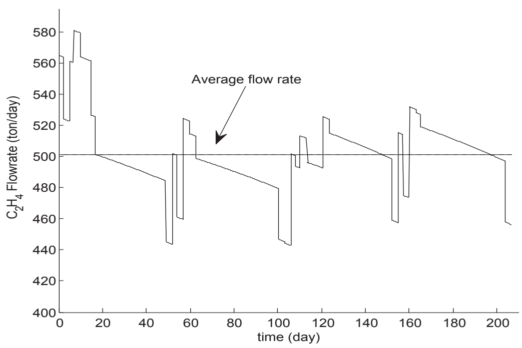

Fig. 6. Ethylene flow rate of '5+1'furnace running mode

5. CONCLUSION

The cyclic scheduling problem of no backup cracking furnace system is fully analyzed in this paper. A new MINLP model is developed with several operational characters.

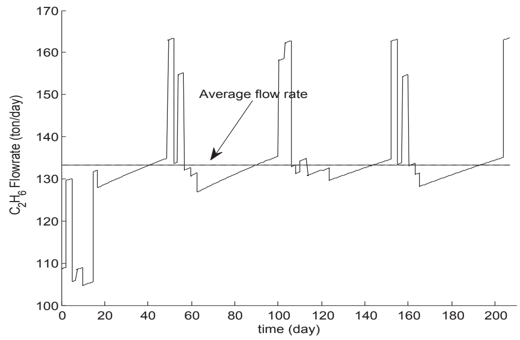

Fig. 7. Propylene flow rate of '5+1'furnace running mode

It is more practical than the previous studies considering more detailed furnace system structure and minimize the production fluctuation with the varying running capacity. The detailed batch processing time and feeds allocaction can be decided in this model. In order to solve the complex MINLP model, an iterative heuristic search solution method is also proposed. The case study and the comparison between the no backup furnace operation mode and the backup furnace opeartion mode have demonstrated the efficiency of the proposed method and proved the economic potential of the new model. Future work will be focused on how to integrate the furnace sytem with the upstream inventory management and the downstream production.

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