Hierarchical approach of planning and scheduling with demand uncertainty and utility disturbance

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***Abstract*— A hierarchical structure of planning and scheduling is introduced in this paper to jointly address the demand uncertainty and utility disturbance. In planning layer, a chance constrained programming model is involved to describe demand uncertainty. In scheduling layer, a vari-period scheduling strategy is proposed to solve the mismatching between period of scheduling and duration time of utility disturbance. Complexity problem is also solved by the hierarchical structure and vari-period scheduling strategy. The planning problem is formulated by a linear programming model with certain confidence level that maximize the product profit with considering cost of backlog and changes in product process. Scheduling model is formulated by an integer nonlinear programming (INLP) with considering cost of shutdown and changes in product process. A case study oriented from process industry is introduced to illustrate the effectiveness of the proposed approaches.**

I. INTRODUCTION

Demand uncertainty which, according to Davis [1], is the most serious uncertainty compared with supply and process uncertainty, mainly arises from the fluctuation of market environment. Utility disturbance is also an important uncertain factor to production process. If utility fluctuates, the production will be affected seriously. Consequently, production planning or scheduling considering well demand uncertainty and utility disturbance is vital to the enterprise competitiveness.

Many approaches have been proposed to address the uncertain demand problem. Moreno and Montagna [2] proposed a two-stage stochastic multi-period LGDP (linear generalized disjunctive programming) model to solve the integrated design and production planning of multiproduct batch plants under demand uncertainty, and through a set of scenarios to represent uncertainty in product demands. A hybrid programming model incorporating the linear programming model with uniform distribution assumption for refinery production planning under demand uncertainty is introduced by Li and He [3]. Fuzzy set theory and robust optimization methodology are also introduced in some literatures to handle demand uncertainty [4,5,6]. Approaches addressing demand uncertainty has been considerably exploited in literatures and has proven to provide reliable and practical results for optimization.

Compared with demand uncertainty, only fewer researchers have studied production planning and scheduling under utility disturbance. As early as the late 80s, some researchers had focused on the synthesis of utilities to satisfy demand [7,8,9]. However, none of these studies treat the problem of how to control the production at utility disturbances. Until recently, Lindholm and Johnsson proposed a MIQP model to present the utility disturbance in production process with the aims at minimizing the total economic loss of site[10,11,12].

Regarding the planning and scheduling under uncertainties, some studies have been done. Wu and Ierapetritou [13] proposed a multi-stage stochastic programming formulation where three stages are considered with increasing level of uncertainty to deal with uncertainties of demand and price. Chu and You [14] developed a hybrid method, which iterates between a mixed-integer linear programming solver for the planning problem and an agent-based reactive scheduling method to handle production uncertainties.

In this paper, a hierarchical structure of planning and scheduling is introduced to jointly address the demand uncertainty and utility disturbance. In planning layer, a chance constrained programming is involved to solve demand uncertainty. In scheduling layer, a vari-period scheduling strategy is proposed to solve the mismatching between period of scheduling and duration time of utility disturbance. And the complexity problem is also solved by the hierarchical structure and vari-period scheduling strategy.

II. SOLUTION APPROACH TO PROBLEMS WITH UNCERTAINTY

A. Hierarchical structure of planning and scheduling

Some literatures regard the product demand as a determinate parameter. However, the product demand is uncertain and affected by a series of factors. It is one of the most dominant uncertain parameters in the production planning problems and seriously impacts the results of production planning. As well as demand uncertainty, utility disturbance is another uncertain factor to production process. In the production process, some utilities are supplied to some areas or product lines, such as steam, cooling water and electricity. Usually, these utilities are shared by different areas. In case of the supply of utility is fluctuant, the production of areas will be affected seriously, and lead to the production planning cannot be completed, where even lead to

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shutdown of product line. For this situation, a hierarchical planning and scheduling method is proposed to deal jointly with demand uncertainty and utility disturbance. The structure of hierarchical planning and scheduling is shown in figure 1.

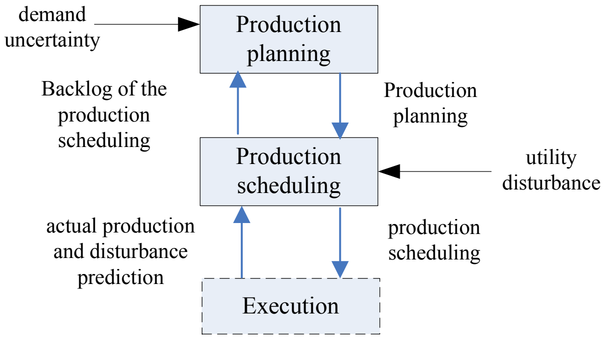

Figure 1. Hierarchical structure of planning and scheduling

Usually, hierarchical integration of planning and scheduling is to address the complexity problem for large-scale. However, hierarchical structure of planning and scheduling can also solve the problem of uncertainty within different levels in sequence [15]. The demand uncertainty and utility disturbance are inherently of respective time properties, that is, demand uncertainty should be settled within long time scale, while utility disturbance should be solved within short time scale. Consequently, it is proper to solve demand uncertainty and utility disturbance in planning layer and scheduling layer respectively.

In planning layer, chance constrained programming model is utilized to reduce the effect of demand uncertainty without considering utility disturbance, namely, the production planning is assumed without the utility limit. By means of the idea of rolling horizon, planning result of the first planning period is as task put into scheduling layer. The aim of production scheduling is to complete the task assigned from production planning with utility disturbance consideration and the backlog of production scheduling is allowed. Then the backlogs of production scheduling are as new orders of the next planning horizon put back into production planning.

B. Relationship between production rate and utility

Utility disturbance is introduced into production scheduling through the relationship between production rate of some areas and the amount of utility supplied to these areas. The operation outside the normal limits for the utility might give serious effect on the production of the areas that require the utility. When a utility operates poorly, capacity of production equipment which requires the utility is affected. How much the capacity is affected depends on how severe the disturbance is. In reality, there could be a minimum amount of a utility that is required for production areas to be able to operate [11]. In this paper, a simple linear relationship between production rate and the amount of utility supplied is supposed.

III. MODEL

A. Planning model in upper layer

In planning layer, deterministic model is proposed originally, and chance constrained programming approach is introduced to present the demand uncertainty. The demand uncertainty is supposed to follow certain probability distribution. Finally, the chance constrained programming model is transformed into a deterministic model with a confidence level.

1) Deterministic model

Mass balance constraints

$$I_{iw} = I_{i,w-1} + P_{iw} - D_{iw} - \sum_{j\in Qi} a_{ij} P_{jw}, \quad i \in A, w = 1,\dots,Np \tag{1}$$

Inventory level of tank i at the end of a period is equal to the inventory level of tank i at the end of previous period plus the difference between production of product i during period w and amount of delivery order of product i during period w minus the summation of consumption of product i during period w as a raw material of downstream.

Capacity constraints

$$p_{iw}^{\min} \le p_{iw} \le p_{iw}^{\max}, \quad i \in A_2, w = 1,\dots,Np \tag{2}$$

$$I_i^{\min} \le I_{iw} \le I_i^{\max}, \quad i \in A, w = 1,\dots,Np \tag{3}$$

Hard restrictions on production rate and inventory level are simply expressed by constraint (2) and (3).

Production rate fluctuation constraints

$$P_{iw} - x_{iw} \le P_{i,w-1} \le P_{iw} + x_{iw}, \quad i \in A_2, w = 1,\dots,Np \tag{4}$$

For reducing the change of production rate, auxiliary variable x_{iw} is introduced in constraint (4) and penalized in the objective function.

Inventory level surpassing constraints

$$I_i^{lb} - z_{iw} \le I_{iw} \le I_i^{ub} + z_{iw}, \quad i \in A_2, w = 1,\dots,Np \tag{5}$$

Auxiliary variable z_{iw} is utilized in constraint (5) to give a penalty on deviating from the reference interval in a buffer tank, where I_i^{lb} and I_i^{ub} are reference upper bound and lower bound of inventory respectively.

Backlogging constraints

$$D_{iw} \le O_{iw} + B_{i,w-1}, \quad i \in A_3, w = 1,\dots,Np \tag{6}$$

$$B_{iw} = B_{i,w-1} + O_{iw} - D_{iw}, \quad i \in A_3, w = 1,\dots,Np \tag{7}$$

Constraint (6) is another restriction that the amount of delivery order should be less than the sum of orders during current period and backlogs of previous period. The backlog of product i at the end of period w is given by constraint (7). Backlog is penalized in the objective function to avoid late delivery of order.

Objective function

$$\sum_{i\in A_2}\sum_{w=1}^{Np}[\varsigma_i m_i D_{iw} - \gamma_i m_i B_{iw} - \theta_i z_{iw} - \lambda_i x_{iw}] \qquad (8)$$

Objective function is to maximize the profit, which includes product profit, backlog cost and so on. The first term is profit on sale. The second term penalizes the backlog of order. The last two terms penalize the auxiliary variables z_{iw} and x_{iw} to consider the buffer tank reference interval and the cost of production rate changes, respectively.

2) Chance constrained programming model

Chance constrained programming model is utilized in the production planning to present the demand uncertainty as a stochastic parameter. In planning model, O_{iw} is order demand of product i in period w, which is a stochastic parameter in constraint (6) and constraint (7). The uncertain demand is assumed to follow a normal distribution , that is, $O_{iw} \sim N(\mathrm{E}\{O_{iw}\}, \mathrm{var}\{O_{iw}\})$. Confidence level α and β are assigned to reformulate the constraint (6) and (7) as

$$\Pr\{O_{iw} \ge D_{iw} - B_{i,w-1}\} \ge \alpha_i, \quad i\in A_3 \qquad (9)$$

$$\Pr\{O_{iw} \ge D_{iw} + B_{iw} - B_{i,w-1}\} \ge \beta_i, \quad i\in A_3 \qquad (10)$$

In constraint (9) and (10), $\Pr\{\bullet\}$ is the operator of the probability computation. Then transform O_{iw} to follow standard normal distribution. By applying the cumulative distribution function, constraint (9) and (10) can further be reformulated as (11) and (12).

$$\frac{(D_{iw} - B_{i,w-1}) - E\{O_{iw}\}}{\sqrt{\mathrm{var}\{O_{iw}\}}} \le \Phi^{-1}(1-\alpha_i), i\in A \qquad (11)$$

$$\frac{(D_{iw} + B_{iw} - B_{i,w-1}) - E\{O_{iw}\}}{\sqrt{\mathrm{var}\{O_{iw}\}}} \le \Phi^{-1}(1-\beta_i), i\in A \qquad (12)$$

The right hand side of the above inequations could be calculated simply. And the chance constrained programming model is transformed into a deterministic model with a confidence level.

B. Scheduling model in lower layer

The aim of scheduling is to complete the task assigned from planning under utility disturbance. Utility disturbance is introduced into scheduling by the relationship between the amount of utility supplied to areas and production rate of these areas. Utility disturbance is forecasted firstly by analyzing historic data and then put into scheduling model to optimize the operation process and reduce the influence of utility disturbance. The model of scheduling is given as follow.

Minimize

$$\sum_{i\in A_3}\left(\sum_{d=1}^{Ns} D_{id} - D_{i1}^{ref}\right)^2 + \sum_{i\in A_2}\sum_{d=1}^{Ns}\left[\eta_i pz_{id} + \theta_i z_{id} + \lambda_i x_{id}\right] \qquad (13)$$

Subject to

$$I_{id} = I_{i,d-1} + P_{id} - D_{id} - \sum_{j\in Qi} a_{ij} P_{jd}, \quad i\in A, d = 1,\ldots,Ns \qquad (14)$$

$$pz_{id}\, p_{id}{}^{\min} \le p_{id} \le pz_{id}\, p_{id}{}^{\max}, \quad i\in A_2, d = 1,\ldots,Ns \qquad (15)$$

$$P_{id} - x_{id} \le P_{i,d-1} \le P_{id} + x_{id}, \quad i\in A_2, d = 1,\ldots,Ns \qquad (16)$$

$$\sum_{i\in \mathrm{M}_k} c_{ki} P_{id} \le U_{kd}, \quad i\in A_2, k\in \kappa, d = 1,\ldots,Ns \qquad (17)$$

$$I_i^{\min} \le I_{id} \le I_i^{\max}, \quad i\in A, d = 1,\ldots,Ns \qquad (18)$$

$$I_i^{lb} - z_{id} \le I_{id} \le I_i^{ub} + z_{id}, \quad i\in A_2, d = 1,\ldots,Ns \qquad (19)$$

$$\sum_{d=1}^{Ns} D_{id} \le D_{i1}^{ref}, \quad i\in A_3, d = 1,\ldots,Ns \qquad (20)$$

$$I_{id}, P_{id}, D_{id}, \mathrm{z}_{id}, x_{id} \ge 0 \qquad (21)$$

Constraints for mass balance, inventory level, production rate change and reference interval of buffer tank in scheduling model are similar with that in planning model. Other constraints are somewhat different with planning model. The objective function consists of two terms. The first term minimizes the deviation between the amount of delivery order and the reference delivery order assigned from planning layer. The second term penalizes the shutdown of equipment, exceeding of buffer tank reference interval and the cost of production rate changes, respectively. Binary variables pz_{id} are utilized in constraint (15) to ensure that the rate of production is not between zero and minimum. pz_{id} is equal to one if equipment in stage i shuts down at period d , and zero otherwise. A big penalty is given in objective function to avoid the shutdown of equipment. Constraint (17) is a limit of utility on the rate of production. The total requirements of utility for equipment should be less than the amount of utility supplied. Constraint (20) is a restriction that the amount of delivery should be less than the reference delivery order assigned from planning.

C. Vari-period scheduling model

To manage the production better under utility disturbance, the characteristic of utility disturbance is a key problem. Utility disturbance has been forecasted in some literatures. Utility disturbance appears randomly, and the duration of utility disturbance is measured in hours or minutes. If scheduling period is larger than generic duration of utility disturbance, then production scheduling can't track the fluctuation of utility. Furthermore, utility disturbance may be disappeared before the end of scheduling period, which leads to the real product situation can't be reflected by production scheduling. In order to reduce the effect of utility disturbance better, scheduling period must match the duration of utility. Generally, most of the period of scheduling is days or longer. Obviously, the scheduling period can't match the duration of generic utility disturbance. Consequently, the scheduling period need to be shorter to match the duration of generic utility disturbance better. However, shortening the scheduling period means increasing the number of periods, which will lead to difficulty on calculated amount, and the real-time of scheduling can't be ensured. In this paper, a vari-period scheduling strategy is introduced to solve the utility disturbance considering the complexity problem.

According to predicted data of utility disturbance, the vari-period scheduling is utilized when there are utility disturbances during scheduling period, otherwise normal scheduling is involved for avoiding unnecessary complexity of calculation. The model of vari-period scheduling is given as follow.

Minimize

$$\sum_{i\in A_3}\left(\sum_{h=1}^{Nsh} D_{ih}-D_{i1}^{ref}\right)^2+\sum_{i\in A_2}\sum_{h=1}^{Nsh}\left[\eta_i pz_{ih}+\theta_i z_{ih}+\lambda_i x_{ih}\right] \quad (22)$$

Subject to

$$I_{ih}=I_{i,h-1}+P_{ih}-D_{ih}-\sum_{j\in Qi} a_{ij}P_{jh}, \quad i\in A, h=1,\ldots,Nsh \quad (23)$$

$$pz_{ih}p_{ih}{}^{\min} \le p_{ih} \le pz_{ih}p_{ih}{}^{\max}, \quad i\in A_2, h=1,\ldots,Nsh \quad (24)$$

$$P_{ih}-x_{ih} \le P_{i,h-1} \le P_{ih}+x_{ih}, \quad i\in A_2, h=1,\ldots,Nsh \quad (25)$$

$$\sum_{i\in \mathrm{M}_k} c_{ki}P_{ih} \le U_{kh}, \quad i\in A_2, k\in \kappa, h=1,\ldots,Nsh \quad (26)$$

$$I_i^{\min} \le I_{ih} \le I_i^{\max}, \quad i\in A, h=1,\ldots,Nsh \quad (27)$$

$$I_i^{lb}-z_{ih} \le I_{ih} \le I_i^{ub}+z_{ih}, \quad i\in A_2, h=1,\ldots,Nsh \quad (28)$$

$$\sum_{h=1}^{Nsh} D_{ih}^{m} \le D_{i1}^{ref}, \quad i\in A_3, h=1,\ldots,Nsh \quad (29)$$

$$I_{ih}, P_{ih}, D_{ih}, z_{ih}, x_{ih} \ge 0 \quad (30)$$

The model of vari-period scheduling is similar with normal scheduling model. However， the scheduling period is much shorter， and calculation time is also longer, especially when utility disturbance appears.

IV. CASE STUDY

In this case study, four products are produced through eight processing stages (tasks) utilizing three feeds, and there are five intermediates which include one product (product 2) in the network. This case study is similar with the example derived from Kondili [16]. STN representation is shown in fig 2, and data for the case study is illustrated in table 1 and 2.

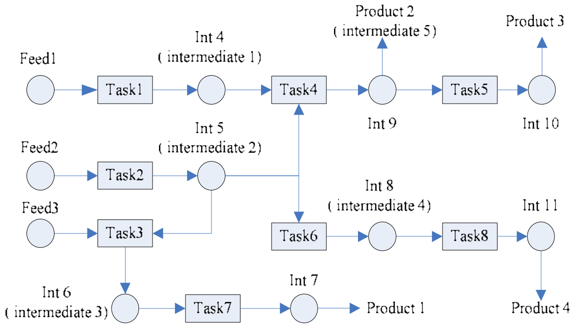

Figure 2. State Task Network for case study

A. *Planning layer simulation*

In planning layer, a one month planning problem is studied. In the 30-day planning horizon, 10 planning periods are considered, that is, 10 3-day planning periods are involved. The amount of delivery order in the first planning period is as reference delivery orders put into scheduling layer.

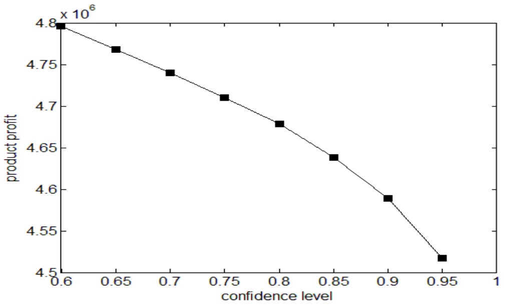

Figure 3. Product profit under different confidence level

The aim of planning layer is to pursue the most profit of enterprise; backlog cost and change cost of product process are also taken into account. Utility disturbance is not considered in this layer. Figure 3 presents the trend of product profit under different confidence level. With the increase of confidence level, the product profit reduces significantly, moreover, the response of product profit to confidence level is more sensitive.

TABLE I. DATA OF PRODUCTION CAPACITY

unit	unit1	unit2	unit3	unit4
Productin capacity	50	100	200	250
suitability	Task 3,7	Task 5,6,8	Task 2,4	Task 1

TABLE II. DATA OF INVENTORY CAPACITY

state	Feed 1,2,3	Int 4,5	Int 6,7	Int 8	Int 9	Int 10,11
Inventory capacity	unlimited	150	30	40	80	60
Initial-amount	1000	90	18	24	48	36

B. *Scheduling layer simulation*

In scheduling layer, the horizon of scheduling is 3days and the scheduling period is 1day, that is, there are three periods in production scheduling. The aim of scheduling is to complete the reference delivery orders assigned from planning with considering utility disturbance. Shutdown cost and change cost of product process are also taken into account. In all, three utilities are required for the whole process. Utilities required at each processing stage are presented in table 3.

TABLE III. UTILITIES REQUIRED AT EACH PROCESSING STAGE

Task	1	2	3	4	5	6	7	8
Utility 1	×		×	×	×		×	
Utility 2	×	×			×	×		×
Utility 3		×					×	×

In this simulation, there are two disturbances, where disturbance of utility 1 appears at hour 9 in the first day with 12-hour duration time; disturbance of utility 2 appears at hour 5 in the second day with 8-hour duration time. Figure 4 is production rates and inventories of all intermediates and products under utility disturbance. Red dashed lines in subfigure of production rate in figure 4 are maximum and minimum of production rate. Red dashed lines in subfigure of inventory in figure 4 are reference intervals of buffer tank.

Due to duration time of the two disturbances are all shorter than the scheduling period (1 day), the result of scheduling can not track the disturbances. Production rate of intermediate 3 is affected badly by the disturbance of utility 1 and keeps production rate at minimum in the whole first period to maintain the operation for avoiding shutdown. However, the disturbance of utility 1 appears at hour 9.The production rate of intermediate 3 was not affected by utility between hour 0 to hour 9. The simulation reflects that scheduling result didn’t accord with the real situation of production process owing to the mismatching of disturbance duration and scheduling period.

The inventory of intermediate 3 is also affected badly, where the buffer tank reference interval is exceeded seriously because of the production rate is too low to meet the requirement of inventory. Furthermore, the production rates of intermediates or products are change sharply, especially intermediate 1,2,3 and product 3.

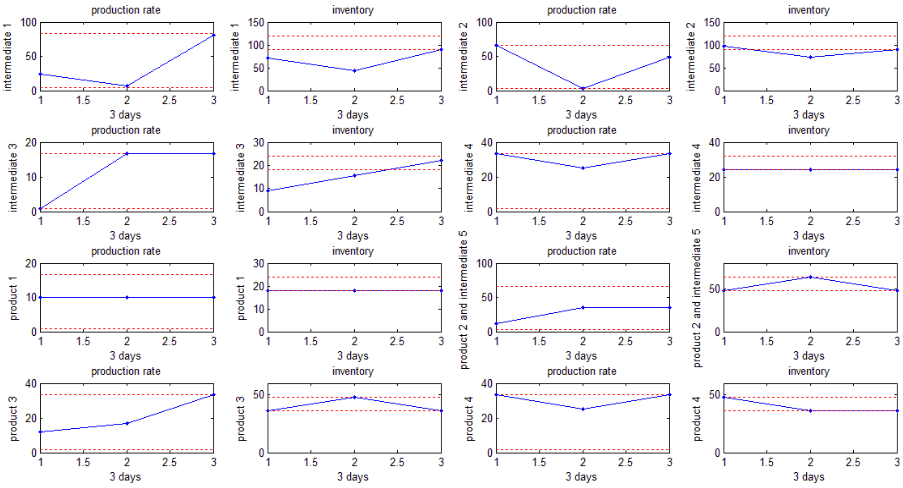

Figure 4. Normal scheduling with 3 1-day periods

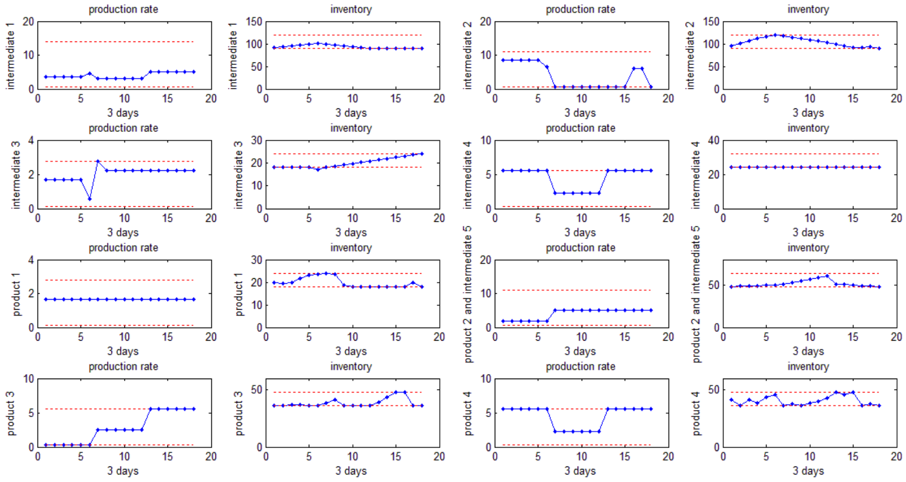

Figure 5. Vari-period scheduling with 18 4-hour periods

To solve the problem, a vari-period scheduling strategy is introduced. The previous scheduling period is divided into 6 periods, and there are 4 hours in each new period. Consequently, a 3-day scheduling horizon, 18 4-hour scheduling periods are involved. The scheduling result is shown in figure 5. Obviously, the vari-period scheduling strategy tracks the utility disturbance better, and can react flexibly according to utility disturbance. Inventory levels are all in reference intervals and changes of production rate are not too much. The objective value of normal scheduling is 4122.137 more than that of vari-period scheduling, which is 4006.769.

Regarding model scale, in normal scheduling, INLP with 630 variables which include 33 binary variable and 844 constraints which include 36 nonlinear constraints are involved. In vari-scheduling, INLP with 1850 variables which include 198 binary variables and 4723 constraints which include 72 nonlinear constraints are involved. The two INLP model are both calculate by lingo 11.0 solver in the same computer.

V. CONCLUSION

In this work, a hierarchical planning and scheduling structure are proposed to jointly address demand uncertainty and utility disturbance. Several contributions can be emphasized in this article. The idea that different uncertainties have respective time scale, which should be solved in different time layer, is pointed out. In planning layer, a chance constrained programming model is introduced to describe the demand uncertainty. In scheduling layer, a vari-period scheduling strategy is proposed to solve the mismatching between period of scheduling and duration time of utility disturbance. And the complexity problem is also solved by the hierarchical structure and vari-period scheduling strategy. A case study is applied for the proposed approaches. The experimental results show that the hierarchical planning and scheduling structure and vari-period scheduling strategy are able to address demand uncertainty and utility disturbance effectively.

NOTATION

Indices

i	product
w	planning period
d	scheduling period in normal scheduling
h	scheduling period in vari-period scheduling
k	utility
Np	number of planning periods
Ns	number of normal scheduling periods
Nsh	number of vari-period scheduling periods

Sets

A	set of materials, intermediates and products
A_2	set of intermediates and products
A_3	set of products
M_k	set of products require utility k for being produced
Q_i	set of areas directly downstream of area i

Parameters

a_{ij}	conversion factor between product i and product j
c_{ki}	utility model constant for utility k, area i
$I_i^{\min}$	minimum inventory level of tank i
$I_i^{\max}$	maximum inventory level of tank i
I_i^{lb}	lower bound of reference interval for tank i
I_i^{ub}	upper bound of reference interval for tank i
$p_{iw}^{\max}$	maximum production of product i during period w
$p_{iw}^{\min}$	minimum production of product i during period w
D_{i1}^{ref}	reference value for sales of product i in the first planning period

Variables

I_{iw}	inventory level of tank i at the end of period w
P_{iw}	production of product i during period w
D_{iw}	amount of delivery order of product i during period w
D_{id}	amount of delivery order of product i during period d
z_{iw}	auxiliary variable for buffer tank reference interval for tank i, during period w
B_{iw}	backlog of product i at the end of period w
x_{iw}	auxiliary variable for production rate changes for area i in period w
m_i	contribution margin of product i
pz_{id}	binary variable for operational mode of stage(task) i (on/off) during period d
o_{iw}	amount of order for product i in period w
U_{kd}	amount of utility k supplied during period d

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