OPTIMAL SCHEDULING OF MULTISTAGE POLYMER PLANTS

Gyeongbeom Yi
Pukyong National University
Busan, Korea 608-739

Gintaras V. Reklaitis
Purdue University
West Lafayette, IN 47906

Abstract

This article introduces a new mixed integer linear programming model of the optimal scheduling of multistage polymer plants. Most commodity polymer plants for products such as HDPE, PP, LDPE, LLDPE, PVC, PS, K-RESIN and CB are composed of reaction, extrusion and packaging stages. The operation of the reaction stage has the characteristics of both a batch process in that one process produces multiple products in sequence as well as a continuous process in that the process runs continuously during product transition and the lot size for each product is variable. The operating mode of the extrusion and the packaging stages are semi-continuous. The scheduler should reduce the number of product transition in order to reduce the sequence dependent product changeover cost in the reaction stage. However, reduction of the number of product changeovers in the reaction stage can cause the overstocking of same products and shortage of the other products in the final packaging stage. These consequences increase costs such as inventory holding cost and back-logging cost of packaged products due to late delivery.

The development of mixed integer linear programming models for optimizing a single production stage has been reported in the literature (see, for example, Karimi and Mcdonald, 1997). In this paper, we exhibit the model to include the extrusion and packaging stages into consideration under mild assumptions. The resulting large-scale model and solution strategy is tested with actual operation data collected from 5 plants.

Keywords

Multistage, Polymer, Scheduling, SOS.

Introduction

The scheduling of Polyolefin processes such as HDPE (High Density PolyEthylene), PP (PolyPropylene), LLDPE (Linear Low Density PolyEthylene) and LDPE (Low Density PolyEthylene), typical down-stream processes of naptha cracker, is the subject of this study.

Karimi and McDonald (1997) introduced two optimization models, called M1 and M2. Although the authors insisted that M2 takes much less computational time than M1, M1 has many good features for understanding the basic characteristics of polymer scheduling problem. Ierapetritou etal.(1999) proposed a simplified model. The authors proposed a binary variable dimension reduction method, which was made by separating the unit and task assignment variables.

Problem Description

Fig. 1 shows the overall production stages of a typical pelletized polymer plant. The production stages of the polymer plants are composed of reactors, silos, extruders, blenders, packaging machines and warehouse. Among these equipments, the operation of reactors is most important and the operation of other equipments is strongly dependent on the reactor operation. An example HDPE plant has two reactors and produces 17 grades. Where a grade constitutes a particular version of the product of the reactor. The reactor operates in a block mode. Most grades are already dedicated to be produced on either of two reactors but three grades can be produced on both reactors. The scheduler does his best to minimize producing grades on both reactors but it is unavoidable because the production run time of both reactors should be equalized under the block operation mode. The fluff, another name given to the reactor output product, is held temporarily in silos before it is fed to extruders for pelletization. The scheduler considers about one day of time delay in silos and does not consider more detailed operation in silos and extruders. For the bulk product, silos have the role of inventory reservoir with maximum limit. The function of a blender is to homogenize the quality of pelletized extruder output product before it is packaged but the plant scheduler ignores its detailed operation by introducing another time delay of one day. Most polymer plants have two types of multiple package machines, called bag and flecon lines. Detailed modeling for the packaging lines is not necessary because the cost of operating packaging lines is not schedule dependent. However, the scheduler should calculate the daily production quantity for each packaged product by considering total packaging capacity and off-times/off-days because packaging work is normally conducted on weekday and during the daytime by contrast to the 24 hours/day operation of the reactors.

The production sequence of grades in a reactor does significantly impact the operating cost. A certain amount of undesirable off-spec product is generated in a reactor during grade changes. This off-spec product can be sold only at much lower value than the on-spec product. The amount of off-spec product is quite different from grade to grade but the scheduler has historical records of this data, which is called type change cost. The grades are grouped into types. The grades in the same type have similar physical properties and the type change cost between grades of the same type is small or zero. The grades of the same type should be produced consecutively as much as possible in order not only to reduce the type change cost but also to reduce any possible operational troubles. The production frequency of each grade or type is a very important decision variable in the block operation. Extending the production run of a grade can reduce the total type change cost but this can cause inventory imbalance and increase the inventory holding cost of the product and the backlogging cost of the other products. Some grades or types should not be produced in sequence because of known operational difficulties. Every reactor, even in the same plant, has its own unique sequence constraints. For example, in a PP plant, an interface grade should be inserted between type changes even though there is no demand for the grade. LDPE is typically produced in increasing or decreasing sequence of Melting Index. Even if some grades do not have demand, they should be produced in a minimum amount to meet the Melting Index sequence. For LLDPE and LDPE plants, the sequence involves a reactor shutdown. The scheduler has the greatest concern about reducing the type change cost rather than other costs such as inventory holding cost and backlogging cost because type change cost is the most visible. The inventory holding cost in chemical plant is commonly considered negligible. Backlogging cost or the cost of lost sales is to be considered very important in principle but there is no way to accurately estimate it in practice. Moreover, it is very common that plants do not have the past record of backlogging or lost sales. Therefore, reducing the type change cost under the condition of satisfying unavoidable scheduling constraints is the performance index for manual scheduling. Another reason to prefer minimizing the type change cost comes from the fact that, as a result, the process operation is much smoother and less troublesome.

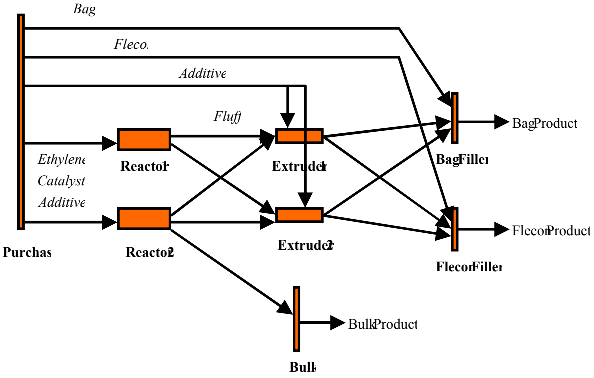


Figure 1. An Example Polymer Plant Block Diagram.

Optimization Model.

The objective function used in Karimi and Mcdonald(1997) is maximizing total profit. The total profit is composed of sales revenue - raw material purchasing cost - variable operating cost - fixed charge cost - type change cost. - inventory holding cost - penalty below safety level - back-logging cost. The constraints are composed of the timing difference between forecast and production campaign, the minimum and maximum lot size, the inventory balance caused by production and shipping, the back-logging balance caused by demand and shipping, the demand restriction, the reactor capacity limit and the insertion of the shut-down or test run. Additional constraints such as the time elapse during type change may be required in reality. The great advantage of the Karimi and Mcdonald(1997) model is that they directly resolve the timing difference between forecast and production campaign. In most cases, the demand forecast is given by time period with constant length such as 1, 5, 10 days but the production run length on reactors is variable. This part of the model constraints is most time consuming because a large number of integer variables must be introduced to define the precedence of activities. In order to improve the computational efficiency, we modified some constraints of the Karimi-Mcdonald model. The timing difference between the time periods and production campaigns are as follows;

$$\sum_t \lambda_{jkt} = 1 \qquad (1)$$

$$\sum_t DD_t \lambda_{jkt} = T_{jk} \qquad (2)$$

$$\sum_i RL_{ijkt} = DD_t \sum_{t' \le (t-1)} (\lambda_{j(k-1)t'} - \lambda_{jkt'}) \qquad (3)$$

Where DD_t is the ending time of t th period. T_{jk} is the ending time of k th campaign on j th reactor. RL_{ijkt} is the run length of i th product in t th period, k th campaign on j th reactor.

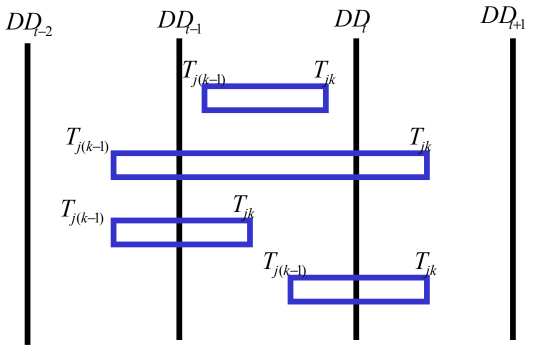
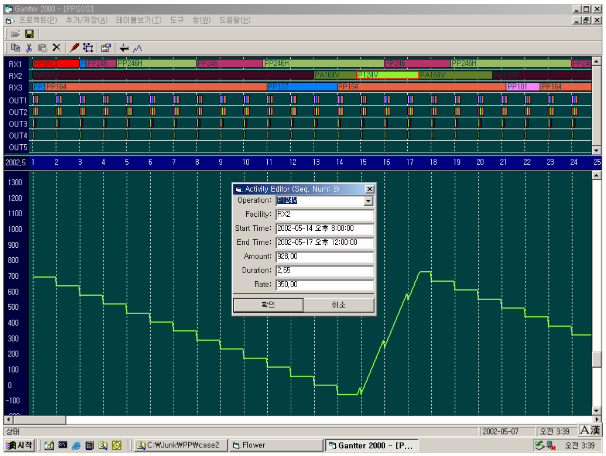


Figure 2. The four cases that k th campaign can exist in t th period.

λ_{jkt} is the second type of Specially Ordered Sets(SOS) as defined in Brooke et. al (1996). Most LP/MILP solver packages provide a special treatment for SOS variables. Eqs. (1) and (2) are very common form to be used with type two SOS variables. For example, separable programming uses the same equations. As Eq. (3) can be obtained by considering the four cases that represent the possible placements of the k th campaign in t th period as shown in Fig. 2. The first case shows that the starting and ending time of k th campaign exist within t th period. The left term of Eq. (3) represents the run length of k th campaign in t th period. At the first case, this equals $T_{jk} - T_{j(k-1)}$ because the k th campaign exists within t th period. Eq. (3) can be driven by replacing T_{jk} with Eq. (1) and (2). The remaining cases can be developed in the same way. All the other constraints are as in Karimi and Mcdonald (1997).

Performance comparison with real plant data

Fig. 3 shows a Gantt chart scheduling result of PP plant that has 3 reactors, 36 grades and 81 packaged products. We compared the computational efficiency of Karimi-Mcdonald model M1 with our modified model. The input data sets were collected from 5 polyolefin plants(HDPE, PP, LDPE, LLDPE, K-RESIN) of Daelim Industrial Company in Korea. The problem sizes of these polyolefin plant scheduling models are summarized in Table 1. The scheduling horizon for all cases was one month with one day period. The computation was performed with Pentium III 300MHz and GAMS/CPLEX 7.0. The convergence criteria were set to 10 % relative bound gap. The comparison results are summarized in Table 1. Note that the column T1+T2 represents the number of SOS Type 1 and 2 variables. The Karimi-Mcdonald model did not converged for a few cases shown as blank in CPU column. Our proposed model showed consistent convergence compared to that obtained with the Karimi-Mcdonald model.



Activity Editor (Seq. Num: 3)
Operation: P124V
Facility: RX2
Start Time: 2002-05-14 오후 8:00:00
End Time: 2002-05-17 오후 12:00:00
Amount: 928.00
Duration: 2.65
Rate: 350.00

Figure 3. Gantt Chart Result of a PP Scheduling.

Conclusions

This study concerned the production scheduling optimization of block operation processes, which can be found in many bulk polymer plants. An optimization model has been reported by Karimi and Mcdonald (1997). In this study, we introduce some modifications of Karimi-Mcdonald model. The part of the Karimi-Mcdonald model that significantly impacts computation time is to determine the precedence of campaign and forecast period timings. We modified those constraints of Karimi-Mcdonald model into a form that could use the SOS capability. The computation efficiency of our modified model was compared with the Karimi-Mcdonald model by using real operation data gathered from 5 polyolefin plants. Our proposed model showed consistent convergence over Karimi-Mcdonald model. Although computational times are too large at present for routine plant use, increase in CPU speed will permit routine use in the near future.

Table 1. Model Statistics and Comparison Results.

	K&M Variable	**K&M Constraint**	**K&M Discrete**	**K&M CPU (min)**	**K&M Gap**	**SOS Variable**	**SOS Constraint**	**SOS T1+T2 Variable**	**SOS CPU (min)**	**SOS Gap**
HDPE Case1	28762	11943	6035		0.44	26018	5845	322+958		0.93
HDPE Case2	28023	11599	6035			25182	5521	322+928	248	0.089
PP Case1	71084	19232	10193		0.55	66968	10085	607+1437	423	0.072
PP Case2	74393	20232	10517	45	0.043	70277	11085	626+1437	533	0.011
LDPE Case1	23539	8990	4903	73	0.099	21677	4916	342+619	64	0.052
LDPE Case2	21922	8495	4702	21	0.023	20060	4421	323+619	13	0.064
LLDPE Case1	40343	14899	7502	127	0.088	36619	6601	456+1278	112	0.087
LLDPE Case2	38140	14455	7283	168	0.081	34416	6157	437+1278	45	0.051
KRESIN Case1	12852	7223	3565	13	0.001	10990	3074	190+639	25	0.001
KRESIN Case2	16713	7912	4762		0.17	14851	3763	247+639	139	0.051

Nomenclature

λ_{jkt} = the second type of Specially Ordered Sets(SOS).

DD_t = the ending time of t th period.

T_{jk} = the ending time of k th campaign in j th reactor.

RL_{ijkt} = the run length of i th product in t th period, k th campaign and j th reactor.

References

Brooke, A, Kendrick D. and Meeraus A. (1996). *GAMS A User Guide*, GAMS Development Cooperation .

Karimi, I. A. and McDonald, C. M. (1997). Planning and Scheduling of Parallel Semicontinuous Processes. 2. Short-Term Scheduling. *I&EC Res.*, **36**, 2701.

Ierapetritou, M. G., Hene T. S. and Floudas C. A. (1999). Effective Continuous-Time Formulation for Short-Term Scheduling. 3. Multiple Intermediate Due Dates, *I&EC Res.*, **38**, 3446.