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Optimum multi-plant, multi-supplier production planning for multi-grade petrochemicals

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A mixed-integer linear programming model is presented for the optimum planning of multi-plant, multi-supplier, and multi-grade petrochemical production. In the production of multiple grades of a given petrochemical product, the amount of transitional off-spec production depends on the sequencing of different grades. For each time period, the discrete-time model determines the optimum mix of petrochemical grades for each plant, the quantity to produce of each selected grade, and the optimum production sequence of different grades. In addition, assuming limited raw-material availability, the model determines the quantity of each raw material to purchase from each supplier. The model incorporates demand, capacity, raw-material availability, and sequencing constraints in order to maximize total profitability. The model is applied to real-life data from multi-grade polypropylene production in a large petrochemical company.

Keywords: mixed-integer linear programming; multi-grade polypropylene; petrochemical production; production planning and scheduling; sequence-dependent switch-overs

1. Introduction

The petrochemical industry is increasingly competitive. During the last few years, the impact of globalization, the World Trade Organization, and increasing environmental regulation has put increasing pressures on petrochemical producers around the world. In order to compete globally, petrochemical industries in Saudi Arabia have been looking for ways to maximize both management effectiveness and manufacturing efficiency. In order to achieve these goals, petrochemical companies have resorted to several modern approaches, aiming to minimize costs and maximize profitability. These include, for example, enterprise-resource-planning systems, supply-chain management, and optimization tools such as linear and integer programming.

In the production of many petrochemicals, it is possible to produce several grades of each product by altering the production conditions (i.e. chemical-reaction-process variables). For example, temperature, pressure, and feed rates of raw materials and catalyst are manipulated in order to control the density, melt flow rate, and production rate of various grades. Different grades of the same petrochemical product differ from each other in chemical and physical properties and therefore in the industrial or consumer use, which leads to widely varying levels of demand. Moreover, the grades vary in their raw-material consumption, production cost, and selling price.

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When switching from one grade to another, there is a changeover period in the reactor, in which a certain amount of transitional material is produced that does not conform to the specification of either grade. Naturally, the non-conforming, 'off-spec' material has a much lower sales value than regular grades. The amount of this off-spec material depends on the production sequence (i.e. the preceding grade and the following grade). This is commonly referred to in the literature as sequence-dependent switch-over cost. Therefore, it is important to determine the right sequence of production of the different grades, in order to minimize off-spec production. In this article, a mixed-integer linear programming (MILP) model is presented to determine the optimum selection, quantity, and sequence of different grades in multi-grade petrochemical production.

In the following section, the relevant literature on multi-grade petrochemical production problem is reviewed. Subsequently, a discrete-time MILP model of this problem is presented. This is followed by a case-study application of this model in the multi-grade polypropylene production. Finally, conclusions are drawn and suggestions for future research are provided.

2. Literature review

Previous approaches to multi-grade petrochemical production generally fall under two main categories: control theory and optimization theory. The literature is presented, below, in that order.

Debling *et al.* (1994) used dynamic simulation to model product-grade transitions in polymerization processes. They found out that the most important factors in grade-transition performance are reactor design, residence time, and runtime per grade. Tjoat and Raman (1999) discussed the need to link the enterprise business data system and the process automation and control systems to optimize the enterprise performance. Meeting this requirement will put a challenge on the process control technology, and will lead to significant supply-chain-management effects on chemical-plant operations.

Using robust control theory, Mahadevan *et al.* (2002) proposed tools and heuristics to identify operationally difficult grade transitions in the presence of uncertainty. The relationship between the cost, gain, and time constant of each transition was investigated to determine the effect of process nonlinearities on the scheduling system. This approach was applied to the scheduling of grade transitions in an isothermal methyl methacrylate polymerization reactor. Wei *et al.* (2002) developed a nonlinear model-predictive-control approach, based on a feed-forward neural network model, to optimally control an industrial polypropylene process during grade transitions. Compared with conventional proportional–integral–derivative (or PID) controllers, this approach results in significant reductions in transition time and product variability.

Feather *et al.* (2004) presented a hybrid approach for the predictive control of polymer grade transition. The controller was represented as a MILP model, incorporating both linear switching models and operating heuristics. The approach was tested in a polypropylene reactor system, leading to robust performance under varying production conditions. BenAmora *et al.* (2004) constructed a nonlinear model predictive control using orthogonal collocation to develop model equations, and used dynamic programming to solve the resulting nonlinear equations. Using an industrial real-time optimization package, they tested the algorithm on two simulated polymerization case studies: continuous methyl methacrylate and gas-phase polyethylene.

Bosgra *et al.* (2004) developed a closed-loop stochastic predictive control framework for production scheduling of multi-grade chemical processes. The procedure involves a deterministic feed-forward optimization stage and a stochastic feedback stage. In a related work, Tousain and Bosgra (2006) formulated multi-grade production scheduling for a continuous chemical process as a MILP model. By considering grade-transition costs and sales orders and opportunities, the model integrates the economics of production and company–market interaction. The approach was illustrated on a gas phase high-density polyethylene manufacturing plant.

In the above, mathematical programming models were used within a control-theory framework. These optimization models have also been used independently. Jeong *et al.* (1997) formulated the multi-grade sequencing problem as a traveling-salesman model with the objective of minimizing off-spec production. This model was solved by three different approaches: branch and bound; dynamic programming; and neural networks. Karmarkar and Rajaram (2001) developed a mixed-integer nonlinear programming (NLP) model of the chemical-grade selection, production, and blending problem. Using heuristics and lower bounds, the model minimizes the total cost while meeting quality and demand constraints. Applied on real-life data from a large European chemical producer, the model reduced the annual costs by $5 million (7%).

Alfares and Al-Amer (2002) developed a MILP model for planning the expansion of Saudi Arabia's petrochemical industry in four product categories: propylene derivatives; ethylene derivatives; synthesis-gas derivatives; and aromatic derivatives. Considering production technologies, capacities, production costs, and selling prices, the model recommends products in each category under different scenarios. Joly *et al.* (2002) presented nonlinear and mixed-integer programming models for planning and scheduling problems in petroleum refineries. Three practical refinery applications were presented: inventory management for crude oil; production, inventory, and distribution for fuel oil and asphalt; and sequencing for liquefied petroleum gas.

Kelly (2004) highlighted key formulation principles of nonlinear optimization models used in petroleum refineries and petrochemical plants. Such models are used in production planning, process control, feedstock selection, and supply-chain management. Wang *et al.* (2006) integrated production planning and process operation into a methodology that includes modeling and solution, production planning, and process simulation and optimization. The optimum production plan is determined by linear programming, and then a stochastic search is performed in a simulation model to find the optimal operation conditions. Gubitoso and Pinto (2007) formulated an NLP model for the operational planning of an ethylene plant. Aiming to maximize net revenue, the model was applied to real-world data and analyzed under several operational scenarios.

Kelly and Zyngier (2007) used mixed-integer linear programming to model sequence-dependent switch-overs in discrete-time batch-process or continuous-process scheduling. Efficient integer cuts were developed by using a traveling-salesman formulation in which the traveling costs are equal to the sequence-dependent switch-over times. Cooke and Rohleder (2006) developed a nonlinear model for planning production and inventory in petrochemical plants that considered sequence-dependent off-grade production, inventory holding costs, and capacity constraints. The model was heuristically solved using a traveling salesman-type integer program for sequencing, and mixed-integer NLP for lot sizing and scheduling. In contrast to the above single-plant approaches, the following section presents a multi-plant, multi-supplier linear model for optimum multi-grade petrochemical production.

3. Mixed-integer linear programming model

The following MILP model is presented to determine the optimum monthly selection, quantity, and sequence of different grades in multi-grade petrochemical production. Off-spec and sequencing constraints are represented using logical binary variables. The assumptions, notation, variables, objective, and constraints of this model are presented below.

3.1. *Assumptions*

- One multi-grade petrochemical product is produced.
- Production is made in several plants.

- Each plant has a limited production capacity.
- Each plant may produce a given subset of grades.
- Each grade has different profit per unit (ton) per plant.
- Each grade has different demand per period (month).
- Each grade has different raw material usage per unit (ton) per plant.
- Demands must be satisfied unless unfeasible (insufficient capacity or raw materials).
- Each raw material has a limited supply from multiple suppliers who differ in prices and available quantities.
- In each plant, off-spec quantity, profit, and raw-material usage in the transition between two 'reactor grades' (j & h) are constant and independent of the order of j & h.

3.2. *Indices*

$i =$ plant number, $i = 1, \ldots, I$
$j =$ grade number, $j = 1, \ldots, J$
$k =$ raw material number, $k = 1, \ldots, K$
$s =$ supplier number, $s = 1, \ldots, S$

3.3. *Parameters*

C_i = production capacity of plant i in tons per month
D_j = net demand in tons for grade j per month
EP = excess production capacity of all plants
ER_k = excess availability of raw material k
EX = minimum excess capacity = $\min(EP, ER_1, \ldots, ER_K)$
M = a large number (as in the big-M method)
O_{ijh} = off-spec production per transition between grades j and h in plant i
P_{ij} = profit margin per ton of grade $j$produced in plant i (sale price minus all fixed and variable costs except raw material cost).
r_{ijk} = consumption of raw material k per ton of grade j in plant i
R_{ks} = availability of raw material k from supplier s in tons per month
T_{ijh} = profit margin of off-spec material produced in transition between grades j and h in plant i
u_{ijkh} = usage of raw material k per transition between grades j and h in plant i
V_{ks} = cost per ton of raw material k from supplier s

3.4. *Decision variables*

X_{ij} = tons of grade j produced at plant i per month
W_{ks} = tons of raw material k purchased from supplier s per month

$$Q = \begin{cases} 1, & \text{if there is excess capacity}(EX > 0) \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{ij} = \begin{cases} 1, & \text{if grade} j \text{ is produced in plant } i \\ 0, & \text{otherwise} \end{cases}$$

$$F_{ij} = \begin{cases} 1, & \text{if grade } h \text{ higher than grade } j \text{ is produced at plant } i \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{ijh} = \begin{cases} 1, & \text{if transition is made between grades } j \text{ and } h \text{ at plant } i \\ 0, & \text{otherwise} \end{cases}$$

Y_{ij}, F_{ij}, and Z_{ijh} are sequencing variables, while Q is a dependent binary slack variable.

3.5. *Objective function*

Maximize total net profit per month (profit margin minus raw material cost) of selected regular grades and off-spec produced in all plants:

$$\text{Max} \sum_{i=1}^{I} \sum_{j \in J_i}^{P_{ij} X_{ij}} + \sum_{i=1}^{I} \sum_{j \in J_i} \sum_{\substack{h \in J_i, \\ h \geq j+1}} T_{ijh} Z_{ijh} - \sum_{k=1}^{I} \sum_{s=1}^{S} V_{ks} W_{ks} \tag{1}$$

The above objective function is optimized subject to the following constraints.

3.6. *Capacity constraints*

Total amount produced per month of regular grades and off-spec material in each plant cannot exceed the plant's monthly capacity:

$$\sum_{j \in J_i} X_{ij} + \sum_{j \in J_i} \sum_{\substack{h \in J_i, \\ h \geq j+1}} O_{ijh} Z_{ijh} \leq C_i, \quad i = 1, \ldots, I \tag{2}$$

3.7. *Raw-material constraints*

The total amount consumed of each raw material k is equal to the total amount purchased per month:

$$\sum_{i=1}^{I} \left(\sum_{j \in J_i} r_{ijk} X_{ij} + \sum_{j \in J_i} \sum_{\substack{h \in J_i, \\ h \geq j+1}} u_{ijkh} Z_{ijh} \right) = \sum_{s=1}^{S} W_{ks}, \quad k = 1, \ldots, K \tag{3}$$

The amount of raw material k purchased from supplier s cannot exceed its monthly availability:

$$W_{ks} \leq R_{ks}, \quad k = 1, \ldots, K, \quad s = 1, \ldots, S \tag{4}$$

3.8. *Demand constraints*

In order to maximize total profits, the model is flexible in terms of satisfying the given monthly demands for different grades. If there is excess capacity, the given demand values are taken as lower bounds. However, in the case of insufficient capacity, the model considers these demands as upper bounds in order to preserve feasibility. If there is no excess capacity ($EX \leq 0$), then $Q = 0$ and the production of each grade should be no more than demand. If excess capacity is available

$(EX > 0)$, then $Q = 1$ and the production of each grade should be no less than demand.

$$\sum_{i=1}^{I} X_{ij} \leq D_j + MQ, \quad j = 1, \ldots, J \tag{5}$$

$$\sum_{i=1}^{I} X_{ij} \geq D_j - M(1 - Q), \quad j = 1, \ldots, J \tag{6}$$

To calculate the value of minimum excess capacity EX:

$$EP = \sum_{i=1}^{I} C_i - \sum_{j=1}^{J} D_j \tag{7}$$

$$ER_k = \sum_{s=1}^{S} R_{ks} - \sum_{i=1}^{I} \sum_{j=1}^{J} r_{ijk} D_j, \quad k = 1, \ldots, K \tag{8}$$

$$EX \leq EP \tag{9}$$

$$EX \leq ER_k, \quad k = 1, \ldots, K \tag{10}$$

To ensure Q satisfies its definition:

$$EX \leq MQ \tag{11}$$

$$QEX \geq 0 \tag{12}$$

3.9. *Sequencing constraints*

Transition can be made from grade j only to one higher grade h, given that both grades are produced in plant i.

To ensure $Y_{ij} = 1$ only if grade j is produced in plant i:

$$X_{ij} \leq MY_{ij}, \quad i = 1, \ldots, I, \quad \cup j \in J_i \tag{13}$$

$$Y_{ij} \leq X_{ij}, \quad i = 1, \ldots, I, \quad \cup j \in J_i \tag{14}$$

To ensure $F_{ij} = 1$ only if at least one grade h higher than j is produced in plant i:

$$\sum_{\substack{h \in J_i, \\ h \geq j+1}} Y_{ih} \leq MF_{ij}, \quad i = 1, \ldots, I, \quad \cup j \in J_i \tag{15}$$

$$F_{ij} \leq \sum_{\substack{h \in J_i, \\ h \geq j+1}} Y_{ih}, \quad i = 1, \ldots, I, \quad \cup j \in J_i \tag{16}$$

To ensure only one of the higher grades h is chosen as the immediate successor of grade j:

$$Z_{ijh} \leq 0.5(Y_{ij} + Y_{ih}), \quad i = 1, \ldots, I, \quad j, h \in J_i, h \geq j + 1 \tag{17}$$

$$\sum_{\substack{j, h \in J_i, \\ h \geq j+1}} Z_{ijh} \geq Y_{ij} + F_{ij} - 1, i = 1, \ldots, I, \quad j, h \in J_i \tag{18}$$

It must be noted that restricting the next reactor grade h to be higher $(h \geq j + 1)$ produces a sequence in increasing order of reactor grades. This restriction reflects the physical realities

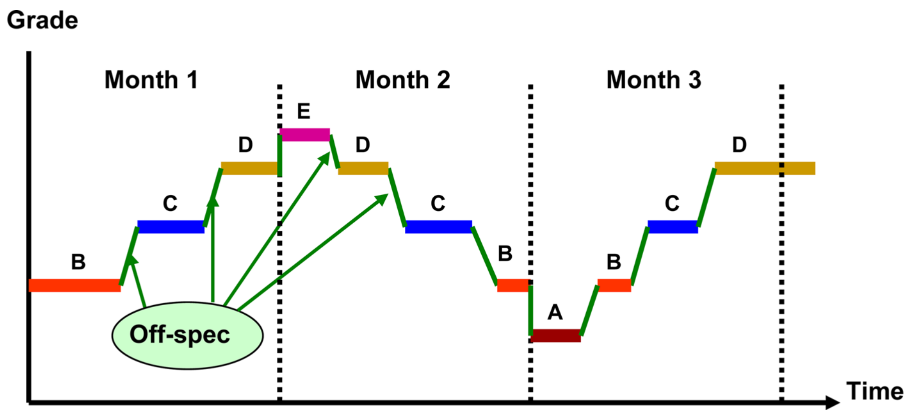

Figure 1. A sample multiple-grade production sequence.

of multi-grade petrochemical production. In order to minimize off-spec production, change in reactor grades must be as gradual as possible. Therefore, the different grades are sequenced in a cycle of two phases: one phase with increasing order of reactor grades, and the other in decreasing order (Bosgra *et al.* 2004). Since the cost structure makes it undesirable to jump grades, the above model gives a gradually increasing grade sequence for the first phase of the production cycle. This sequence is simply reversed to obtain the decreasing-order sequence for the second phase of the cycle. A sample multiple-grade production sequence is shown in Figure 1.

3.10. *Non-negativity constraints*

$$X_{ij} \geq 0, \quad i = 1, \ldots, I, \quad j = 1, \ldots, J \tag{19}$$

$$W_{ks} \geq 0, \quad k = 1, \ldots, K, \quad s = 1, \ldots, S \tag{20}$$

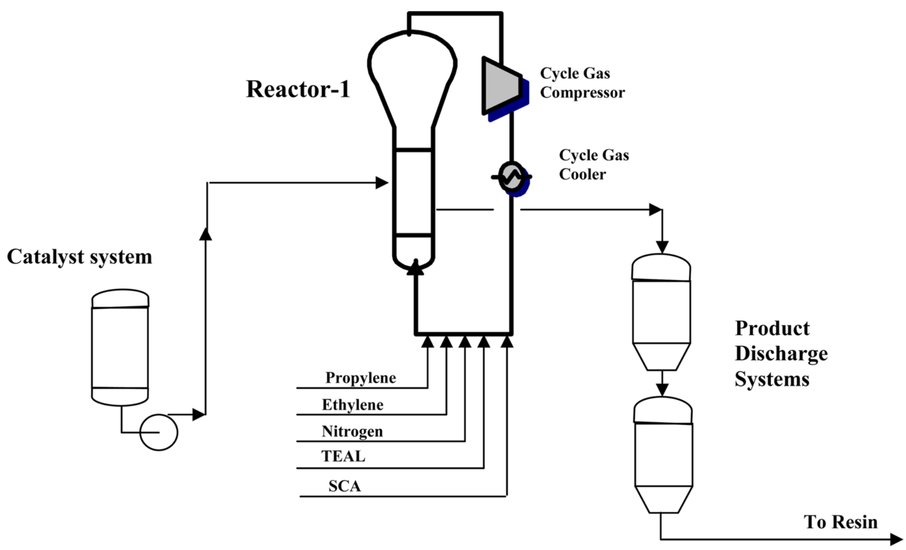

Figure 2. Schematic flow diagram of polypropylene Plant 1.

4. Case study

The above model was applied using real-life data from a large petrochemical company with two polypropylene plants. There are 14 homo-polymer polypropylene grades that can be produced in either plant, and 6 impact polypropylene grades that can be produced only in Plant 1. Although both plants are simultaneously considered in the case study, only Plant 1 data is shown in this article for the sake of brevity. Each plant has an installed capacity of 320,000 tons per year. A schematic process flow diagram of Plant 1 is shown in Figure 2.

Table 1. Polypropylene grades data relevant to Plant 1, and total monthly demand.

Grade no.	Pelleting grade	Melt flow rate	Silo size (ton)	Propylene use (ton/ton)	Demand D_j (tons/month)
1	Homopolymer	3	250	1.04	4750
2	Homopolymer	3	250	1.04	2750
3	Homopolymer	3	250	1.04	500
4	Homopolymer	12	250	1.04	750
5	Homopolymer	18	235	1.04	2250
6	Homopolymer	25	235	1.04	3525
7	Homopolymer	25	235	1.04	3525
8	Homopolymer	10	250	1.04	1250
9	Homopolymer	3	250	1.04	6500
10	Homopolymer	3	250	1.04	379
11	Homopolymer	8	250	1.04	1250
12	Homopolymer	11	250	1.04	750
13	Homopolymer	15	235	1.04	1000
14	Homopolymer	25	235	1.04	470
15	Impact	8	250	0.945	5000
16	Impact	12	250	0.945	4500
17	Impact	25	235	0.945	500
18	Impact	7	200	0.945	0
19	Impact	25	200	0.945	0
20	Impact	14	200	0.945	0

Table 2. Actual Plant 1 production of different grades in 2006.

Grade no.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	109	0	0	964	4142	2859	8185	264	1437	8012	3142	264
2	2733	1494	2985	2849	2356	0	3147	3467	1960	2806	2975	3467
3	0	498	966	456	496	0	0	0	0	490	963	0
4	65	2225	1917	3172	241	2456	4802	1109	2488	0	1389	1109
5	1115	0	2525	2496	540	2826	2855	1195	0	1420	706	1195
6	2179	7559	5479	4123	2355	8514	3274	2104	0	4939	5367	2105
7	3341	1751	4589	5183	5918	0	6123	6421	918	6380	4570	6421
8	0	4325	2358	2864	3088	2958	1232	498	0	3943	2140	498
9	6862	3137	6242	8147	3492	11740	3194	6214	252	8344	7773	6214
10	379	0	774	818	987	0	503	1356	504	975	760	1356
11	0	1409	976	2332	465	1697	646	711	0	2211	2226	711
12	0	2160	3590	3556	3116	4631	4218	1804	0	5728	481	1804
13	0	952	1928	1415	190	1625	1983	954	0	707	1932	954
14	444	0	0	2127	687	1164	1963	1629	0	940	0	1630
15	4237	0	0	0	0	0	0	0	0	0	2402	551
16	2876	612	0	0	0	0	0	0	0	0	0	3009
17	0	0	0	0	0	0	0	0	0	0	0	878
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Optimum Plant 1 production of different grades in 2006.

Grade no.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1013	0	0	0
3	0	0	0	0	0	0	0	0	250	0	0	0
4	0	0	0	0	0	0	0	0	3500	0	0	0
5	0	0	0	0	0	0	483	0	250	0	0	0
6	0	0	0	0	0	0	3290	0	2546	2492	0	0
7	0	0	0	0	2	0	6110	6086	0	7285	0	0
8	247	2047	0	0	3500	285	2501	0	0	5250	1663	0
9	6500	7000	0	0	6750	9500	7250	3750	0	13500	6000	7303
10	4122	12324	30654	32090	10819	21526	9079	15138	0	4177	14298	21967
11	1250	1500	0	796	1000	1250	1500	250	0	3500	1000	250
12	750	2250	2423	3751	3250	4750	7000	1750	0	8250	1250	500
13	1000	1000	1250	1750	1500	1750	3500	750	0	1500	1500	500
14	470	0	0	2115	1250	1410	1410	0	0	940	2115	1645
15	5000	0	0	0	0	0	0	0	0	0	3000	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1013	0	0	0
3	0	0	0	0	0	0	0	0	250	0	0	0
4	0	0	0	0	0	0	0	0	3500	0	0	0
5	0	0	0	0	0	0	483	0	250	0	0	0

For each grade, monthly demands and total actual monthly production levels in each plant were recorded for a whole year (2006). Table 1 shows data relevant to Plant 1, as well as total demand for one sample month. Table 2 shows the actual production quantities of the different grades in Plant 1.

The model was applied using the 12-monthly demand data, in order to determine the optimum monthly production quantities of different grades, as well as their sequences in each plant. Table 3 shows the production quantities of the different grades recommended by the model in Plant 1. Compared with actual production, the optimum solution increased the annual profit by \$4.7 million. In addition, in spite of abundant production capacity and raw-material availability, the actual production plan frequently failed to meet the demands of different grades. The optimum solution produced by the model eliminated all such unnecessary shortages.

The model achieves these improvements because it integrates both plants, all grades, and all relevant factors simultaneously into one optimization problem to achieve the best solution for the overall system. On the other hand, the current manual approach considers different parts of the system separately, never optimizing the system as a whole.

5. Conclusions and suggestions

In this article, a discrete-time MILP model was presented to determine the optimum selection, quantity, and sequence of producing a multi-grade petrochemical product on different plants. The model maximizes total monthly profit subject to production capacity, raw-material availability, demand, and sequence-dependent off-spec production. The model assumes multiple suppliers for each raw material, with different prices and different limited availabilities. The model adjusts the role of given demands in light of available capacity, treating them as upper bounds in case of insufficient capacity and as lower bounds in case of excess capacity.

The model has been successfully applied to real-life multi-plant, multi-grade multi-supplier polypropylene production planning in a large petrochemical company. The model generated significant additional profit when compared with the existing manual production scheduling system.

In addition, the model avoided unnecessary shortages of different grades, resulting from failures to meet demand in spite of abundant capacity. The model could be extended by including nonlinear relationships, multiple periods, and linking to inventory control. Extending the model from one period (month) to multiple periods will allow it to make scheduling as well as planning decisions.

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