A Stochastic Programming Model for Production Planning and Sequencing of multi-grade petrochemicals

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Abstract

In multi-grade petrochemical production, switching of production from one grade to another grade, a certain amount of transitional grade called off-spec is produced. The quantity of the off-spec depends on the sequencing of grades production. The off-spec is a cheap product and to enhance its quality it should be blended with premium grades. Therefore, sequencing of multi-grade petrochemical production is vital issue. Usually petrochemical production companies try to minimize off-spec production by ordering grades production according to their melt flow rates. Following the melt flow rate without taking into consideration customer needs will negatively affect the performance of the petrochemical companies. Therefore, a stochastic mixed-integer linear programming model is developed to determine the optimal production plan and the right sequence. The proposed model also take into consideration the impact of demand variations on the integrated production planning and sequencing. The model enforces the production to follow the melt flow rate and satisfy the customer demand, simultaneously. In addition, the obtained results indicate that uncertainty in demand has a high impact on the performance of the proposed model.

Keywords

Two-stage stochastic programming; Mixed-integer linear programming; Production planning and sequencing; Value of Perfect Information.

1. Introduction

The petrochemical industry is a competitive and sensitive sector. Petrochemical products are used in household, engineering plastics, automotive parts, medical appliances and prosthetic implants. Due to the multi uses of petrochemical products, globalization, governments' regulation, the global demand for petrochemical products is increasing with high rate. Therefore, petrochemical stakeholders have to look for ways to maximize both production efficiency and management effectiveness. During the last few years, it has been noticed a considerable variation in petrochemical markets. Therefore, some companies faced a budget deficit, and then some projects were stopped. Therefore, decision-makers have to adapt their production plans to tackle and incorporate any possible uncertainty.

In petrochemical production, different multi-grades are being produced from a single raw material by altering some parameters such as the temperature of reactor, the pressure of reactor, catalysts, and volume of raw materials. These grades differ in physical and chemical properties, which leads to different levels of demand, prices, and production cost. Switching production from one grade to another grade will produce a certain amount of transitional grade called off-spec. The quantity of off-spec product depends on the production sequence (i.e. the preceding grade and the following grade). Each grade has its specific melt flow rate, and to reduce the off-spec production and get a smooth production, the grades production can be ordered based on their melt flow rate. The melt flow rate is a measure of the ease of flow of melted plastic. However, following the melt flow rate without taking into consideration customer needs will negatively affect the performance of the petrochemical companies.

Usually, the off-spec has low-quality features that disable it from being sold and in rare cases, some off-spec could be sold at low price. Therefore, it is curtail to follow an optimal sequence of producing the different grades in order to minimize the off-spec production and at the same time satisfy customer needs. Therefore, in this study, a stochastic mixed integer programming approach is employed to determine production planning and the right sequence of different grades in multi-period basis and to tackle the effect of changes in demand on optimal production and sequence.

In real word situations the values of uncontrolled (uncertain) parameters are not known at the start of the planning period. The petrochemical industry is a complex and dynamic system that is subjected to uncertainties in many factors such as supply, prices and demand (Lima, Relvas, and Barbosa-Póvoa 2018). The variation in input parameters may cause potentially significant impacts on the overall performance of the petrochemical industry. Therefore, to increase the petrochemical industry performance and maintain its operations, the uncertainties must be taken into consideration during modeling. To tackle uncertainties, different approaches have been employed such as robust optimization (Chunpeng and Gang 2009; Ben-Tal and Nemirovski 1999), chance constraint optimization (Gassmann and Prékopa 2005), fuzzy programming (Herrera and Verdegay 1995), and stochastic programming (Khor et al. 2008; Birge and Louveaux 2011). The stochastic programming approach is suitable when the uncertain parameter follows a particular distribution [16].

In the last two years, huge variations in the energy demand was noted. Therefore, during modeling the petrochemical production and sequencing it is important to take into account the uncertainty in the demand and in a way to not losing market share and satisfying products demand.

The stochastic model is formulated based on the two-stage programming approach with the assumption of a finite number of realizations of the demand parameter. The two-stage stochastic programming formulation is a decision-making approach in which decisions are taken sequentially in two stages. The first stage decisions x are made before having clear information about the uncertain parameters $\lambda(\omega)$. After recognition of the uncertain parameter λ, the second stage decisions y are made. A recourse action is taken during the second stage after the uncertainty is resolved. The stochastic formulation for the two-stage problem is shown below, and its corresponding deterministic equivalent is provided in (Conejo, Carrión, and Morales 2010).

$$\text{Maximize}_x\ z = C^T x + E\{Q(\omega)\}, \qquad (1)$$
$$\text{Subjected to}\quad A\,x = b, \qquad (2)$$
$$x \in X, \qquad (3)$$

Where

$$Q(\omega) = \{\text{Maximize}_{y(w)}\ q(\omega)^T y(\omega), \qquad (4)$$
$$\text{Subjected to}\quad T(\omega)\,x + W(\omega)\,y(\omega) = h(\omega), \qquad (5)$$
$$Y(\omega) \in y \qquad (6)$$

The deterministic equivalent model of the above formulation is shown below:

$$\text{Maximize}_{x},\ y(\omega)\ z = C^T x + \sum \omega\ \pi(\omega)\ q(\omega)^T y(\omega), \qquad (7)$$
$$\text{Subjected to}\quad Ax = b, \qquad (8)$$
$$T(\omega)\,x + W(\omega)\,y(\omega) = h(\omega)\ , \qquad (9)$$
$$Y(\omega) \in y, \qquad (10)$$
$$x \in X$$

In this study, the deterministic equivalent model above will be used to model the production and sequencing of the polyethylene process. To prove the importance of considering demand as stochastic, the Expected Value of Perfect Information (EVPI) measure is used (Dantzig 1955). The EVPI represents the quantity that decision-maker(s) is willing to pay for obtaining perfect information about the future. The EVPI is calculated as the difference between the wait-and-see solutions and the stochastic solutions. The wait-and-see solution is the average of the objective function obtained by solving the problem separately for each scenario.

Several authors; Lima et al. (Lima, Relvas, and Barbosa-Póvoa 2016), AlOthman et al. (Al-Othman et al. 2008), and Leiras et al. (Leiras et al. 2013) used a stochastic programming models to tackle uncertain parameters by discretizing the normal distribution into scenarios. Several studies have been conducted on the area of optimizing and sequencing of multi-grades. Bosgra et al. (Bosgra, Tousain, and van Hessem 2004) developed a scheduling approach for multi-grade petrochemical production in a single-machine using closed-loop stochastic model predictive control. The proposed model takes into account production and sales plans. Karmarkar and Rajaram (Karmarkar and Rajaram 2001) formulated a nonlinear programming model for planning grade selection, production, and mixing. The model optimizes the production and blending costs. KElly (KElly 2004) emphasized the formulation principles of using nonlinear optimization models in production planning, process control, feedstock selection, and supply-chain management of refineries and petrochemical industries. Gubitoso and Pinto (Gubitoso and Pinto 2007) addressed the operational planning of an ethylene plant using a nonlinear programming model. The model is validated using a real-world petrochemical plant. The aim of the model is to optimize the revenue from selling of ethylene and other hydrocarbon products. Alfares (Alfares 2007) formulated a mixed-integer linear programming model for two petrochemical plants for determination of optimum production quantities and the sequence to take in processing of different grades. The model optimized the profit subject to the availability of raw materials, demand, production capacity, and the off-spec production sequence. In a later study, Alfares (Alfares 2009) extended the (Alfares 2007) work by assuming multiple suppliers of raw materials each having different prices but with limited availability.

Al-haj Ali (Al-haj Ali 2010) developed a non-linear control system that combined an off-line optimizer and non-linear model-based controller to be used in performing optimal grade transition problems in a continuous pilot plant reactor. Xu et al. (Xu et al. 2017) studied the transitions that occur between different grades and the amount of off-specs produced in the process. They employed first discretized the state and control variables to convert the optimization model into an NLP-problem. Trust region method was then integrated with swarm optimization particle. Shi et al. (Shi et al. 2014) proposed a novel mixed integer programming model using a predictive control system for a refinery system. The control system was used as a basis for refinery scheduling. Modeling of the transitions accurately and efficiently was also presented. The model also considered transitions that occur during the operations when switching the modes of operation of the various production units. Mrad and Alfares (Mrad and Alfares 2016) presented a mixed-integer linear programming model for examining a multi-period, multi-plant, and multi-supplier production planning of multi-grade petrochemical company. The model was represented using a graphical network structure. The aim of the model is to optimize the off-spec and regular grades production and sequencing decisions to improve the utilization of the facility.

Al-Amer et al. (Al-Amer, Al-Fares, and Rahman 1998) develop a mixed integer linear model for guiding and recommending petrochemical industries in Saudi Arabia to locally produce some valuable products. Kadambur, R.; Kotecha (Kadambur and Kotecha 2016) extended Al-Amer et al. (Al-Amer, Al-Fares, and Rahman 1998) work by proposing a mathematical formulation for the production planning in a petrochemical industry. Abdullah et al. (S. Abdullah, Shamayleh, and Ndiaye 2016) developed a mathematical model for multi-period planning and scheduling of a petrochemical company that runs multiple plants to produce multiple product grades using three stage production. A mixed-integer linear program was developed to integrate the planning process of selecting suppliers, lot-sizing and sequencing decisions and inventory levels as well as the logistics involving transportation and housing to minimize the total cost which contributes to overall increased efficiency of the whole supply chain of the company. Alqahtani et al. (Alqahtani, Shaikh, and Ndiaye 2018) proposed a mixed-integer linear programming model for a petrochemical plant that produces multi-grades. The focused approach was applied to the various grades by assigning focused grades or limited grades to a selected reactor based on reactor capacity and constraints. Abdullah et a. (Sari Abdullah, Shamayleh, and Ndiaye 2019) developed a MIP model that integrates lot-sizing, grades sequencing, and warehousing decisions for petrochemical supply chain.

It has been noted that researchers have optimized petrochemical production problems under the assumption of fixed and known demand. Therefore, this paper is an attempt to fill the above-mentioned gap by developing a multi-period and multi-plant stochastic mathematical model under uncertainty of demand. The impact of variation in demand on the integrated production planning and sequencing will be investigated. In addition, the transition cost is assumed to be function of the of sequence.

2. Material and Methods

In this section, the proposed two-stage stochastic mathematical model is developed under the following assumptions:

- The transition cost is estimated as the difference between the prices of premium grade minus the price of off-spec produced in the transition period between any two successive grades. In other words, the transition cost is sequence dependent and represents the loss in price of premium grades due to producing off-spec.
- Production is done in two production lines.
- Each production line has a limited capacity.
- Demand is a stochastic parameter.

The uncertain parameter is represented by discrete possible realization/scenarios with a specific probability of occurrence. The model is formulated based on a two-stage stochastic programming approach with recourse (Dantzig 1955; 2004), also known as scenario-based analysis (Birge and Louveaux 2011). The model aims to minimize the total cost; including transition cost, production cost, and holding cost. The following notations (Table 1) are used for the model formulation.

Table 1. Notations

Sets:	
i	Production line, i = 1, . . . , I,
j	Grade number, j = 1, . . . , J,
u	Scenarios, u= 1,2, . . ., U
t	Time period, t= 1, . . . , T,
Decision variables:	
P_{ijt}	A binary decision variable equals 1 if a production line i is producing grade j during time t, and 0 otherwise.
F_{ijt}	A binary decision variable equals 1 if grade h higher than j is produced in production line i during time t, and 0 otherwise.
T_{ijht}	A binary decision variable equals 1 if a transition is made between grades j and h in production line i during time t, and 0 otherwise.
X_{ijut}	Tonnes of grades j produced production line i at time period t and under in scenario u,
I_{jut}	Inventory level of grade j at time period t under scenario u,
Parameters:	
R_{ijh}	Transition cost between grade j and grade h in production line i,
C_j	Production cost of grade j,
H_{jt}	Holding cost of grade j at time period t,
D_{jut}	Demand of grade j at time period t and under scenario u,
PC_{it}	Production capacity of production line i at time t,
W_j	Warehouse capacity of grade j,
S_{jt}	Safety stock of grade j at time period t,
P_u	The likelihood of scenario u.

The objective function involves minimizing the expected total cost of production, cost of transition between grades, and cost of holding. In the first stage, the model will generate a sequence of transitions between grades, then once the information of demand has been resolved, the second decisions will be made which are the amount of production and inventory level at each period t.

$$\text{Min Z} = \sum_{\substack{h\in J_i \\ h\geq j+1}} \sum_{j\in J_i} \sum_{t} TR_{ijh}\, T_{ijht} \; + \sum_{u} p_u \left\{ \sum_{i}\sum_{j}\sum_{t} C_j\, X_{ijut} + \sum_{i}\sum_{t} H_{jt} I_{jut} \right\} \qquad (11)$$

The model will optimize the objective function subjected to the following constraints:

Equation (12) represents that the production cannot exceed the capacity of the production line i at time t and under scenario u.

$$\sum_{j \in J_i} X_{ijut} \leq PC_{it} \qquad \forall\, i, u, t \qquad (12)$$

Equation (13) represents the production will be based on the demand and inventory level of every scenario u.

$$\sum_{i} X_{ijut} + I_{jut-1} = D_{jut} + I_{jut} \qquad \forall\, j, u, t \qquad (13)$$

Equation (14) represents the remaining quantity of each grade after sale should satisfy the safety stock for all months. The level of the inventory for all months should not exceed the specified space in the warehouse.

$$I_{jut} \geq S_{jt} \qquad \forall\, j, u, t \qquad (14)$$

$$I_{jut} \leq W_j \qquad \forall\, j, u, t \qquad (15)$$

The sequencing constraints: this constraint is to make sure that grades production is following the right sequence of the reactor, to minimize the amount of transitional off-spec and number of defects. Every time period, one of grades must be produced in every production line (Production is continuous).

To verify that $P_{ijt} = 1$ only if grade i is being produced at period j in production line i under scenario u.

$$X_{ijut} \leq M\, P_{ijt} \qquad \forall j, t, u, \quad \cup\, t \epsilon j_{ik} \qquad (16)$$

$$X_{ijut} \geq M\left(P_{ijt} - 1\right) \qquad \forall\, j, t, u, \quad \cup\, t \epsilon j_{ik} \qquad (17)$$

To ensure Fijt=1 only if grade h higher than j is produced in production line i, the following two constraints should be added.

$$\sum_{h \geq j+1} P_{iht} \leq M\, F_{ijt} \qquad \forall\, i, j, t \qquad (18)$$

$$\sum_{h \geq j+1} P_{iht} \geq M\left(F_{ijt} - 1\right) \qquad \forall\, i, j, t \qquad (19)$$

To ensure one of the higher grades h is chosen as the immediate successor of grade j, the following three equations added to the model.

$$T_{ijht} \leq 0.5\left(P_{iht} + P_{ijt}\right) \qquad \forall\, i, j, t, h \geq j+1 \qquad (20)$$

$$\sum_{h \geq j+1} T_{ijht}\, P_{ijt} + F_{ijt} - 1 \qquad \forall\, i, j, t \qquad (21)$$

$$\sum_{h \geq j+1} T_{ijht} \geq 1 \qquad \forall\, i, j, t \qquad (22)$$

The following equations the non-negativity constraints and the integer decision variables.

$$P_{ijt},\, F_{ijt},\, T_{ijht} \in \{0,1\} \qquad \forall\, i,j,u,t \qquad (23)$$

$$X_{ijut},\, I_{jut} >= 0, \qquad \forall\, i,j,u,t \qquad (24)$$

3. Case study

A petrochemical company in Saudi Arabia produces a variety of petrochemical products. It has a huge division called petrochemical complex in Jubail where they have two production lines producing polypropylene products with a production capacity of 29000 and 33000 tons per month, for production lines 1 and 2, respectively. Seventeen different grades of polypropylene with different melting flow rate are produced. The forecasted monthly demand are listed in Table 2. All grades share the same raw material and also follow the same process of production. The differences between the grades are the quantity of raw material per ton and some parameters related to the production process such as temperature and pressure of reactor. A schematic process flow diagram of the two production lines is shown in Figure 1.

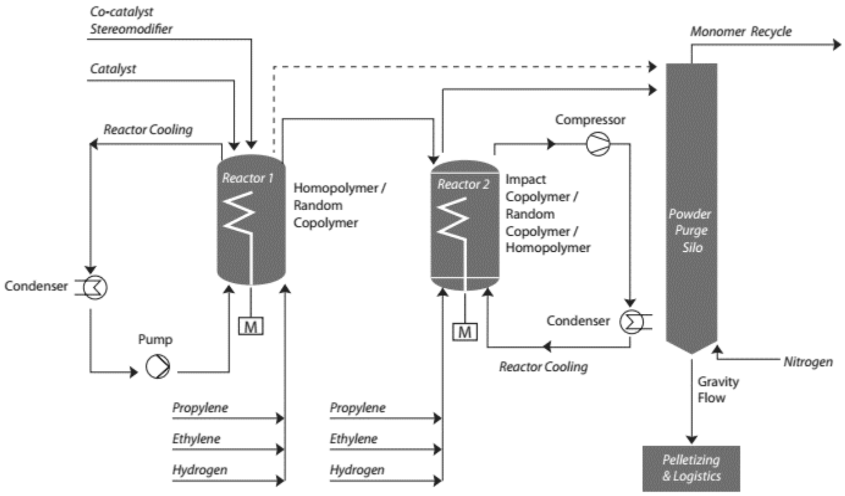


Figure 1. Schematic representation of Polypropylene production.

Even though, the production department receives the monthly demand forecasting from the marketing department at the beginning of each month. The company faces high variations in the actual demand. Therefore, to consider the effects of uncertainty in demand, stochastic model is developed based on scenario analysis. The high scenario considers a 25% higher than the current demand (base scenario), while the low scenario assumes a 25% lower than the current demand. The probabilities of the three possible scenarios (low, base, and high) are assumed to be (0.25, 0.5, and 0.25), respectively. The considered scenarios were constructed based on the expertise of employees of the industry under study.

Table 2. Demand and melt flow rate for the base case.

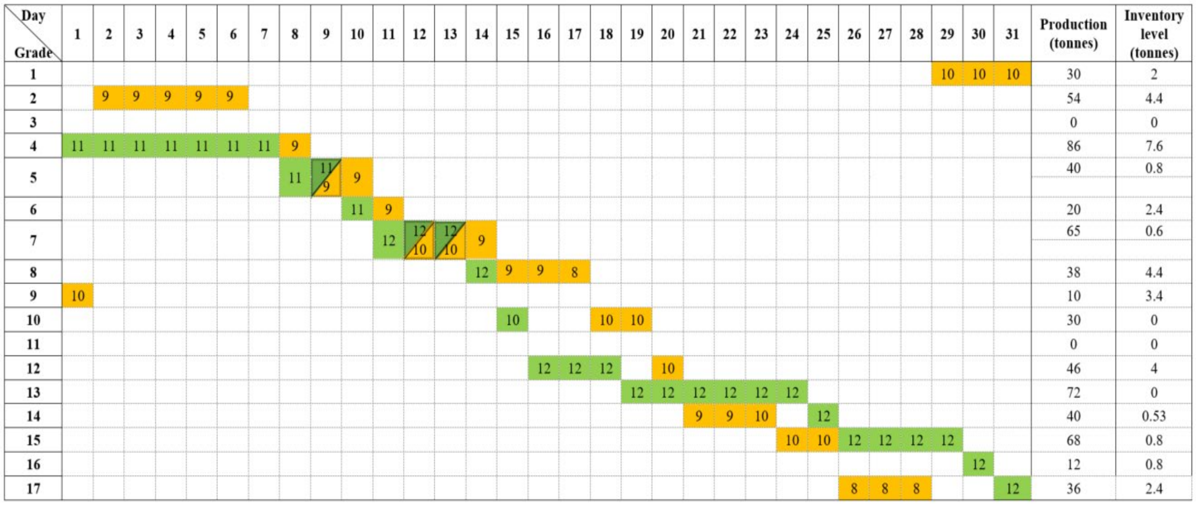
Grade no.	**Melt flow rate**	**Monthly Demand (tonnes)**											
		January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	3	2800	2500	3774	2500	2520	3700	2240	2500	3700	4500	3500	3200
2	3	4960	3360	2400	2240	1960	2200	2240	0	0	2200	2240	2156
3	3	0	280	280	560	560	200	0	0	300	300	0	243
4	7	7840	3739	4789	3739	4760	4800	3080	4200	4800	3900	4189	4529
5	8	3920	4548	4048	4998	5000	4500	2240	5100	4500	4500	5098	4059
6	8	1760	2240	4760	3920	3657	7000	3360	3600	2500	3100	3600	3597
7	10	6440	4647	4647	4647	5320	4600	4667	4600	4600	3900	2800	4665
8	12	3360	3160	4480	2800	2800	3600	2520	5000	2800	2800	3400	3406
9	12	560	400	0	550	280	500	0	600	500	100	550	412
10	14	3000	0	0	0	0	0	1960	0	0	0	1120	858

11	14	0	0	280	560	600	0	560	0	0	600	0	400
12	15	4200	4500	4200	5040	9240	1100	1120	4600	4300	5600	4480	7084
13	15	7200	7746	7746	7746	7700	7700	7756	7700	7700	9800	7746	8162
14	18	3947	5315	6440	4312	4300	5000	5040	5500	6200	5300	5600	5112
15	18	6720	8459	8259	8459	1170	8300	8259	8500	8300	10900	10459	9074
16	25	1120	1120	2550	2800	0	2500	2520	1100	800	2000	0	1277
17	25	3360	4760	4000	4647	4480	4600	4644	6440	4200	4300	5040	3250

In addition, the company suffered for years from the production of off-spec, which is produced in the transition phase. The off-spec products have low-quality features and are then sold at low prices. In 2019, the two production lines produced 6000 tons monthly of off-spec, which accounts to 10% of the total production capacity. Therefore, the management decided to change this situation by finding a way to sequence grade production, satisfy customer needs, as well as take into consideration the variation in demand. The stochastic optimization model was suggested to the management as it is a powerful tool for generating integrated optimal production and sequencing plans under uncertainty in demand.

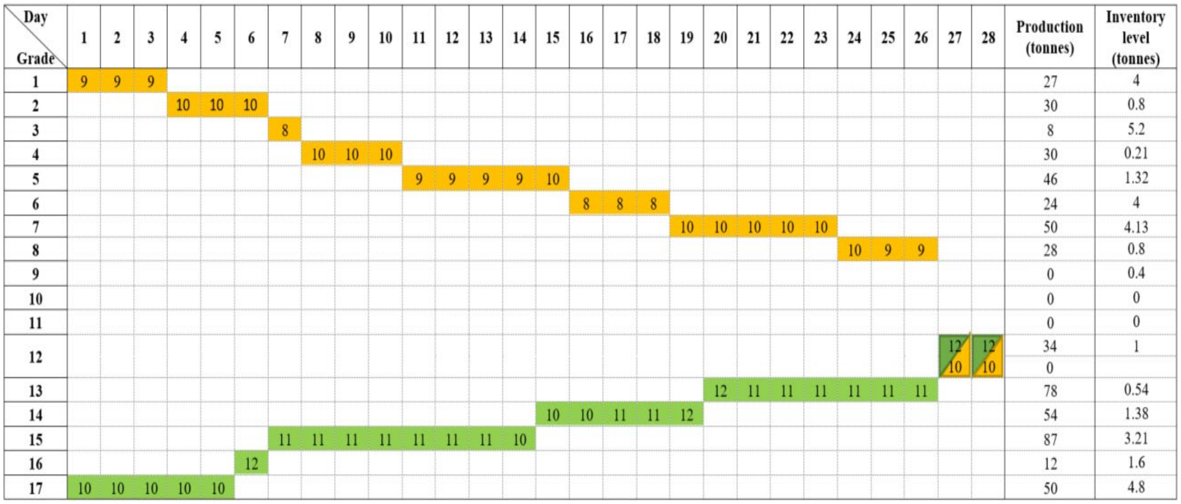
4. Results and discussion

The scenario bases stochastic model is coded and solved using the GAMS 24.1.2 -32 bit (General Algebraic Modeling System) (Brook, Kendruck, and Meeraus 1988). A PC type Intel (R) Core (TM) i7-6600U CPU processor with 2.60 GHz and 8 GB RAM was used for all computations. A sample of the optimal grades production and sequence for the base case scenario for the two production lines during January, February, and December are displayed in Figure 2. The obtained results shows that the stochastic MIP model enforces the production to follow the melt flow rate and at the same time satisfy the customer needs, simultaneously.



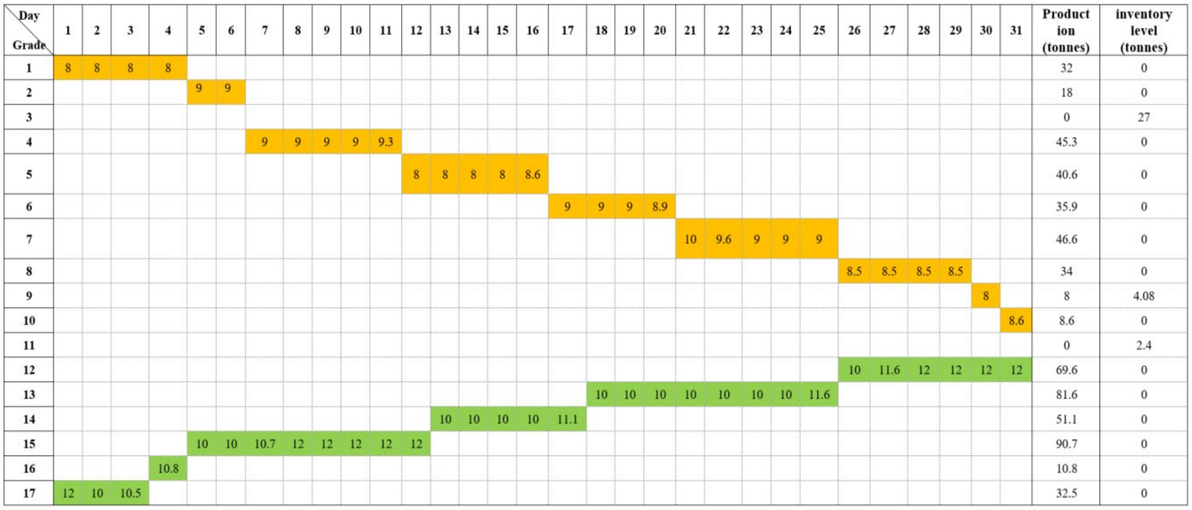
Day Grade	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Production (tonnes)	Inventory level (tonnes)
1																													10	10	10	30	2
2		9	9	9	9	9																										54	4.4
3																																0	0
4	11	11	11	11	11	11	11	9																								86	7.6
5								11	11 9	9																						40	0.8
6										11	9																					20	2.4
7											12	12 10	12 10	9																		65	0.6
8														12	9	9	8															38	4.4
9	10																															10	3.4
10															10			10	10													30	0
11																																0	0
12																12	12	12		10												46	4
13																			12	12	12	12	12	12								72	0
14																					9	9	10		12							40	0.53
15																								10	10	12	12	12	12			68	0.8
16																														12		12	0.8
17																										8	8	8			12	36	2.4

a) Production and sequencing for January



Day Grade	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Production (tonnes)	Inventory level (tonnes)
1	9	9	9																										27	4
2				10	10	10																							30	0.8
3							8																						8	5.2
4								10	10	10																			30	0.21
5											9	9	9	9	10														46	1.32
6																8	8	8											24	4
7																			10	10	10	10	10						50	4.13
8																								10	9	9			28	0.8
9																													0	0.4
10																													0	0
11																													0	0
12																											12 10	12 10	34 0	1
13																				12	11	11	11	11	11	11			78	0.54
14															10	10	11	11	12										54	1.38
15							11	11	11	11	11	11	11	10															87	3.21
16						12																							12	1.6
17	10	10	10	10	10																								50	4.8

b) Production and sequencing for February



Day Grade	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Production (tonnes)	inventory level (tonnes)
1	8	8	8	8																												32	0
2					9	9																										18	0
3																																0	27
4							9	9	9	9	9.3																					45.3	0
5												8	8	8	8	8.6																40.6	0
6																	9	9	9	8.9												35.9	0
7																					10	9.6	9	9	9							46.6	0
8																										8.5	8.5	8.5	8.5			34	0
9																														8		8	4.08
10																															8.6	8.6	0
11																																0	2.4
12																										10	11.6	12	12	12	12	69.6	0
13																		10	10	10	10	10	10	10	11.6							81.6	0
14													10	10	10	10	11.1															51.1	0
15					10	10	10.7	12	12	12	12	12																				90.7	0
16				10.8																												10.8	0
17	12	10	10.5																													32.5	0

c) Production and sequencing for December
Figure 2. Optimal production plans and sequences of multi-grade during three selected months. (Orange color for production line 1 and green color for production line 2)

The ability of the stochastic programming approach to capture uncertainty in demand is evaluated using the Expected Value of Perfect Information (EVPI). The EVPI measure is determined as the difference between the stochastic solution and the wait-and–see solution and it indicates how much it is worth to know the future with full certainty. The stochastic solution was equal to $23.5 million which is 4% better than the actual cost of year 2019. The wait-and-see solution is $21.7 million.

Therefore, the Expected Value of Perfect Solution is $1.8 million which represents the amount that the decision-maker is willing to pay for obtaining perfect information about the demand. This indicates that uncertainty in demand has high impact on the generated plans. Consequently, the marketing department should accurately forecast the future demand. To summarize, the issue of uncertainty is very important in petrochemical production, and it is vital to consider randomness during optimization.

Conclusion

In this study, a stochastic mixed-integer programming model was developed to effectively integrate and determine the optimal petrochemical multi-grade production planning and sequencing on multi-period and multi-production lines. The model has been successfully applied to a real petrochemical plant in which a multi-grade polypropylene is produced. The advantage of using the stochastic modeling approach over the deterministic approach has been proven using the EVPI quality measure. The generated plans have considerably high EVPI values when considering demand as stochastic, which indicates that demand has high impact on the obtained plans. Therefore, it is vital to take care of the demand parameter during forecasting and estimation. Therefore, the aim of the proposed model is to jointly generate an optimal sequence as well as optimal production volumes to satisfy customer needs.

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