Production planning and scheduling for an iron and steel production system

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This paper considers serial multiproduct, multistage production in an iron and steel factory. Two models are developed for planning optimal production and balancing the utilization of unidentical drawing machines. The models are applied by using real data obtained from the subject factory. Sensitivity analysis is performed to give management insight on allocating budget to appropriate resources.

Keywords: production planning, production scheduling, iron and steel plant, mathematical programming

Introduction

Production systems, by and large, are complex. Oversimplification of the complexity often leads to solutions that are suboptimal and inappropriate for implementation. But with the advancement of computer technology and software engineering, many efficient programming packages have been developed for solving large, complex practical problems that formerly were inefficiently, if not impossibly, solved.

This paper concerns a real case in a steel wire department of an iron and steel factory. There are two kinds of raw materials that can be used: One is called the piano wire rod or free patenting wire rod, which has high carbon content; the other is called the patent wire rod or lead patenting wire rod, which has low carbon content. The prices of raw materials are quite different, and significant savings can be made by proper control of raw material utilization. Prices are uncontrollable, since these materials are imported.

Price differences and availabilities of raw materials and limitations of the production process capacities and storage spaces are among the major causes of difficulty in production planning. In addition, there are several nonidentical machines in some stages and a wide variety of finished goods, making scheduling and balancing utilization of machines more difficult.

This paper develops production models for proper utilization of raw materials to minimize production cost while satisfying short- and medium-term demands. It also tries to balance the capacity utilization of machines.

Process description

The production process is composed of several major stages, namely, patenting, pickling, and coating; drawing, stranding; and straightening, bluing, and packing (see Figure I).

Only the wire rod with high carbon content has to pass through the patenting furnace to change its microstructure from coarse pearlite to homogeneous austenite. It is then fed into the lead batch for transformation into fine pearlite, a structure suitable for drawing.

There are two modes of pickling and coating: batch and continuous. Batch processing proceeds one coil at a time, whereas in continuous processing, all coils of wire rod are processed simultaneously and continuously. At this stage, zinc phosphate is coated on the surface of the wire rod for protection against dies during the drawing stage.

The wire rod then passes through the drawing machines through the dies to reduce its size according to the final product specification. The process is "cold drawn," meaning that the wire rod is not heated before being drawn.

Stranding applies only to prestressed concrete (PC) strand products. PC wire products will have to go directly to the straightening machines, and then the stress is relieved by heating in the bluing furnace. The wire rod is then cooled by water and air and wound as coil for delivery to customers.

Model development

Because the problem is multiproduct, multistage production planning (see Figure I), the solution procedure is divided into two steps. The first step determines the aggregate production plan of every product and every stage in a planning horizon. The second step determines the production schedule of the drawing machine.
STAGE 3
(Drawing)

PC strand → PC wire

STAGE 4
(Straightening, Bluing & Packing)

Stage 1: Aggregate production planning model

It takes about eight hours to heat the chemical solution in the pickling and coating stage and about 24 hours to heat in the patenting furnace; thus the steel wire department has to operate three shifts in a day. Since the department hires fixed labor power and pays a fixed wage for each worker, the direct labor cost is constant for every period in the same year. Overtime cost is not considered because the capacity of the machines cannot increase with an increase of overtime. So the aggregate production planning model is a fixed work force, fixed wage without overtime model. The conditions and constraints of the model are the following:

1. The forecasted customer demand for every type of product in every time period is deterministic.
2. The planning horizon is nine months, and the duration for each production period is one month.
3. The cost of raw materials fluctuates between planning horizons.
4. Back-ordering is not allowed; that is, if demand cannot be satisfied in any period, it will be treated as a shortage amount in that period. The shortage cost is specified only for finished goods, not for raw materials nor for works-in-process (WIP). Penalty, which is assumed to be constant per unit, is incurred for any shortage of this sort.
5. The production and shortage costs are assumed to be linear during the planning horizon.
6. The inventory holding cost is assumed to be linear during the planning horizon. The average inventory level in each period is the average of initial and ending inventories in that period.
7. The setup time for each product on each machine can be ignored, since it is much less than the production time.
8. The in-process material losses are negligible.
9. Raw materials are assumed to be always available without shortage except in the first period.
10. The works-in-process and finished goods inventories are limited by storage capacity.
11. The effective working time (available time - preventive maintenance time - shutdown time - holidays) for each machine during the planning horizon is known.

The model is given below. Related models available in the existing literature include those of Gabbay, Von Lanzenauer, and Zangwill.

Minimize

\[ Z = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{i=1}^{I} C_{ijr}X_{ijt} + \left( \frac{1}{2} \right) z_{ij}(H_{ijt} - H_{ij0}) + S_{ijt} \]

subject to

1. The demand, production, inventory, and shortage equations

   Work-in-process:
   \[ H_{ijt} = H_{ijt-1} + X_{ijt} - \sum_{k=j+1}^{J} \alpha_{ik}X_{ikr} \quad \forall i, t; \quad j = 1, \ldots, J - 1 \]  

   Finished good:
   \[ H_{ijt} = H_{ijt-1} + X_{ijt} - D_{ijt} + S_{ijt} \]  

2. The storage capacity restrictions

   \[ \sum_{i=1}^{I} H_{ijt} \leq T_{jt} \quad \forall j, t \]  

3. The machine and equipment capacity restrictions

   \[ \sum_{i=1}^{I} \Gamma_{ij}X_{ijt} \leq E_{ij} \quad \forall j, t \]  

Figure 1. Production process
Step 2: Production scheduling of drawing machine stage

The purpose of this model is to make a production schedule of drawing machines for the first period. It tries to balance the utilization of drawing machines. To satisfy the solution of this model in terms of the aggregate production planning model, the input to this model is the total production amount of the drawing stage \( X_{t,1} \) in period 1, which is obtained from the solution of the aggregate production planning model.

The basic conditions of this model are the following:

1. The setup times of the dies for every product on every machine are equal.
2. The number of setups for each product on each machine is only once in a period. When a product is set up on any machine, its production is uninterrupted.
3. The setup time is treated as production loss time without considering setup cost.
4. The production costs of the same type of product on any machine are equal.
5. Machines are not identical.
6. The effective working time (available time - preventive maintenance time - shutdown time - holidays) for each machine is known.
7. The minimum working time for each machine can be assigned so as to balance the utilization of all machines.
8. The due dates of all finished goods occur at the ends of periods.

The decision variables are \( X_{t,j} \), \( H_{t,j} \), and \( S_{t,j} \). The setup cost is relatively very small and thus is ignored. All production costs are linear.

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4. The limitation of raw materials in the first period

\[
X_{t,j} \geq RM_{t,j} \quad t \in I(j); \quad j = 1, 2 \quad (8)
\]

5. The maximum allowable shortage amount of product

\[
0 \leq S_{t,j} \leq S_{t,j,\text{max}} \quad \forall t \quad (9)
\]

6. Nonnegative production restriction

\[
X_{t,j} \geq 0 \quad \forall i, j, t \quad (10)
\]

7. Nonnegative inventory restriction

\[
H_{t,j} \geq 0 \quad \forall i, j, t \quad (11)
\]

where

- \( C_{t,j} \) = additional raw material and variable operating cost to produce one unit of stage \( j \)'s product \( i \) during period \( t \)
- \( D_{t,j} \) = market demand/requirement of production stage \( j \)'s product \( i \) during period \( t \)
- \( E_{t,j} \) = available working time on stage \( j \)'s product \( i \) during period \( t \)
- \( H_{t,j} \) = amount of product \( i \) in the inventory of stage \( j \) at the end of period \( t \)
- \( I \) = total number of types of finished good
- \( k \) = set of works-in-process or finished goods produced by stage \( j \)
- \( J \) = total number of stages of the process
- \( RM_{t,j} \) = available raw material to produce stage \( j \)'s product \( i \) during period \( t \)
- \( S_{t,j} \) = unit shortage cost of stage \( j \)'s product \( i \) during period \( t \)
- \( S_{t,j} \) = amount of the demand (product \( i \), stage \( j \)) that will not be filled during period \( t \)
- \( S_{t,j,\text{max}} \) = maximum allowable shortage amount of stage \( j \)'s product \( i \) during period \( t \)
- \( T_{t,j} \) = available in-process inventory capacity in stage \( j \) during period \( t \)
- \( T_{t} \) = total effective working time during period \( t \)
- \( X_{t,j} \) = amount of product \( i \) produced in stage \( j \) during period \( t \)
- \( Z \) = the objective function value
- \( z_{t,j} \) = unit inventory carrying cost of stage \( j \)'s product \( i \) during period \( t \)
- \( \alpha_{k}^{n} \) = number of units of production stage \( j \)'s product \( i \) required to produce one unit of stage \( k \)'s \( (k = j + 1, j + 2, \ldots, J) \) product \( n \) \( (n = 1, 2, \ldots, I) \)
- \( \Gamma_{j} \) = time (including setup time) required to produce one unit of production stage \( j \)'s product \( i \)

The objective function to minimize is:

\[
Z = \sum_{m \in M(3)} \sum_{i \in I(3)} (r_{im} Y_{im} + s N_{im}) \quad (12)
\]

subject to

1. The drawing machine capacity restrictions

\[
\sum_{i \in I(3)} (r_{im} Y_{im} + s N_{im}) \leq T_{m} \quad m \in M(3) \quad (13)
\]

2. The minimum working time for each machine restrictions

\[
\sum_{i \in I(3)} (r_{im} Y_{im} + s N_{im}) \geq W_{m,\text{min}} \quad m \in M(3) \quad (14)
\]

3. The total production amount for stage 3 in the first period

\[
\sum_{m \in M(3)} Y_{im} = X_{t,1} \quad i \in I(3) \quad (15)
\]

\[
Y_{im} \leq X_{t,1} N_{im} \quad i \in I(3); \quad m \in M(3) \quad (16)
\]

4. The minimum production amount for each product type on each machine restrictions

\[
Y_{im} \geq A_{im} N_{im} \quad i \in I(3); \quad m \in M(3) \quad (17)
\]

5. Nonnegative production restrictions

\[
Y_{im} \geq 0 \quad i \in I(3); \quad m \in M(3) \quad (18)
\]
6. Setting up each product type on each machine restrictions

\[ N_{im} = 1 \quad \text{if product } i \text{ is set on machine } m \]
\[ N_{im} = 0 \quad \text{otherwise} \]  

(19)

where \( A_{im} = \min \{X_{i31}, \text{ production rate of product } i \text{ on machine } m \} \) if \( X_{i31} > 0 \)

or

\( = \text{ production rate of product } i \text{ on machine } m \) if \( X_{i31} = 0 \)

\( I(3) = \text{ set of all works-in-process produced by stage 3} \)
\( M(3) = \text{ set of all drawing machines in stage 3} \)
\( N_{im} = 1 \text{ if product } i \text{ is set on machine } m \)

or

\( = 0 \) otherwise
\( r_{im} = \text{ time (excluding setup time) required to produce one unit of product } i \text{ on machine } m \)
\( s = \text{ setup time for every type of product} \)
\( T_{im} = \text{ total available time for machine } m \)
\( W_{m,\text{min}} = \text{ minimum working time for machine } m \)
\( X_{i31} = \text{ total production amount of product } i \text{ on stage 3 during period 1 obtained from aggregate production planning model} \)
\( Y_{im} = \text{ amount of product } i \text{ produced on machine } m \)

The decision variables are \( N_{im} \) and \( Y_{im} \). This model is a mixed integer linear programming model, which can be solved by a mixed integer linear programming package on a microcomputer.

**Results**

There are several linear programming packages that can solve the models. The specific package used was a microsoftware package known as XA (SUNSET). In fact, in this case study, the results were obtained mainly by the use of the XA package on an NEC APC IV microcomputer.

Given the types of products involved, the planning model gives the best raw material mix. The model also balances the load distribution between stages. The bottleneck of the system is the drawing stage.

Two phenomenal patterns concerning inventory are noticeable. One is that inventories just before a tight period (the period at which demand is more than production capacity) are more than those during the non-tight period. The other observation is that inventories and shortages of the same finished good can occur in the same period. This is so because the model allows a shortage before a tight period, keeping some inventories. The required quantity of production in the tight period will be lower. The priority of shortage of any finished good is ordered according to the production rate of its works-in-process, from lowest to highest.

As for the scheduling model, it tries to distribute production to all machines to balance capacity utilization. Machines’ working times are balanced.

About 35 minutes of CPU time was required to obtain results from the aggregate planning model, while only 5 minutes of CPU time was needed for the scheduling model. Both were run on a NEC APC IV microcomputer using XA software.

**Rolling implementation scheme of the models**

The schematic diagram in Figure 2 shows the rolling implementation of the models. When the demands for all finished goods have been forecasted for a planning horizon (nine months) and the necessary parameters have been updated as specified, the aggregate production planning model is then run to determine the periodic production of all products in every stage during that planning horizon. This solution can be divided into two parts: The first part is the periodic production of...
all products during periods 2 to 9; the second part is the production for period 1. The former is used for future production planning, especially during periods 4 to 9. The raw material purchasing policy can be determined from this solution to prepare raw materials for future production and to minimize investment in raw materials. The latter part is used for current period production.

After obtaining the first model solution the parameters required for the second model are updated. Then the production scheduling model for the drawing stage is run to determine the production schedule of all drawing machines. These decisions are then implemented.

Concluding remarks

The XA package applied for solving these two models on a microcomputer proved to be an efficient package. Its capacity is such that it can solve even large problems with appropriate CPU time. The total CPU time for these two models is about 40 minutes, which is significantly acceptable.

The proposed production planning and scheduling system can improve and systematize several management decisions such as a raw material purchasing policy for supplying appropriate quantities to production processes, as well as an optimal production planning and scheduling policy for producing, carrying inventories, and balancing utilization of machines in the short- and medium-term.

References