Chapter 16
An Optimal Product Mix Decision Model Considering Unit-Batch-Product Level Cost for Steel Plant

Hu-sheng Lu and Guo-qiang Lv

Abstract In recent years, the iron and steel industry's operation condition has been continuously worsening, profitability reducing, thus the product mix decision (PMD) for the iron and steel enterprises became research focus to reduce manufacturing costs and maximize profits. Taking into account unit-level, batch-level and product-level cost, an integrated model conducting product mix decision for steelmaking, continuous casting and hot rolling (SM-CC-HR) process was proposed in this paper. A numerical example was presented to illustrate data input, solution method and result analysis. By comparing the model with two traditional ones, it was showed that the model attained higher profit and smoother implementation, because it traced the cost appropriately and effectively reduced the volume of left slabs in manufacturing processes and that of left steel products after order-delivery.

Keywords Activity-based costing (ABC) • Iron and steel enterprises • Product mix decision model

Introduction

With the increasingly fierce market competition and severe management environment and production process transformation, only by well coordinating product mix can iron and steel enterprises achieve high profit and low cost in current conditions. Whereas the product mix problem is to maximize profit from the mix of manufactured products subject to constraints on the available capacity of resources. Kee and Robert provided a numerical example that integrated activity-based

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R. Dou (ed.), *Proceedings of 2012 3rd International Asia Conference on Industrial Engineering and Management Innovation(IEMI2012)*,
DOI 10.1007/978-3-642-33012-4_16,

costing (ABC) with the theory of constraints (TOC) to illustrate the economic consequences of the production-related decisions. ABC and TOC represented alternative paradigms to traditional cost-based accounting systems. Both paradigms were designed to overcome limitations of traditional cost-based systems (Kee 1995). Later, Kee and Schmidt developed a more general product mix decision model that overcame the stringent requirements of the TOC and ABC and demonstrated that TOC and ABC were special cases of their model (Kee and Schmidt 2000).

On the basis of these studies, there was much work in the literature about deciding which paradigm to select for production-related decisions. Baykasoglu developed a new approach based on digraph theory and matrix algebra to quantify flexibility (Baykasoglu 2009). Balakrishnan and Chun-hung CHENG proved that LP was a useful tool in the TOC analysis by re-examining TOC and linear programming (LP) (Balakrishnan and Chun-hung Cheng 2000). Tsaia and Hung integrated ABC and performance evaluation and established the green supply chain (GSC) model which not only helped decision makers to monitor GSC comprehensive performance but also could facilitate further improvement and development of GSC management (Tsaia and Shih-Jieh Hung 2009). Weeks, Gao, Alidaeec and Rana studied the impact of two reverse logistics business strategies on profitability of the firm through operations management (OM) (Weeks et al. 2010). Souren, Ahn and Schmitz analyzed several examples, which showed that the TOC-based approach may be used within a wide range of product mix decisions and could lead, sometimes with some slight modifications, to optimal or at least acceptable solutions (Souren et al. 2005). Leaa, Fredendallb tested three alternative product-costing systems in a more realistic model of the manufacturing environment than had been used in prior tests (Bih-Ru Leaa and Fredendallb 2002). Karakas, Koyuncu, Erol and Kokangul presented a fuzzy programming for product mix selection in the light of obscure estimation of parameters for the capacities of the activities and the demands of each product (Karakas et al. 2010). Bhattacharya and Vasant used fully fuzzified-LP model to guide decision makers in finding out the optimal product mix with the higher degree of satisfaction with the lesser degree of fuzziness under tripartite fuzzy environment (Bhattacharya and Vasant 2007). Tsaia, Kuob, Linc, Kuod and Shena developed an enhanced general model that incorporated all four factors: capacity constraint, management's degree of control over resources, capacity expansions, and purchase discount to determine the optimal product mix (Wen-Hsien Tsaia et al. 2010). Hu-sheng LU, Sen WU, Bing LIU and Zhen-gang LIU developed a maximum profit flow algorithm for optimizing production planning of steel works (Hu-sheng Lu et al. 2004). Li-xin TANG reviewed the theories and methods of the planning and scheduling on the basis of the stimulation in iron and steel industry (Li-xin Tang 2005). Ren-qian ZHANG and Yi-yong XIAO built a distributed production decision model based on activity processes and the bill of materials (BOM). A heuristic algorithm was proposed to solve the model, which was based on particle swarm optimizer (PSO) (Ren-qian Zhang and Yi-yong Xiao 2007). Bo-xiong LAN, Nan JIANG and Yan ZHENG

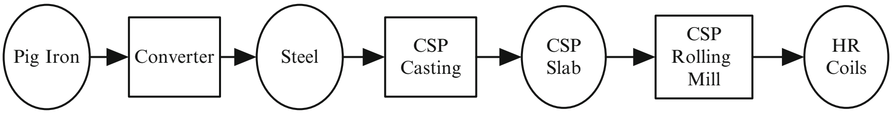

Fig. 16.1 Flow chart of CSP process

developed a heuristic lot-sizing algorithm for large scale lot-sizing problem to optimize enterprise resources (Bo-xiong Lan et al. 2010).

In this paper, the ideas of Kee (1995) and Kee and Schmidt (2000) were integrated and a more integrated model was developed which had taken into account unit-level, batch-level and product-level cost. In addition, this study also considered three-stage global optimization of steelmaking, continuous casting and hot rolling (SM-CC-HR) to help decision makers to find an optimal product mix solution.

To better understand the process, a flow chart is listed as follows:

In Fig. 16.1, circle stands for material; box stands for machine. Between two circles, there are arrows to represent the transition route.

Model Formulation

To model the product mix decision, the following notation will be used:

1. i, m, n, z represent steel product, slab, steel and pig iron index respectively.
2. j_1, j_2, j_3 represent the resource index in HR, CC and SM process respectively.
3. k_1, k_2, k_3 represent the machine index in HR, CC and SM process respectively.
4. r_1, r_2, r_3 represent the transition route index in HR, CC and SM process respectively.
5. P_i: price of product i.
6. D_i: market demand for product i.
7. $X1_i$, $Y1_m$, $Z1_n$, Z0 represent volume of steel product i, slab m, steel n and pig iron produced.
8. UC_{Z0}: unit cost of pig iron.
9. UC_{j1}, UC_{j2}, UC_{j3} represent unit cost of resources in HR, CC and SM process respectively.
10. N_{j1}, N_{j2}, N_{j3} represent quantity of resources can be obtained in HR, CC and SM process respectively.
11. $N_{j1}{*}$, $N_{j2}{*}$, $N_{j3}{*}$ represent consumption of resources in HR, CC and SM process respectively.
12. UC_{k1}, UC_{k2}, UC_{k3} represent unit cost of rolling mill, casting machine and converter hours respectively.
13. $N_{k1}{*}$, $N_{k2}{*}$, $N_{k3}{*}$ represent consumption of rolling mill, casting machine and converter hours respectively.

14. Qx1, Px1, Qx2, Px2, Qx3, Px3; Qy1, Py1, Qy2, Py2, Qy3, Py3; Qz1, Pz1, Qz2, Pz2, Qz3, Pz3 represent the amounts of resources and hours used to produce a unit of steel product/slab/steel, a batch of steel products/slabs/steels and a kind of steel product/slab/steel respectively.
15. $\rho_{A1}, \rho_{B1}, \rho_{C1}$ represent the volume of transition in HR, CC and SM process respectively.
16. $\rho_{A2}, \rho_{B2}, \rho_{C2}$ represent the number of transition batches in HR, CC and SM process respectively.
17. $\rho_{A3}, \rho_{B3}, \rho_{C3}$ determine if transition in HR, CC and SM process is taken place respectively.
18. AvgX, AvgY, AvgZ represent the average batch sizes in HR, CC and SM process respectively.
19. η_m, η_n, η represent yield in HR, CC and SM process respectively.

The process of selecting an optimal product mix may be expressed as:

Maximized profit = Total revenue-Total costs of pig iron-Total costs of resources and machine hours in SM-CC-HR process- Total fixed costs in SM-CC-HR process.

$$\begin{aligned} Maximized \quad profit = & \sum_i (P_i * X1_i) - \sum_{z0} (UC_{Z0} * Z0) \\ & - \sum_{j_1} (UC_{j_1} * N^*_{j_1}) - \sum_{j_2} (UC_{j_2} * N^*_{j_2}) - \sum_{j_3} (UC_{j_3} * N^*_{j_3}) \\ & - \sum_{k_1} (UC_{k_1} * N^*_{k_1}) - \sum_{k_2} (UC_{k_2} * N^*_{k_2}) - \sum_{k_3} (UC_{k_3} * N^*_{k_3}) - C \end{aligned} \tag{16.1}$$

Subject to

Constraints in Hot Rolling Process

Resources constraints:

$$\begin{aligned} \sum_{r_1} [& (Qx1)_{r_1,j_1} * (\rho_{A1})_{r_1} + (Qx2)_{r_1,j_1} * (\rho_{A2})_{r_1} \\ & + (Qx3)_{r_1,j_1} * (\rho_{A3})_{r_1}] - N^*_{j_1} = 0 \qquad \forall j_1 \end{aligned} \tag{16.2}$$

$$N^*_{j_1} \le N_{j_1} \qquad \forall j_1 \tag{16.3}$$

Transition level constraints:

$$(\rho_{A1})_{r_1} - AvgX_{r_1} * (\rho_{A2})_{r_1} \le 0 \qquad \forall r_1 \tag{16.4}$$

$$(\rho_{A2})_{r_1} - M\,^*(\rho_{A3})_{r_1} \leq 0 \qquad \forall r_1 \tag{16.5}$$

Sales constraint:

$$X1_i \leq D_{\mathrm{i}} \qquad \forall i \tag{16.6}$$

Machine Constraints:

$$\sum_{r_1} [(Px1)_{r_1,k_1} * (\rho_{A1})_{r_1} + (Px2)_{r_1,k_1} * (\rho_{A2})_{r_1} + (Px3)_{r_1,k_1} * (\rho_{A3})_{r_1}] - N^*_{k_1} = 0 \qquad \forall k_1 \tag{16.7}$$

$$N^*_{k_1} \leq N_{k_1} \qquad \forall k_1 \tag{16.8}$$

Constraints in Continuous Casting Process

Resources constraints:

$$\sum_{r_2} [(Qy1)_{r_2,j_2} * (\rho_{B1})_{r_2} + (Qy2)_{r_2,j_2} * (\rho_{B2})_{r_2} + (Qy3)_{r_2,j_2} * (\rho_{B3})_{r_2}] - N^*_{j_2} = 0 \qquad \forall j_2 \tag{16.9}$$

$$N^*_{j2} \leq N_{j2} \qquad \forall j2 \tag{16.10}$$

Transition level constraints:

$$(\rho_{B1})_{r_2} - AvgY_{r_2} * (\rho_{B2})_{r_2} \leq 0 \qquad \forall r_2 \tag{16.11}$$

$$(\rho_{B2})_{r_2} - M * (\rho_{B3})_{r_2} \leq 0 \qquad \forall r_2 \tag{16.12}$$

Machine constraints:

$$\sum_{r_2} [(Py1)_{r_2,k_2} * (\rho_{B1})_{r_2} + (Py2)_{r_2,k_2} * (\rho_{B2})_{r_2} + (Py3)_{r_2,k_2} * (\rho_{B3})_{r_2}] - N^*_{k_2} = 0 \qquad \forall k_2 \tag{16.13}$$

$$N^*_{k_2} \leq N_{k_2} \qquad \forall k_2 \tag{16.14}$$

Constraints in Steelmaking Process

Resources constraints:

$$\sum_{r_3} [(Qz1)_{r_3,j_3} * (\rho_{C1})_{r_3} + (Qz2)_{r_3,j_3} * (\rho_{C2})_{r_3} + (Qz3)_{r_3,j_3} * (\rho_{C3})_{r_3}] - N^*_{j_3} = 0 \qquad \forall j_3 \tag{16.15}$$

$$N^*_{j_3} \le N_{j_3} \qquad \forall j_3 \tag{16.16}$$

Transition level constraints:

$$(\rho_{C1})_{r_3} - AvgZ_{r_3} * (\rho_{C2})_{r_3} \le 0 \qquad \forall r_3 \tag{16.17}$$

$$(\rho_{C2})_{r_3} - M * (\rho_{C3})_{r_3} \le 0 \qquad \forall r_3 \tag{16.18}$$

Machine constraints:

$$\sum_{r_3} [(Pz1)_{r_3,k_3} * (\rho_{C1})_{r_3} + (Pz2)_{r_3,k_3} * (\rho_{C2})_{r_3} + (Pz3)_{r_3,k_3} * (\rho_{C3})_{r_3}] - N^*_{k_3} = 0 \qquad \forall k_3 \tag{16.19}$$

$$N^*_{k_3} \le N_{k_3} \qquad \forall k_3 \tag{16.20}$$

Mass Balance Constraints

Output constraints:

$$X1_i = \sum_{r_1} \rho_{A1} \qquad \forall i \tag{16.21}$$

$$Y1_m = \sum_{r_2} \rho_{B1} \qquad \forall m \tag{16.22}$$

$$Z1_n = \sum_{r_3} \rho_{C1} \qquad \forall n \tag{16.23}$$

Consumption constraints:

$$Y1_m \geq \sum_{r_1} \rho_{A1}/\eta_m \qquad \forall m \tag{16.24}$$

$$Z1_n \geq \sum_{r_2} \rho_{B1}/\eta_n \qquad \forall n \tag{16.25}$$

$$Z0 \geq \sum_{r_3} \rho_{C1}/\eta \tag{16.26}$$

Pig Iron's Upper Bound

$$Z0 \leq L \tag{16.27}$$

Where:

$\rho_{A2}, \rho_{B2}, \rho_{C2}$ are integer variables.
$\rho_{A3}, \rho_{B3}, \rho_{C3}$ are binary variables.

M stands for a very big number. L stands for the upper bound of pig iron. C stands for the facility-level cost (fixed cost). All variables are greater than or equal to zero.

A Numerical Example

This paper adopts the actual production data of B Iron and Steel enterprise in March 2012 to test and analyze the performance of the above model. Time horizon is 1 month. The data of this example are described as follows.

The CSP rolling mill produces nine products (Hot rolling coils), using six kinds of slabs and three kinds of steels. Table 16.1 shows the details of steel products' information and resources and machine hours' usage in the hot rolling process.

Based on the actual production data, the unit costs of pseudo-resource in SM, CC and HR are RMB 2.0, 1.7 and 1.5 respectively. Unit costs of machine hours in SM, CC and HR are RMB 0.8, 0.7 and 0.5 respectively. The average batch sizes in SM, CC and HR are 210, 5,250 and 26 t respectively.

In ABC models, the hierarchy of company activities is composed of the following categories: unit-level activities (performed one time for one unit of product or service, e.g., machining, finishing); batch-level activities (performed one time for a batch of products or services, e.g., setup, scheduling); product-level activities (performed to benefit all units of a particular product or service, e.g., product

Table 16.1 Steel products' information and resources and machine hours' usage in hot rolling process

ID	Material	Dimension	Price	Demand	Qx1	Qx2	Qx3	Px1	Px2	Px3
1	Q235AB,SS400	≥2.5 < 4.0	3623.93	18,124.25	68.401	444.606	2,171,882	0.055	1.417	0.000
2	Q235AB,SS400	<2.5	4209.40	2,028.180	82.572	536.715	238,682	0.050	1.417	0.000
3	Q235AB,SS400	≥12	4081.20	2,645.748	33.948	220.659	308,462	0.071	1.417	0.000
4	Q235AB,SS400	≥4.0 < 12	4038.46	100,115.6	48.310	314.016	11,741,076	0.063	1.417	0.000
5	Q345	≥4.0 < 12	4166.67	36,969.42	49.712	323.130	4,309,901	0.065	1.417	0.000
6	Q345	≥12	4252.14	1,154.316	39.904	259.378	134,003	0.071	1.417	0.000
7	Q345	≥2.5 < 4.0	4252.14	139.224	90.811	590.271	16,601	0.056	1.417	0.000
8	SPHC,SPHD	≥2.5 < 4.0	4294.87	60,039.08	39.405	256.130	7,117,176	0.057	1.417	0.000
9	SPHC,SPHD	<2.5	4380.34	638.808	65.837	427.938	77,045	0.051	1.417	0.000

Table 16.2 Resources and machine hours' usage in continuous casting process

Slab	Qy1	Qy2	Qy3	Py1	Py2	Py3
Y1	163.765	214,942	872,508	0.148	30.000	0.000
Y2	163.765	214,942	271,611	0.148	30.000	0.000
Y3	163.765	214,942	430,724	0.148	30.000	0.000
Y4	167.859	220,315	894,321	0.148	30.000	0.000
Y5	167.859	220,315	278,401	0.148	30.000	0.000
Y6	167.859	220,315	441,492	0.148	30.000	0.000

Table 16.3 Resources and machine hours' usage in steelmaking process

Steel	Qz1	Qz2	Qz3	Pz1	Pz2	Pz3
Z1	149.483	7,848	1,612,996	0.152	6.000	0.000
Z2	208.066	10,923	698,908	0.152	6.000	0.000
Z3	152.308	7,996	811,324	0.152	6.000	0.000

design); and facility-level activities (performed to sustain the manufacturing or service facility, e.g., plant guard and management). ABC uses these four categories of activities to facilitate the identification of costs and drivers. Furthermore, appropriate activity drivers should be chosen for different kinds of activity costs. As indicated in Tables 16.1, 16.2 and 16.3, the unit-level, batch-level and product-level resources and machine hours' usage are presented.

Based on the information provided in Tables 16.1, 16.2 and 16.3, this section runs the proposed model, which is 0–1 mixed integer linear programming model and is solved by software 'LINGO 11.0 LGSL2-112164'.

First, we name the model I considering unit-level, batch-level and product-level cost. Second, we name the model II considering unit-level and batch-level cost. And then we name the model III only considering unit-level cost. Three models are solved one by one.

A comparison between the optimal solutions of the three models is shown in Table 16.4. In that table, an income statement for the product mix selected with each model is given. The product mix selected with model III produces all the products, leading to the highest income. However, the product mix selected with the model I leads to the highest profit though products 1, 2 and 7 are not produced, because product-level cost of those three products will be reduced to zero and less fixed cost of the firm will be deducted from revenue.

Comparing model I with model II, it can be seen that profit of model II is RMB 59,283,465.45, RMB 1,360,194.00 lower than that of model I, though products 1 and 2 are produced in model II. When some products are not produced, the product-level cost of those products will be reduced to zero. As to the example, RMB 50,840,094 is declined when products 1 and 2 are not produced.

Comparing model I with model III, it can be seen that model III is not the least acceptable solution. However, both continuous casting and hot rolling are batch production process, batch size is almost constant, and batch number is integer. Extra slab (WIP) and extra steel product (finished product) will be produced if we follow the product mix plan of Model III which relaxes the integer constraints of batch number. As to the example, 133.374 t of extra steel products, 11,587.114 t of

Table 16.4 A comparison between the optimal solutions of the three models

	Model I	Model II	Model III
X1	0.000	18,080.340	18,124.250
X2	0.000	2,028.000	2,028.180
X3	2,645.748	2,645.748	2,645.748
X4	100,115.600	100,115.600	100,115.600
X5	36,969.420	36,969.420	36,969.420
X6	1,154.316	1,154.316	1,154.316
X7	0.000	0.000	139.224
X8	60,039.080	60,039.080	60,039.080
X9	638.808	638.808	638.808
Revenue	102,240,100.000	151,720,000.000	152,305,100.00
Fixed cost	41,596,440.546	92,436,534.546	92,436,534.546
Profit	60,643,659.454	59,283,465.454	59,868,565.454

Table 16.5 Left slabs in model III

Slab	Produced volume	Batch number	Left slabs
Y1	104,062.100	20	937.900
Y2	38,606.310	8	3,393.690
Y3	0.000	0	0.000
Y4	20,407.520	4	592.480
Y5	140.986	1	5,109.014
Y6	61,445.970	12	1,554.030
Batch size 5,250.000; Total left slabs 11,587.114			

extra slabs are left. Table 16.5 shows the details of left slabs. Left steel products follow the same principle.

In short, the model I can get optimal and operable solutions, and it can be used in production planning and control.

Summary and Conclusion

In this paper, a product mix model was presented with its numerical example based on the expanded ABC approach proposed by Kee (1995) and Kee and Schmidt (2000) and considered three ABC's cost levels: unit-level, batch-level and product-level for steelmaking, continuous casting and hot rolling process.

The comparisons of optimizing results with that of model considering unit-level and batch-level cost and with that of model only considering unit-level cost showed that the model not only attained higher profit, but also could be implemented smoothly. The model traced the cost appropriately and effectively reduced the volume of left slabs in manufacturing processes and that of left steel products after order-delivery.

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