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A multi-objective model for purchasing of bulk raw materials of a large-scale integrated steel plant

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Abstract

The cost of purchasing raw materials and components accounts for a significant fraction in the production and manufacturing industry. Modeling of purchasing issues and hence using quantitative methods to study the purchasing issues are significant for a purchasing decision-maker (DM) with comparable schemes. This paper is grounded on purchasing of bulk raw materials of a certain large-scale steel plant. It establishes a multi-objective linear programming model (MOLP) for the special issues of purchasing these raw materials, and indicates selecting items, selecting vendors and deciding ordering quantity as the key issue in optimizing purchasing policies. A kind of multi-objective optimal method, the point estimate weighted-sums, is used to solve this model. A group of really numeral computational results show that the model is effective and can take effect on the determination of purchasing decision. In the end of this paper, the future research directions on purchasing of raw materials are pointed out.

Keywords: Purchasing; Multi-objective linear programming; Point estimate weight-sums method; Efficient solution

1. Introduction

Since late 1960s, the purchasing issues of raw materials have been tackled well by enterprises, and it is regarded as a strategic management decision as well as a competitive weapon (Reck and Long, 1988; Browning et al., 1983; Anthony and Buffa, 1977). Essentially, this is due to the importance of the purchasing of raw materials; it is not only the beginning of all production operation activities and linked to the connection between production operation activities, but also is the major part of the production cost for an enterprise. By estimating, it has been seen to account for 60–80% (Bender et al., 1985). The question as to how to make effective purchasing policies, i.e. 'optimal purchasing policies' has come to have many new charactersistics in the recent 10 years because of that the trend of globalization of markets and development of supply chains.This important research area now is based on mathematical models and is using

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quatitative methods (Roy and Guin, 1999; Virolainen, 1998; Gunasekaran, 1999; Jahnukainen and Lahti, 1999).

This paper is based on the purchasing of raw materials of a large-scale steel plant, studies this special purchasing issue involved, proposes the multi-objective linear programming (MOLP) model for these purchasing issue and uses point estimate weighted-sums to solve it; this kind of method suggests a new mathematical attempt for purchasing issues research.

The rest of this paper is organized as follows. Section 2 describes the problems of purchasing of raw materials in a large-scale steel plant. In Section 3, we introduce this model and give a detailed description of every part of it. In Section 4, we give a real example shrunk to computation. Finally, conclusions and future research directions are drawn.

2. Problems description

2.1. The background

Fig. 1 is the raw materials supply system of a certain large-scale integrated steel plant in China. In this plant, approximately 10 million tons of steel-iron products are produced per year, they are slabs, hot rolled coils, wire, cold rolled plates, sheets, etc.; consequently, a large quantity of raw materials are required in this plant per year. The *bulk* of raw materials has over 100 items, and the total quantity reaches 30 million tons per year. Its requisite raw materials mainly supply to coking, sintering, power plant, making iron, making steel, and so on. These raw materials can be divided into four classes: basic raw materials, heavy oil, scrap steel-iron, and ferroalloy. The basic raw materials in these include primary raw materials, secondary raw materials, and fuels. The primary raw materials include iron ores (e.g., crude ore, size preparation ore, fine ore, ore screenings, pellet ore, sinter ore, etc.) and manganese

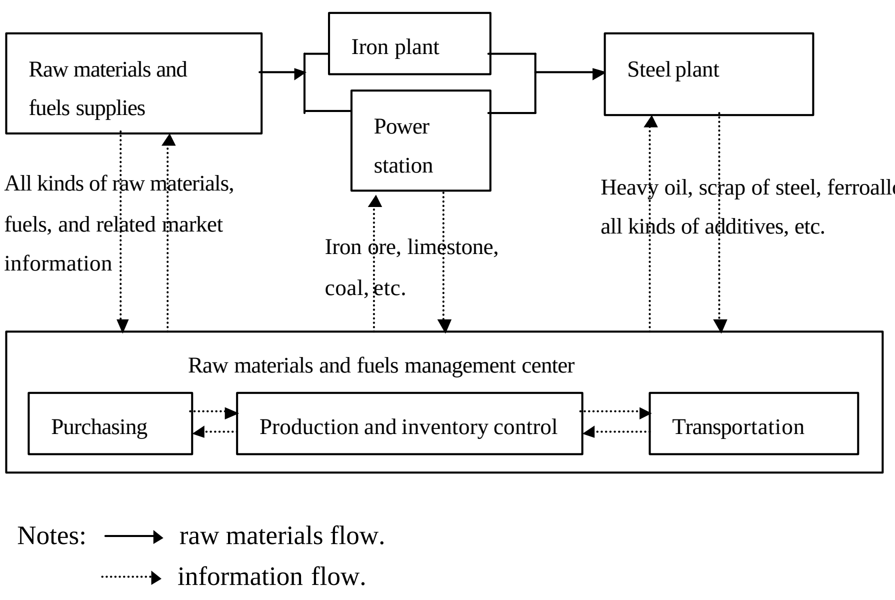

Fig. 1. Raw materials supply system.

ore. The secondary raw materials include limestone, light-burned dolomite, primary lime, etc. Fuels includes coal, coke, etc. Facing such a large requirement of raw materials in item and quantity, the question as to how to rationally organize purchasing in order to make it not only meet the production requirement, but also obtain maximum benefit from purchasing policies is important to an enterprise.

2.2. Purchasing issues of raw materials in the steel plant

The main problem of purchasing of raw materials faced is how to make purchasing decisions, in order to obtain required raw materials at lower price and in the meantime meet production demand in item, quality, quantity, due date, and so on. However, in general, this is not easy to achieve, because these criteria are often in conflict with each other. For example, the better the quality of the product, the higher the price, while the lower the price, the poorer the quality. Therefore, one of the main objectives of optimizing the purchasing decisions is often a trade-off criteria. These factors decide the complexity of making the purchasing decisions. On the other hand, we can see that the criteria mentioned above are in connection with three kinds of decisions, i.e., items decision, quantities decision and vendor selection decision. The details will be stated in the following.

First is to decide items. In the steel-iron industry, the bulk raw materials chiefly are of iron ores, secondary raw materials and fuels. There are approximately 100 items, and the meaning of item is based on the classification to which it belongs. Iron ores, secondary raw materials, and fuels can be divided further into a number of classes, and each class can then be subdivided into a number of sub-classes, e.g. the same kind of iron ore can be divided into a number of grades. Consequently, the number of the items is very large. In addition, considering various items combination situations because the steel-iron making process is a very complex metallurgical process, influenced by used raw material items, operation conditions, and working sequence, different items or items combination may produce the same molten iron or molten steel, but different items combination cost varies significantly. Consequently, how to select appropriate items is the key to reduce the production cost.

Second is to decide quantities. The steel-iron production not only requires more number of items, but also more quantity of raw materials compared to other industries. For satisfying customers' requirement, guaranteeing product quality in the steel-iron production process, different items are required in different quantities and they must satisfy definite proportionality relations. For example, in the traditional iron-making technology, the iron ore, secondary raw materials and fuels proportion are in the proportion 2:0.5:1. Therefore, for making a purchasing decision one should consider quantity proportion relations among items. We call such decision as the proportionality relation in the process as selecting 'assigning ore and assigning coal schemes'. This decision needs strong professional knowledge on steel-iron metallurgy.

Third is to select vendors. To keep the stability and quality of the supply of raw materials, a plant must consider the influence of external suppliers. Actually, this integrated steel plant has about 30 vendors distributed over the world, and every vendor supplies 1–4 kinds of bulk raw materials. Every raw material item differs from vendor to vendor in item, quality, price, service and so on. Thus selecting-vendor decision will directly affect item, quality, price decision, etc., better. Within the model, we regard the vendor selection as an important consideration. Selecting vendor and deciding the order quantity of selected vendor is also 'the vendor selection problem'. The vendor selection problem had already been studied in many papers in the past 30 years (Weber et al., 1991; Weber and Current, 1993; Pan, 1989; Verma and Pullman, 1998; Yahya and Kingsman, 1999). We focus on studying a special kind of 'the vendor selection problem' under satisfying 'assigning ore and assigning coal schemes' to purchasing of raw materials of a steel plant.

3. Model formulation

3.1. Basic assumptions

The model is a single time phase and the unit of time measure is 1 month. The demand and inventory level are given for the required raw materials.

3.2. Decision variables

Our aims of proposing the model is to decide what items of raw materials should be purchased and how much quantity order ought to be placed with each selected vendor. Therefore, we use the two-dimensional vector x_{ij} denoting the order quantity of the jth item of raw materials from the ith vendor.

3.3. Objective functions selecting

Usually, there are many objectives for purchasing decision, but the most important three factors regarded by the decision maker (DM) are quality, price, and due date (Weber et al., 1991). The unit of measure of quality is the scrap ratio of raw materials, but the unit of measure of due date is tardy-delivery fraction. Therefore, we proposed a multi-objective linear programming model with three objectives. The first objective is minimum cost, the second is lowest scrap ratio and the last is least tardy-delivery fraction. We selected the minimization objectives for all factors owing to its ready-to-use linear programming solving techniques. In addition, a multi-objective approach has several advantages over single-objective; firstly, it allows various criteria to be evaluated in their natural units of measurement and, therefore, eliminates the necessity of transforming them into a common unit of measurement such as dollars; secondly, multi-objective techniques permit the DM to incorporate personal experience and insight in the decision process; thirdly, the multi-objective approach provides the decision maker with a method to systematically analyze the effects of policy decisions on the relevant criteria space when making decisions. This very important feature makes the DM see the potential effects of different decisions. The formulations are as follows:

$$\min\left\{z1=\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij}\right\}, \tag{1}$$

$$\min\left\{z2=\sum_{i=1}^{m}\sum_{j=1}^{n}r_{ij}x_{ij}\right\}, \tag{2}$$

$$\min\left\{z3=\sum_{i=1}^{m}\sum_{j=1}^{n}s_{ij}x_{ij}\right\}, \tag{3}$$

where c_{ij} is the one unit purchasing cost of the jth item from the ith vendor, r_{ij} the tardy-delivery ratio of the jth item from the ith vendor, s_{ij} the scrap fraction of the jth item from the ith vendor, m the number of vendors, and n the number of items.

3.4. Constraints consideration

3.4.1. Purchasing budget

The purchasing capital budget depends on purchasing supply planning and the price fluctuation situation when that is considerable. The raw materials are classified into a number of classes, such as iron-ores, secondary raw materials, fuels, etc. They ought to satisfy their own the purchasing budget and at the same time, satisfy the total quantity control. Thus, the following relations exist:

$$\sum_{i=1}^{m} c_{ij}x_{ij} \leqslant c_j, \quad j = 1, 2, \ldots, n, \tag{4}$$

where m is the number of vendors, n the number of items, c_{ij} the one unit purchasing cost of the jth item of raw materials from the ith vendor, c_j the purchasing budget of the jth item of raw materials, and c the total budget for purchasing of raw materials.

3.4.2. Production demand

The raw materials purchased must satisfy demands in items, quality, and quantities in a given time period. Therefore, we have

$$\sum_{i=1}^{m} d_{ij}x_{ij} \leqslant d, \quad j = 1, 2, \ldots, n, \tag{5}$$

where d_{ij} is the unit converting rate to the requisite from the jth item of raw materials from the ith vendor, and d_j the total demand for the jth item of raw materials

3.4.3. Inventory capacity constraints

Holding safe-stock at a certain level is necessary. In general, safe-stock held in the integrated steel plant is between 15 and 50 days quantity required by production and by market supply situation, and changes as this is usually small. Here, the inventory considers quantity as well as volume. So, the relation is as follows:

$$\sum_{i=1}^{m} x_{ij} \geqslant 1.5d_j - I_{j0}, \quad j = 1, 2, \ldots, n, \tag{6}$$

$$\sum_{i=1}^{m} x_{ij} \leqslant 2.5d_j - I_{j0}, \quad j = 1, 2, \ldots, n, \tag{7}$$

where d_j is the demand of the jth item of raw materials (1 month), and I_{j0} the initial stock for the jth item of raw materials.

The formulations of (6), (7) are given by the following deductive relation:

Since, $I_j = I_{j0} + P_j - d_j$, but exists: $0.5d_j \leqslant I_j \leqslant 1.5d_j$ (by given), (6), (7) are rational, where I_j is the denoting the end inventory for the jth item of raw materials, P_j denotes the purchasing amount for the jth item of raw materials.

3.4.4. Technology constraints

In the purchasing process, we need to consider proportionality relations among a variety of items. For example, in the iron-making technology, making 1 unit molten-iron needs 2 units of iron ore, 0.5 unit lime and 1 unit coal, etc. So, the following relations hold:

$$\sum_{i=1}^{m} x_{ik} = a_{kl} \sum_{i=1}^{m} x_{il}, \quad k, l \in \{1, 2, \ldots n\}, \ k \neq l, \tag{8}$$

where a_{kl}'s are proportional constants.

3.4.5. Vendor resource constraints

Due to different geographical places, resource situations, transportation conditions, etc., the plant can get the ordering quantity from each vendor differently. So, we have

$$x_{il} \leqslant U_{il}, \quad l \in L, \tag{9}$$

where U_{il} is the maximum ordering quantity for the lth item of raw materials from the ith vendor, and L the given special set.

3.5. The multi-objective linear programming model

See Eqs. (1)–(9) above, where meaning of notations are as explained before.

3.6. Suggested solution method—point estimate weighted-sums method

The model proposed above is an MOLP model. By the theory of multi-objective optimization, the optimal solutions of the MOLP are non-inferior; that is, no solution exists that is optimal for all of the objectives; that of non-dominance or non-inferiority replaces the notion of optimality. A non-dominated or non-inferior solution is one in which an improvement in any one objective value will result in the degradation of at least one of the other objective's values. With regard to methods to solve the multi-objective programming, White (1990) gives a review. Two most commonly used methods for generating non-inferior solutions or efficient solutions to multi-objective problems are the weighting method and the constraint method. We use point estimate weight-sums method to solve these. This method is a kind of weighting method to solve MOLP; with this method, we can convert the MOLP to a general linear programming problem (LP) and obtain the efficient solution by assigning strictly positive weights.

This conclusion is guaranteed by the following two propositions:

Proposition 1. *Let $\bar{x} \in S$ minimize the weight-sums LP—$\min\{\bar{\lambda}^{\mathrm{T}} Cx | x \in S\}$, where $\bar{\lambda} \in \wedge = \{\lambda \in R^k | \lambda_i > 0, \Sigma\lambda_i = 1\}$, C is $k \times n$ criterion matrix whose rows are gradients of the k objectives. Then, $\bar{x}$ is efficient.*

Proof. Assuming $\bar{x}$ is inefficient, there exists an $x^* \in S$ such that $Cx^* \leqslant C\bar{x}$, $Cx^* \neq C\bar{x}$. Since $\bar{\lambda} \in \wedge$ is strictly positive, $\bar{\lambda}^{\mathrm{T}} Cx^* < \bar{\lambda}^{\mathrm{T}} C\bar{x}$, which contradicts the fact that $\bar{x}$ minimizes the weighted-sums LP.

Proposition 2. *Let $\bar{x} \in S$ be efficient. Then, there exists a $\bar{\lambda} \in \wedge = \{\lambda \in R^k | \lambda_i > 0, \Sigma\lambda_i = 1\}$ such that $\bar{x}$ is a minimal solution of $\min\{\bar{\lambda}^T Cx | x \in S\}$.*

Proof. Leaving out, the interested readers consult Steuer (1986).

4. Computational results

4.1. Data collection and model processing specification

The resource of data for this concrete model comes from a certain large-scale steel plant. This plant has 30 vendors and 100 items. We selected the 3 months data from real purchasing business and shrunk this real problem model to have only 7 vendors and 13 items that belong to four large kinds of bulk raw materials—F, L, P and C, respectively. F, L, P, and C denote fine ore, lump ore, pellet, and coal, respectively. In addition, due to the point estimate weighted-sums method to our problem. We often have a need to scale the objective functions for normalization; we used this kind of scaling method to our model. The coordinated model is as follows:

$$
\begin{aligned}
\text{(P) Min } Z &= \{Z1, Z2, Z3\} \\
&= \{(0.112x_{11} + 0.127x_{31} + 0.122x_{41} + 0.115x_{51} + 0.119x_{71} + 0.0654x_{12} + 0.0621x_{22} \\
&\quad + 0.0586x_{32} + 0.0602x_{62} + 0.195x_{33} + 0.185x_{53} + 0.09521x_{14} + 0.0975x_{34}), \\
&\quad \times (0.1x_{11} + 0.155x_{31} + 0.17x_{41} + 0.12x_{51} + 0.2x_{71} + 0.1x_{12} + 0.25x_{22} \\
&\quad + 0.15x_{32} + 0.3x_{62} + 0.15x_{33} + 0.12x_{53} + 0.1x_{14} + 0.15x_{14}), \\
&\quad \times (0.2x_{11} + 0.1x_{31} + 0.15x_{41} + 0.17x_{51} + 0.13x_{71} + 0.2x_{12} + 0.1x_{22} \\
&\quad + 0.15x_{32} + 0.22x_{62} + 0.15x_{33} + 0.17x_{53} + 0.2x_{14} + 0.15x_{34})\}
\end{aligned}
$$

s.t.

$$
\begin{aligned}
&0.112x_{11} + 0.127x_{31} + 0.122x_{41} + 0.115x_{51} + 0.119x_{71} + 0.0654x_{12} + 0.0621x_{22} \\
&+ 0.0586x_{32} + 0.0602x_{62} + 0.195x_{33} + 0.185x_{53} + 0.09521x_{14} + 0.0975x_{34} \leqslant 16.373, \qquad (10)
\end{aligned}
$$

$$1.2x_{11} + 0.9x_{31} + x_{41} + 1.1x_{51} + 0.95x_{71} \geqslant 60, \qquad (11)$$

$$1.25x_{12} + 0.95x_{22} + 1.15x_{32} + 1.05x_{62} \geqslant 30, \qquad (12)$$

$$1.3x_{33} + 1.1x_{53} \geqslant 10, \qquad (13)$$

$$1.12x_{14} + 1.24x_{34} \geqslant 70, \qquad (14)$$

$$2x_{12} + 2x_{22} + 2x_{32} + 2x_{62} + 3x_{33} + 3x_{53} = x_{11} + x_{31} + x_{41} + x_{51} + x_{71} + x_{14} + x_{34}, \qquad (15)$$

$$x_{ij} \geqslant 0, \quad i = 1, 2, \ldots, 7; \quad j = 1, 2, 3, 4. \qquad (16)$$

4.2. Computational results and remarks

Table 1 is the computational results for this specific model. We can see the impact of various weights preferred by the DM on the objective function values. For example, the important degree of each objective is 100, 60, and 40, then corresponding weights are 0.5, 03, and 0.2, respectively. Thus Scheme 1 indicated that the purchasing costs is the most important criterion among the three criteria. The cost is the smallest, $15{,}770 \times 10^4$ Yuan, the scrap quantity is 2.108×10^4 tons, and tardy-delivery quantity is 2.6868×10^4 tons, selected vendors are 1, 3 and 5. Scheme 2 slightly differs from Scheme 1 in the objective value and item. Scheme 3 illustrated while the delivery timing is the first important criterion, the tardy-delivery quantity is the smallest, 1.884×10^4 tons. However, the cost is higher, $16{,}373 \times 10^4$ Yuan; the purchasing quantity also changes. Scheme 4 emphasized that the scrap quantity be minimum. Therefore, it possess minimum scrap quantity 2.481×10^4 tons, and selected vendors are 1, 2, 3, and 5. With the above computational results, the DM can readily select his or her preferred scheme.

The selection of items, determination of quantities and selection of vendors is very complex problem, and is also critical to optimize the purchasing policies for purchasing of raw materials of the steel plants. In general, we need to use expert system method or man–computer interactive programs for studying these problems. For research on these problems, the so-called deciding ‘assigning ore and assigning coal scheme’ and ‘subcontractor selecting’ in steel enterprises, are very important works. The modeling of this problem in this paper supplies a useful mathematical tool to process this very hard problem. It has a potential application value in enterprises.

Table 1
Results for 7 vendors and 13 items of raw materials

Solutions number (No.)	Objective functions (z_i)	Weights (w_i)	Objective values (z_i)	Percentages		Vendors and items (x_{ij})	Ordering quantities (10^4 tons)
				r_{ij}	s_{ij}		
1	Z_1	0.5	1.577	0.01	0.02	x_{11}	53.33
	Z_2	0.2	2.108	0.0155	0.01	x_{31}	0.0
	Z_3	0.3	2.6868	0.017	0.015	x_{41}	0.0
				0.012	0.017	x_{51}	0.0
				0.02	0.013	x_{71}	0.0
				0.01	0.02	x_{12}	0.0
				0.025	0.01	x_{22}	0.0
				0.015	0.015	x_{32}	41.26
				0.03	0.022	x_{62}	0.0
				0.015	0.015	x_{33}	0.0
				0.012	0.017	x_{53}	9.09
				0.01	0.02	x_{14}	0.0
				0.015	0.015	x_{34}	56.45
2	Z_1	0.5	1.586	0.01	0.02	x_{11}	53.33
	Z_2	0.3	1.902	0.0155	0.01	x_{31}	0.0
	Z_3	0.2	2.893	0.017	0.015	x_{41}	0.0
				0.012	0.017	x_{51}	0.0
				0.02	0.013	x_{71}	0.0
				0.01	0.02	x_{12}	41.26
				0.025	0.01	x_{22}	0.0
				0.015	0.015	x_{32}	0.0
				0.03	0.022	x_{62}	0.0
				0.015	0.015	x_{33}	0.0
				0.012	0.017	x_{53}	9.09
				0.01	0.02	x_{14}	0.0
				0.015	0.015	x_{34}	56.45
3	Z_1	0.3	1.6373	0.01	0.02	x_{11}	53.33
	Z_2	0.5	1.884	0.0155	0.01	x_{31}	
	Z_3	0.2	2.816	0.017	0.015	x_{41}	
				0.012	0.017	x_{51}	
				0.02	0.013	x_{71}	
				0.01	0.02	x_{12}	
				0.025	0.01	x_{22}	
				0.015	0.015	x_{32}	
				0.03	0.022	x_{62}	
				0.015	0.015	x_{33}	
				0.012	0.017	x_{53}	
				0.01	0.02	x_{14}	
				0.015	0.015	x_{34}	
4	Z_1	0.3	1.6373	0.01	0.02	x_{11}	53.33
	Z_2	0.2	2.3739	0.0155	0.01	x_{31}	0.0
	Z_3	0.5	2.4816	0.017	0.015	x_{41}	0.0
				0.012	0.017	x_{51}	0.0
				0.02	0.013	x_{71}	0.0
				0.01	0.02	x_{12}	0.0
				0.025	0.01	x_{22}	31.58
				0.015	0.015	x_{32}	0.0

Table 1 (*continued*)

Solutions number (No.)	Objective functions (z_i)	Weights (w_i)	Objective values (z_i)	Percentages		Vendors and items (x_{ij})	Ordering quantities (10^4 tons)
				r_{ij}	s_{ij}		
				0.03	0.022	x_{62}	0.0
				0.015	0.015	x_{33}	5.93
				0.012	0.017	x_{53}	9.62
				0.01	0.02	x_{14}	0.0
				0.015	0.015	x_{34}	56.45

5. Conclusions

The purchasing of raw materials is a very important problem. Its research is not only valuable to the steel industry, but also valuable to other production and manufacturing industries. Especially, using mathematical model to study purchasing issues is very important as it supplies more helpful information to a purchasing decision maker. This paper is only an attempt to use this kind of method. However, there are many problems that need to be studied in the future: purchasing lot size problem, quantity discount problems, etc.

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