Scientia Iranica E (2016) 23(3), 1384–1398

SCIENTIA IRANICA

Sharif University of Technology

Scientia Iranica

Transactions E: Industrial Engineering

www.scientiairanica.com

Compound mechanism design in multi-attribute and multi-source procurement of electricity coal

C.J. Rao[a,c,1,*], **J.J. Zheng**[b], **Z. Hu**[a] **and M. Goh**[c,d]

a. *Institute of Systems Engineering, Huazhong University of Science and Technology, Wuhan 430074, P.R. China.*
b. *School of Economic and Management, Wuhan University, Wuhan 430072, P.R. China.*
c. *The Logistics Institute-Asia Pacific, National University of Singapore, Singapore.*
d. *School of Business IT and Logistics, RMIT University, Australia.*

Received 13 September 2014; received in revised form 12 November 2014; accepted 4 August 2015

KEYWORDS

Electricity coal procurement;
Multi-attribute and multi-source procurement;
Compound mechanism;
Multi-attribute auction;
Negotiation mechanism.

Abstract. In this paper, the decision making problem of electricity coal procurement in power industry is investigated and a two-stage compound mechanism based on auction and negotiation is designed for multi-attribute and multi-source procurement of electricity coal. In the first stage of this compound mechanism, a multi-attribute auction mechanism of electricity coal is designed. Concretely, the buyer's utility function and the supplier's utility function are defined, and the scoring rules and bidding rules are given. Moreover, aiming at maximizing the buyer's expected utility, an optimization model of selecting winners in multi-attribute auction of electricity coal is established; then, the suppliers' optimal bidding strategies are discussed and the feasibility of auction mechanism is proved. Based on the winners' scheme and corresponding pre-allocation results of electricity coal supply in the auction stage, a negotiation mechanism, which can further improve the allocation efficiency and optimize the attribute combination, is designed in the second stage of this compound mechanism and the bidding efficiency is calculated by using the method of Data Envelopment Analysis (DEA) for each winner. Finally, the specific implementation steps are given to show how to apply this two-stage compound mechanism in the actual procurement of electricity coal.

1. Introduction

Electric power industry is an important part of the energy industry and it is one of the most important basic industries to support and promote the development of social economy. By the limitation of the structure of energy resources, coal is the main fuel for electricity power and the degree of dependence on electricity coal is more than 70% in China and more than 50% in the world [1,2].

In thermal power generation, the procurement of electricity coal is the basis of electric power production. By implementing effective procurement strategies of electricity coal, the power generation enterprises will establish a continuously stable mechanism of fuel supply. It is of great significance to guarantee the safety in production, reduce costs, increase revenue, and enhance the comprehensive competitiveness of enterprises. Like the country's basic industries, the electric power production is continuous production with the characteristics of security and stability, which determine that the electricity supply must be sustained, balanced, and stable and the quality of electricity coal (calorific value, moisture, ash, volatile matter, ash melting point, and sulfur coal classification) must

1. *Present address: School of Science, Wuhan University of Technology, Wuhan 430070, P.R. China.*
*. *Corresponding author.*
E-mail address: cjrao@163.com (C.J. Rao)

comply with the requirements of the boiler and reach the environmental protection standard.

Electricity coal procurement involves a wide range. It not only relates to the coal mine production, but also relates to railway transportation, highway transportation, and waterway transportation. In order to guarantee both quality and quantity to meet the power requirements of production and to gain more economic benefits, the power generation enterprises must consider electricity procurement strategy under the multi-attribute conditions like price, quality, quantity, supplier's transport capacity, credibility, and so on. In addition, the demand for electricity coal in thermal power generation is great and the power generation enterprises need many different kinds of electricity coal; therefore, considering quantity and variety, the supply by a single supplier is limited. It is often difficult to meet the needs of buyers within a specified time. For this reason, the buyer can select multiple suppliers to supply the electricity coal at the same time. Therefore, the electricity coal procurement can be regarded as a kind of multi-attribute and multi-source procurement.

In the procurement management of electricity coal, supplier evaluation and selection is a core problem [3]. Scientific and rational selection of suppliers can not only reduce the cost and risk of procurement and improve the product quality, but also enhance the market competitiveness of the supply chain. The suppliers' declaration information in the selection of suppliers is a kind of private and asymmetry information in essence. The authenticity of information is difficult to guarantee; therefore, it may lead to an inefficient allocation result, and it is difficult to achieve effective allocation of electricity coal. Based on this background, in order to reduce the procurement cost, optimize the procurement channels of coal, and improve the electricity coal quality, how to design reasonable and effective multi-attribute and multi-source mechanism for electricity coal procurement is an important research topic in the procurement management of electricity coal.

Electricity coal is a kind of rare resource with the characters of continuity, homogeneity, and divisibility ('divisible goods' means that one unit of goods can be divided into more arbitrary small units; for example, emission rights, stocks, treasury bills, and spectrum are all divisible goods. 'Indivisible goods' means that each unit of goods is independent, e.g. an antique vase, an antique painting, a procurement contract, a fish, a bottle of wine, and so on) and electricity coal procurement is a kind of multi-attribute and multi-source procurement; thus, we can reference the thought and method of multi-attribute auction to design an incentive multi-attribute and multi-source procurement mechanism. In a multi-attribute auction of electricity coal, the buyer will select the winning suppliers according to the supplier's bidding and the corresponding method of winner determining and then give the pre-allocation results of electricity coal supply in this auction stage. In order to reduce the risk of coal procurement, it is necessary to make further negotiation with suppliers for the buyer before signing the procurement contract. Negotiation is an important and inevitable phase of consultation. In the negotiation phase, the winner will negotiate with buyers about all attribute values and then a new protocol will be produced under the condition that the buyer and suppliers' utilities are not decreased and the allowed supply quantity for each winner is not decreased. Therefore, this new allocation result can further improve the allocation efficiency of procurement.

Multi-attribute auction theory provides the support for the implementation of valid negotiation in multi-attribute and multi-source procurement by combining the decision analysis tools and auction mechanism [4-7]. Multi-attribute auction is an auction mode which considers multiple attributes in the transaction between buyers and sellers [8-14] and is also negotiating in price and other attributes. With the rapid development of procurement economy and electronic commerce, especially wide application of online procurement, the research on multi-attribute auction has gradually become one of the most active fields in auction theory in recent years. There are many successful cases and theoretical results in the research on multi-attribute auction, but the multi-attribute auction with the characters of continuity, homogeneity, and divisibility has some new problems for further research in the theory [13,15,16], e.g. the problem of determining the winner, the problem of equilibrium excursion (multiple equilibrium points), and the incentive strategy design problem of ideal equilibrium.

Multi-attribute auction draws wide attention by the scholars because of its characteristics of competitive negotiations and its advantages such as high efficiency and time saving. In recent years, the multi-attribute auction has become quite active in the field of auction study. Practice has proved that multi-attribute auction is a short-term and efficient procurement mechanism [5,6,11,17,18]. Bichler [4] defined multi-attribute auctions as a class of market mechanisms, which enable automated negotiation on multiple attributes (such as delivery time, quantity, quality, and credibility) of a deal.

Thiel [14] pioneered the multi-attribute auction theory and he was the first to discuss the multi-attribute auction in detail. He showed that the problem of multi-attribute procurement can eventually be simplified to a single-attribute and private-value auction model, and the problem of designing optimal multidimensional auctions will be equivalent to the design of unidimensional auctions. However, in his paper, the hypothesis of the bidder's goal to maximize the utilities of buyers does not meet reality. In addition to Thiel, Che and Branco are also the pioneers in multi-attribute auction research. Che [5] provided a thorough analysis of the design of multi-attribute auctions and derived a two-dimensional version of the revenue equivalence theorem. Branco [8] extended Che's work. His analysis was based on Che's independent cost model and derived an optimal auction mechanism for the case when the bidding firms' costs were correlated. Unlike Che's independent cost model, the optimal auction mechanism cannot achieve the optimal effect through the auction process and the buyer must take two-stage mechanism. Branco also proved that both the two-stage first price auction and two-stage second price auction are the optimal auction mechanisms. The works of Che and Branco were among the first considering multi-dimensional auctions. But both were studying auction design only in a context with two issues, i.e. price and quality. Teich [18] divided the multi-attribute into two stages in the relevant literature, i.e. good attributes and supplier attributes, and pointed out that the combination multi-attribute procurement had more realistic meaning and he made it a further research direction. David et al. [19] discussed the three-attribute procurement auction model based on the background of international logistics market and chose the concrete linear scoring function to determine the winner.

Later, David et al. [20] continued to extend their research work; they generalized the tender attribute to any numbers and used the quasi linear score function to determine the winner. This set of studies by David et al. followed Che and Branco's research thought and it supposed that the costs of the bidders were independent from each other. The improvement of their work is that there is no limit to the number of bid attributes and it can be any number. At the same time, the set of studies by David et al. introduced the English auction into the multi-attribute auction field and proposed the orders of full information disclosure auction and English auction, which enriched the theory of multi-attribute auctions. However, there are also several disadvantages for the work of David et al. Firstly, the bidder's choice on quality is independent of price, which does not meet reality. Secondly, the assumption of cost parameters being independent of each other is unreasonable. Thirdly, from the perspective of buyers, the choice, by which the optimal auction comes down to optimal weighted score function, cannot consider the whole social welfare. Finally, when choosing winners, David et al. adopt simple weighted score function form.

Considering the insufficiency in the study of David et al., Jin and Shi [21] presented an increasing bidding multi-attribute auction. The study showed that this auction mechanism improved the work of David and it could replace the previous ascending bid multi-attribute auctions. Wang [22] discussed the problem of N bidders who compete with a franchise distribution with the bidding consisting of quality and price and presented the optimal bidding competition mechanism from the viewpoint of maximizing social expectations of welfare. Huang et al. [23] supposed that the bidding consisted of price and quality and established an optimization model of dynamic multi-attribute procurement auction mechanism. Then, Huang et al. [24] discussed the design of a hybrid mechanism for e-procurement, which implemented a multi-attribute combinatorial auction followed by a bargaining process to achieve desirable procurement transaction outcomes. Sun and Feng [25] presented a more realistic demand that improved multi-attribute auction model based on the form of simple weighted score function in the existing multi-attribute auction model. Pla et al. [26] presented a new Vickrey-based reverse multi-attribute auction mechanism, which took the different types of attributes involved in the auction into account and allowed the auction customization in order to suit the auctioneer needs. Wang and Liu [27] proposed a nonlinear scoring rule, which transformed multiple attributes of a bid into comparable dimensionless ones in practical multi-attribute auctions. They found that as the number of bidders increased, the equilibrium quality improved, whereas the equilibrium price decreased.

In recent years, scholars have focused on multi-attribute auction theory combined with practice research. Perrone et al. [28] designed engineering services procurement mechanism of new product development in the automation environment based on multi-attribute auction theory and used numerical experiments to simulate the purchase process. Strecker [29] studied information superiority of the multi-attribute auction from the viewpoint of auction efficiency in the two aspects of theory and laboratory experiment. He concluded that the more the information disclosure, the higher efficiency the auction had. Karakaya and Köksalan [30] proposed an interactive multi-attribute reverse auction method for the single-good auction and designed the experiment that verified its feasibility and rationality. Liu et al. [31] studied multi-attribute procurement auction mechanism with the supplier under risk aversion and focused on in-depth study of the number of suppliers and risk attitude effects on the equilibrium price. Ray et al. [32] conducted web-based experiments to validate this theoretical observation in multi-attribute reverse auctions. They compared incentive oriented and standard multi-attribute reverse auctions and demonstrated that the results in the laboratory setting corroborated the theoretical findings. In addition, there are some studies carried out on the beneficial discussion from the perspective of suppliers bidding composite auxiliary decision-making tools and on realization of the multiple-attribute decision making evaluation software. For example, Jain et al. [33] considered the major internalization methods in different contexts and proposed the multi-stage auction mechanism analyzing two-way competitions, a Bertrand and Cournot competition where prices per unit and per quantity are two underlying parameters in a utility analysis. Yang et al. [34] constructed a linear programming model to infer the preference model(s) of the auctioneer so that the estimations were as consistent as possible with the given preference statements in multi-attribute electronic procurement auctions. Furthermore, they presented a method to select a representative preference model from the set of compatible ones. These are all the important and valuable research results in multi-attribute auctions in the past few years. But the auction goods mentioned in most of the studies are a single product or indivisible multiple goods and the bid winner is only one. The research on the multi-attribute auctions for divisible goods, which its aims are the characteristics of homogeneity and divisibility, is very little.

In recent years, the amount of studies on negotiation has been very rich, but most of them consider the properties and implementation conditions of the bilateral negotiation mechanism from the angle of economics. Many studies on the mechanism design put the possibility of ex-post bargaining as constraint condition into the prior-mechanism or contract design and then prove robustness of the mechanism after negotiations. In the literature on bargaining, there is no research on combination of goods or bargaining for multiple goods. Most of them concentrate on the price argument for a single good for the bargaining parties [35,36]; for example, Cramton [36] studied the negotiation strategy with time-delay under the condition of bilateral information asymmetry. It is of great significance for the follow-up study. Wang et al. [37] proposed the concept of Bargaining Track Chart in order to solve the bargaining problems of centralized procurement in the environment of e-commerce. This Bargaining Track Chart recorded the negotiation opponent's historical data and provided a reference for the current negotiation.

On the combination of auction and negotiation, Branco [8] considered a compound mechanism based on auction and negotiation for the single-good procurement under the assumption that all cost functions of bidders were related. He only analyzed the properties of the corresponding optimal mechanism and did not discuss the equilibrium in the stages of negotiation or bargaining. Wang [38] also discussed the combination of auction and negotiation for a single-good procurement, but he did not get the equilibrium strategy because of the complexity of the model. He only discussed the existence and some properties of equilibrium strategies. Subsequently, Huang and Chen [39] investigated a combined auction-bargaining model in a setting where a buyer procured a good/service from one of the multiple competing sellers with invisible effort. The two-stage procurement model is a sequential mechanism consisting of an auction phase followed by a possible bargaining phase. They also presented the criteria according to which the procurer decided whether to bargain or keep the contact in auction stage. Chen and Tseng [40] also designed the mixed procurement mechanism based on combination of auction and negotiation. A common point of these studies is that the auction object is a single unit of goods or a combination of multiple different heterogeneous goods. Practice shows that in many transactions of multi-objects, to study the sequential mechanism consisting of an auction phase followed by possible negotiation is very important. This paper just tries to do the mechanism design work in this aspect. Later, Kersten et al. [41] presented a theory of concessions which could be applied to both auctions and negotiations and provided experimental verification of the theory. The theory-based assessment of concession-making in multi-attribute auctions and multi-issue multi-bilateral negotiations makes their comparison possible.

In a study on electricity coal procurement, Shiromaru et al. [42] used fuzzy satisfaction methods to deal with the fuzzy information on procurement objective of coal-fired power generation enterprises and solved the supplier selection problem of electricity coal by using the genetic algorithm. Lai and Yang [43] analyzed the Nash equilibrium problem for the power supply chain and presented a multi-layer optimization procurement model to make a joint decision for the suppliers and the power generation enterprises. Liu and Nagurney [44] proposed a network model of power supply chain coal and explained how the change of electric power demand would affect the electricity and electricity coal market. Dai et al. [45] proposed an electricity supply chain coordination model based on quantity discount contract. Liu [46] established a coordination decision model of procurement management for the power supply chain alliance in the environment of BIC. Yan [47] gave a possible solution for the supply chain procurement coordination under the condition of internet e-commerce; also, he established an experimental platform of E-commerce coordinate system. Zhao and Qi [48] analyzed the performance and the source of cooperative conflict for the coal supply chain and then proposed a cooperative conflict model for the coal supply chain. From the existing studies in the literature, most of them offer the procurement mechanisms and methods based on the classical decision theory. In practical procurement, these procurement mechanisms and methods are difficult to use for motivating the suppliers to offer the real information. They may lead to an inefficient allocation result and it is difficult to achieve effective allocation of electricity coal. To solve this problem, we can directly aim at providing the characteristics of continuity, homogeneity, and divisibility for the electricity coal and design incentive multi-attribute and multi-source mechanism for electricity coal procurement combined with multi-attribute auction theory and negotiation theory.

This paper studies the decision making problem of multi-attribute and multi-source procurement for electricity coal in power industry and presents a two-stage compound mechanism based on auction and negotiation by considering multiple attributes like price, electricity coal quality (calorific value, moisture, ash, volatile matter, ash melting point, and sulfur coal classification), quantity, delivery time, supplier transport capacity, credibility, and so on. This study can provide theoretical basis and decision reference for the relevant enterprises to implement scientific management of electricity coal procurement and has important theoretical significance and academic value to the improvement and development of the design and optimization of multi-object auction mechanism; it also has the important application value to promote the combination of auction theory and a kind of real economic activity like supply chain management, e-commerce, and so on.

2. Problem description

Suppose that a buyer in a power generation enterprise wants to purchase Q_0 tons of electricity coal to use it in generating electricity. Now, $n(n \geq 2)$ risk neutral suppliers participate in the supply competition. The set of suppliers is denoted by $N = \{1, 2, \cdots, n\}$. In the procurement management of electricity coal, the buyer will consider multiple attributes, i.e. price, quantity, quality (including calorific value, moisture, ash, volatile matter, ash melting point, and sulfur coal classification), and delivery time, where the six quality attributes must satisfy the relative national standard GB/T7562-2010 [49]. The meanings of the quality attributes are described as follows:

- p The price of electricity coal per ton ($/ton);
- q The supply quantity (ton);
- T The delivery time (day) which reflects the transport capacity of suppliers; short delivery time represents high transport ability;
- A_1 Calorific value (MJ/kg) which is an important basis for boiler design. In practice, the calorific value of coal must meet the requirements of boiler design. The calorific value is generally divided into five grades: $> 24, 21.01 \sim 24, 17.01 \sim 21, 15.51 \sim 17, > 12$;
- A_2 Volatile matter (%) which is the core index to distinguish the combustion characteristic for steam coal. The higher the value of the volatile matter, the easier on fire the electricity coal is. According to the requirements of boiler design in the power plant, the change of the coal volatile matter should not be too large; otherwise, it will affect the normal operation of the boiler. The volatile matter is generally divided into five grades: $6.5 \sim 10, 10.01 \sim 20, 20.01 \sim 28, > 28, > 37$, and also the corresponding calorific value has the limits, which are $> 24, 21.01 \sim 24, 17.01 \sim 21, 15.51 \sim 17, > 12$, respectively;
- A_3 Ash melting point (°C). Generally, the temperature of flame kernel in pulverized coal furnace hearth is more than 1500°C. In such a high temperature, coal ash mostly shows softening or fluid states. The ash melting point is generally divided into four grades: $> 1150 \sim 1250, 1260 \sim 1350, 1360 \sim 1450, > 1450$;
- A_4 Ash (%). Ash content can reduce the speed of flame propagation, delay the ignition time, cause combustion instability, and reduce the furnace temperature. Ash is generally divided into three grades: $\leq 20, 20 \sim 30, 30 \sim 40$;
- A_5 Moisture (%), which is one of the harmful substances in the combustion process which can absorb a great deal of heat in the combustion process; its impact on the combustion is much bigger than ash. Moisture is generally divided into four grades: $\leq 8, 8.1 \sim 12, 12.1 \sim 20, > 20$;
- A_6 Sulfur coal classification (%). Sulfur is a harmful impurity in coal. It has no effect on the combustion itself, but if its content is too high, the equipment corrosion and environment pollution will be quite serious. The sulfur content in burning coal cannot be too high and the general requirement cannot be more than 2.5%. Sulfur coal classification is generally divided into four grades: $\leq 0.5, 0.51 \sim 1, 1.01 \sim 2, 2.01 \sim 3$.

For the above nine attributes, we denote the values of attributes $P, q, T, A_1, A_2, \cdots, A_6$ by $p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6} (i = 1, 2, \cdots, n)$, respectively.

In the practical procurement, the buyer can select multiple suppliers to supply electricity coal in a certain procurement. At the beginning of the procurement, the buyer will announce some standards and rules as follows:

1. For six quality attributes (including calorific value, moisture, ash, volatile matter, ash melting point,

and sulfur coal classification), the quality level should not be lower than the given reserve values $\underline{a} = (\underline{a}_1, \underline{a}_2, \cdots, \underline{a}_6)$. The detailed values can be determined by the quality standards of the relative national standard GB/T7562-2010;

2. The submitted price given by the suppliers should not be more than the reserve price $\bar{p}$, i.e. $p_i \leq \bar{p}$;
3. Each supplier's delivery time cannot exceed the prescribed time limit, i.e. it must satisfy $t_i \leq \bar{t}$, where $\bar{t}$ is the longest delivery time;
4. To look for more partners and establish more extensive cooperation, and to let more suppliers have the chance to supply electricity coal, the buyer will limit the suppliers' maximum supply quantities, i.e. $q_i \leq \bar{q}$, $i = 1, 2, \cdots, n$, where $\bar{q}$ is the limitative maximum supply quantity for all suppliers.

All the suppliers' submitted information must satisfy the above standards and rules. Otherwise, the suppliers will be eliminated in the competition.

In addition, the buyer will consider the credibility of suppliers. Reliable information of this attribute can be collected through visits, market research, and other ways. The result of this attribute can be regarded as the prerequisite for supplier selection. The suppliers with bad credibility have no competition's qualifications and will be eliminated first.

According to above basic information, the buyer will select several winners between n suppliers of electricity coal and all winners should supply Q_0 tons of electricity coal, which satisfies the given quality standards and other rules to the buyer within a specified time.

3. Two-stage compound mechanism for electricity coal procurement

Considering the fact that electricity coal is a kind of goods with the characteristics of continuity, homogeneity, and divisibility, we will design a two-stage compound mechanism for multi-attribute and multi-source procurement of electricity coal. The first stage is multi-attribute auction stage. In this stage, the buyer will determine winners among all suppliers and give pre-allocated results according to the suppliers' bidding and the corresponding method of determining winners. The second stage is the negotiation stage. In this stage, the buyer will negotiate with each winner on all attribute values and then a new protocol will be produced to improve the allocation efficiency of procurement. We will present these two stages of compound mechanism, respectively.

3.1. The first stage: multi-attribute auction mechanism

In the multi-attribute procurement auction of electricity coal, the buyer is an auctioneer and the suppliers are bidders. The entire procurement process can be seen as a game process between the buyer and suppliers. In this process, the auctioneer is the game's leader who will design optimal bidding rules and scoring rules to maximize his own utility. As the game's followers, the bidders will select their optimal bidding strategies to achieve their goals of utility maximization based on the bidding rules and scoring rules given by the buyer. Now, we design a multi-attribute procurement auction mechanism of electricity coal. The main idea of mechanism design is as follows. At the beginning of the auction, the buyer in a power generation enterprise will announce the basic requirement and the scoring rules for electricity coal procurement to all suppliers. Then, every supplier submits a sealed bid with the form $(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$. Within the auction, every supplier has only one chance to submit the bid. When all suppliers submit their bids, the buyer will analyze the statistic data according to the suppliers' bids and then publish the scores and rank order in time. The buyer will select winners among all suppliers by aiming at maximizing his expected utility and allocate the allowable supply quantities of electricity coal to winners.

3.1.1. The utility functions of buyer and suppliers

Now, we define the utility functions of buyer and suppliers in the multi-attribute procurement auction of electricity coal.

For the suppliers, the cost of supplying one unit of electricity coal consists of two parts. The first one is the production cost to produce the electricity coal with quality values $a_{i1}, a_{i2}, \cdots, a_{i6}$. It is denoted by $C_i(a_{i1}, a_{i2}, \cdots, a_{i6})$. The second one is transportation cost. Let the transportation cost be the function of delivery time t_i, denoted by $c_i(t_i)$, where $c_i(t_i)$ is increasing in type t_i. (In fact, here, we suppose that the delivery time t_i includes production time and transportation time. Further, let the production time and the transportation cost per unit time be invariable; then, the longer the transportation time, the longer the delivery time t_i and the higher the transportation cost will be. Thus, here, we suppose that transportation cost $c_i(t_i)$ is increasing in delivery time t_i.) Then, the total cost of one unit of electricity coal can be expressed as:

$$C_{si} = C_i(a_{i1}, a_{i2}, \cdots, a_{i6}) + c_i(t_i).$$

For six quality attributes, calorific value (A_1), volatile matter (A_2), and ash melting point (A_3) are the benefit type attributes, which means the greater their values, the higher the quality of electricity coal is. This makes the supplier's cost higher, but the buyer's utility greater. Moreover, ash (A_4), moisture (A_5), and sulfur coal classification (A_6) are three cost type attributes, which means the smaller their values, the higher the quality of electricity coal is. This also makes the supplier's cost higher and the buyer's utility greater. For these tree cost type attributes, we denote a_{i4} as the inverse of ash, a_{i5} as the inverse of moisture, and a_{i6} as the inverse of sulfur coal classification in order to obtain a positive relation between the quality attributes a_{i4}, a_{i5}, a_{i6}, and the production cost.

Let the supplier i's ($i \in N$) cost function $C_i(a_{i1}, a_{i2}, \cdots, a_{i6})$ be additive across six quality attributes and $c_{ij}(a_{ij})$ be the supplier i's cost function when the value of the j's ($j = 1, 2, \cdots, 6$) quality attribute is a_{ij}. Then, the utility of supplier i, who will supply the buyer with q_i units of electricity coal with the unit price p_i, can be expressed as:

$$U_{si}(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6}) = q_i[p_i - C_{si}]$$

$$= q_i \left[p_i - \sum_{j=1}^{6} c_{ij}(a_{ij}) - c_i(t_i) \right].$$

It is obvious that the supplier i's total utility increases with the increase in the bid price p_i, and decreases with the increase in the value a_{ij} of attribute $A_j (j = 1, 2, \cdots, 6)$.

To simplify the analysis, here we set:

$$c_{ij}(a_{ij}) = k_j a_{ij}, \qquad j = 1, 2, \cdots, 6, \quad i = 1, 2, \cdots, n,$$

$$c_i(t_i) = h t_i, \qquad i = 1, 2, \cdots, n,$$

where k_j is the quality attribute coefficient of the jth attribute A_j and the same for all suppliers; and h is the transportation cost coefficient of unit time and also the same to all suppliers. Then, the utility function of supplier i can be rewritten as:

$$U_{si}(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6}) = q_i[p_i - C_{si}]$$

$$= q_i \left(p_i - \sum_{j=1}^{6} k_j a_{ij} - h t_i \right).$$

For the buyer, we suppose that the buyer's utility function is additive across quality attributes $A_1, A_2, \cdots, A_6$ and t_i; the buyer's revenue function is denoted by $u_{ij}(a_{ij})$ on the j's ($j = 1, 2, \cdots, 6$) quality attribute value a_{ij} and the buyer's revenue function on delivery time t_i is denoted by $u_i(t_i)$; then, when the supplier i supplies the buyer with q_i units of electricity coal with the unit price p_i, the buyer's total revenue can be expressed as:

$$U_{bi}(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$$

$$= q_i \left[\sum_{j=1}^{6} u_{ij}(a_{ij}) + u_i(t_i) - p_i \right],$$

where $u_{ij}(a_{ij})$ is the revenue function on attribute $A_j (j = 1, 2, \cdots, 6)$ and $u_{ij}(a_{ij})$ is increasing, concave, and twice continuously differentiable in a_{ij}. $u_i(t_i)$ is decreasing in t_i. This is because the delivery time t_i is a cost type attribute for the buyer. A longer delivery time t_i will bring smaller utility to the buyer.

To simplify the analysis, here we set:

$$u_{ij}(a_{ij}) = w_j (a_{ij})^{\frac{1}{3}}, \quad j = 1, 2, \cdots, 6, \quad i = 1, 2, \cdots, n,$$

$$u_i(t_i) = \frac{w_7}{t_i}, \qquad i = 1, 2, \cdots, n,$$

where $w_1, w_2, \cdots, w_7$ are the weights given by the buyer for six quality attributes and delivery time t_i, which means the buyer's preference to all attributes, and w_k satisfies the condition $\sum_{k=1}^{7} w_k = 1$. When the supplier i submits the bid $(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$, the buyer's total utility from the supplier i can be expressed as:

$$U_{bi}(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$$

$$= q_i \left[\sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i \right].$$

3.1.2. The scoring rules and bidding rules

1. *The scoring rules for suppliers.* The scoring rule (or score function) is the function which is used to select the optimal bid. The buyer will announce this scoring rule to all suppliers at the beginning of the procurement auction. Because the scoring rule is given by the buyer, the buyer can design a scoring rule from his total utility function:

$$U_{bi} = q_i \left[\sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i \right].$$

   In order to achieve the goal of maximizing utility, and to induce suppliers to announce their actual costs truthfully, the buyer can define the scoring function as follows:

$$s_i = \sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i.$$

   Obviously, the score s_i is increasing in the value of a_{ij}, and decreasing in the price p_i and the delivery time t_i; also, the income of unit electricity coal increases with increase in the score s_i. Thus, the buyer will choose the suppliers whose scores are higher as the winners.

2. *Bidding rules.* In the auction, every supplier has only one opportunity to submit the bid. By Section 2, every supplier's sealed bid must satisfy some

basic access rules; for example, the quality level should not be less than the given reserves values $\underline{a} = (\underline{a}_1, \underline{a}_2, \cdots, \underline{a}_6)$, the submitted price given by suppliers should not exceed the reserve price $\overline{p}$, each supplier's delivery time cannot exceed a prescribed time limit $\bar{t}$, the suppliers' maximum supply quantities must satisfy $q_i \leq \bar{q}$, and so on. All suppliers' submitted bids must satisfy these standards and rules or they will be eliminated in the auction.

3. *Prepaid rules.* The prepaid rules after the auction and before the beginning of negotiation are as follows. Each winning supplier must provide the promised quality level of the electricity coal to the buyer within the delivery time given in his bid. His received payment is different from the uniform price auction and discriminatory price auction. If the buyer chooses the discriminatory price auction, then the market clearing price is the unit price in the bid submitted by each winner. If the buyer chooses the uniform price auction, the market clearing price will be discussed in the latter section.

3.1.3. The optimization model of supplier selection

Considering that the demand of electricity coal in thermal power generation is great and the power generation enterprises need many different kinds of electricity coal, the supply of a single supplier is limited considering quantity and variety; also, it is often difficult to meet the needs of buyer within the given time. Thus, the buyer can select multiple suppliers to supply electricity coal at the same time, i.e. the final winner is not only one and can be one or more. Next, we established the optimization model of supplier selection for multi-attribute and multi-source procurement of electricity coal.

In multi-attribute auction of electricity coal, the buyer will announce the basic requirement and the scoring rules for the procurement of electricity coal to all suppliers; then, n suppliers will submit the bids $(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$, $i = 1, 2, \cdots, n$, to the buyer. The task of the buyer is to design a supplier selection method to select winners and then determine the allowable supply quantity q_i^* for each winner.

For the buyer, his goal is to maximize the utility, i.e.:

$$\max U_b = \sum_{i=1}^{n} q_i^* \left[\sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i \right] = \sum_{i=1}^{n} q_i^* s_i.$$

To achieve this goal, the following conditions must be satisfied:

1. The limitation of the allowable supply quantity. The sum of the allowable supply quantities for all winners is Q_0, i.e.:

$$\sum_{i=1}^{n} q_i^* = Q_0;$$

where the allowable supply quantity q_i^* must satisfy $q_i \leq \bar{q}$.

2. Based on the bid $(p_i, q_i, a_{i1}, a_{i2}, \cdots, a_{im})$, $i = 1, 2, \cdots, n$, the buyer's utility and the suppliers' utility must be non-negative, i.e.:

$$U_{bi} = q_i \left[\sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} \right] \geq 0,$$

$$i = 1, 2, \cdots, n,$$

$$U_{si} = q_i \left(p_i - \sum_{j=1}^{6} k_j a_{ij} - h t_i \right) \geq 0,$$

$$i = 1, 2, \cdots, n.$$

Based on the above analysis, the optimization model of selecting winners in multi-attribute auction of electricity coal can be expressed as:

$$\max U_b = \sum_{i=1}^{n} q_i^* s_i,$$

s.t.

$$(M_1) \qquad \begin{cases} \sum\limits_{i=1}^{n} q_i^* = Q_0 \\ 0 \leq q_i^* \leq q_i \leq \bar{q}, & i = 1, 2, \cdots, n \\ u_{si} \geq 0, & i = 1, 2, \cdots, n \\ u_{bi} \geq 0, & i = 1, 2, \cdots, n \end{cases}$$

Obviously, after all suppliers submit their bids, $(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$ are all known numbers. By solving model M_1, the allowable supply quantity q_i^* can be obtained. When $q_i^* > 0$, the corresponding supplier i is a winner. When $q_i^* = 0$, the corresponding supplier i loses his bid.

3.1.4. Equilibrium analysis

Now, we analyze the equilibrium for the above multi-attribute procurement auction of electricity coal. The equilibrium price under a uniform price auction is given in the following Proposition 1.

Proposition 1. Suppose that the multi-attribute procurement auction of electricity coal is under a uniform price, i.e. all suppliers supply electricity coal to the buyer with a uniform price. Let the minimum value and maximum value of bid price submitted by all suppliers be $L = \min\limits_i p_i$ and $H = \max\limits_i p_i$, respectively; then, the equilibrium price is $p^* = L = \min\limits_i p_i$.

Proof. By the above analysis, in a uniform price auction, the total revenue can be rewritten as:

$$U_b=\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}-p\right)$$

$$=\sum_{i=1}^{n}\left[q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right]-p\sum_{i=1}^{n}q_i\right.$$

$$=\sum_{i=1}^{n}\left[q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right]-pQ_0.\right.$$

We set:

$$\sum_{i=1}^{n}\left[q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right]=A_1,\qquad pQ_0=A_2,\right.$$

then, we have $U=A_1+A_2$. Obviously, U_b is only relevant to A_2 and decreasing in price p. By the constraint condition $\min_i p_i\leq p\leq\max_i p_i$, we can obtain the equilibrium price as $p^*=\min_i p_i$, which can realize the total revenue maximization of the buyer. □

In the practical auction of electricity coal, if the buyer's actual utility function:

$$s_i=\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}-p_i,$$

is taken as scoring rule, then the total utility of buyer and suppliers (system's total welfare) is:

$$\begin{aligned}U=&U_b+U_s=\sum_{i=1}^{n}\left[q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}-p_i\right)\right]\\&+\sum_{i=1}^{n}\left[q_i\left(p_i-\sum_{j=1}^{6}k_ja_{ij}-ht_i\right)\right]\\&=\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right)\\&-\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}k_ja_{ij}-ht_i\right),\end{aligned}\tag{1}$$

which means when the suppliers realize the maximization total revenue, the system's total welfare U is maximal and is not relevant to the transaction price of the auction. Based on this precondition, in the equilibrium, the optimal values of quality attribute and delivery time are given as follows.

Proposition 2. In the uniform price auction of electricity coal, the optimal values of quality attribute and delivery time in the equilibrium are:

$$a_{ij}^*=\left(\frac{3k_i}{w_i}\right)^{-\frac{3}{2}}\quad\text{and}\quad t_i^*=\left(\frac{h}{w_7}\right)^{-\frac{1}{2}},$$

respectively.

Proof. From Eq. (1), the optimal values of quality a_{ij}^*, which maximize the system's total welfare, must satisfy the following condition:

$$\begin{aligned}\left.\frac{\partial U}{\partial a_{ij}}\right|_{a_{ij}^*}=&\frac{\partial}{\partial a_{ij}}\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right)\\&-\left.\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}k_ja_{ij}-ht_i\right)\right|_{a_{ij}^*}=0.\end{aligned}$$

By simplifying it, we have:

$$\left.\left[\frac{1}{3}q_iw_i(a_{ij})^{-\frac{2}{3}}-q_ik_i\right]\right|_{a_{ij}^*}=0.$$

Solving this equation, we obtain:

$$a_{ij}^*=\left(\frac{3k_i}{w_i}\right)^{-\frac{3}{2}}.$$

Moreover, the optimal values of delivery time t_i^* must satisfy:

$$\begin{aligned}\left.\frac{\partial U}{\partial t_i}\right|_{t_i^*}=&\frac{\partial}{\partial t_i}\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}w_j(a_{ij})^{\frac{1}{3}}+\frac{w_7}{t_i}\right)\\&-\left.\sum_{i=1}^{n}q_i\left(\sum_{j=1}^{6}k_ja_{ij}-ht_i\right)\right|_{t_i^*}=0.\end{aligned}$$

Then, we have $[-q_iw_7(t_i)^{-2}+q_ih]|_{t_i^*}=0$. Solving it, we obtain $t_i^*=(\frac{h}{w_7})^{-\frac{1}{2}}$. □

3.1.5. Feasibility analysis of auction mechanism

Based on the above allocation rules, payment rules, and scoring rules given by the buyer, now we prove that our multi-attribute auction mechanism is a feasible mechanism. We give a relative conclusion in Proposition 3, which can show that our multi-attribute auction mechanism is a feasible mechanism.

Proposition 3. For the above auction mechanism, the higher the score of supplier i, the greater the proportion of the allowable supply quantity q_i^* of supplier i and the supply quantity q_i submitted by supplier i in his bid are, which means the supplier i has the priority to get the supply right of electricity coal.

Proof. For n suppliers, we suppose that their scores satisfy $s_1 \geq s_2 \geq \cdots \geq s_n$. By the constraint condition $\sum_{i=1}^{n} q_i^* = Q_0$ in model M_1, we have $q_1^* = Q_0 - \sum_{i=2}^{n} q_i^*$. Thus, the total revenue of the buyer is:

$$U_b = \sum_{i=1}^{n} q_i^* s_i = \left(Q_0 - \sum_{i=2}^{n} q_i^*\right) s_1 + \sum_{i=2}^{n} q_i^* s_i = Q_0 s_1$$
$$-[(s_1 - s_2)q_2^* + (s_1 - s_3)q_3^* + \cdots + (s_1 - s_n)q_n^*].$$

Since $s_1 \geq s_2 \geq \cdots \geq s_n$, we have:

$$s_1 - s_2 \geq 0, s_1 - s_3 \geq 0, \cdots, s_1 - s_n \geq 0.$$

Moreover, $Q_0 s_1$, $s_1 - s_i$ and q_i^*, $i = 2, 3, \cdots, n$ are all constant, and $\sum_{i=1}^{n} q_i^* = Q_0$, so we conclude that the smaller the values of $q_2^*, q_3^*, \cdots, q_n^*$, the greater the value of U_b is, which means when $s_1 \geq s_2 \geq \cdots \geq s_n$, if the value of q_1^* reaches a maximum value, then the value of U_b will reach the maximum value. Together with $0 \leq q_1^* \leq q_1 \leq \bar{q}$, we have $q_1^* = q_1$, which means the allowable supply quantity q_1^* of supplier 1 is equal to the supply quantity q_i submitted by supplier 1 in his bid. By the same method, we have the following conclusions.

When $s_2 \geq \cdots \geq s_n$, the value of U_b increases with the increase in the value of q_2^*. Thus, if $q_2 \leq Q_0 - q_1$, then we have $q_2^* = q_2$, and if $q_2 > Q_0 - q_1$, then $q_2^* = \frac{Q_0 - q_1}{q_2} Q_0$, and $q_3^* = \cdots = q_n^* = 0$. Similarly, for any q_k^*, $k = 3, 4, \cdots, n$:

$$\text{if} \quad q_k \leq Q_0 - \sum_{i=1}^{k-1} q_i, \quad \text{then} \quad q_k^* = q_k,$$

and:

$$\text{if} \quad q_k > Q_0 - \sum_{i=1}^{k-1} q_i, \quad \text{then} \quad q_k^* = \frac{Q_0 - \sum_{i=1}^{k-1} q_i}{q_k} Q_0$$

and:

$$q_{k+1}^* = q_{k+2}^* = \cdots = q_n^* = 0.$$

From the above analysis, we can conclude that the higher the score of supplier i, the greater the proportion of the allowable supply quantity q_i^* of supplier i and the supply quantity q_i submitted by supplier i in his bid are. □

From the proof process of Proposition 3, we can directly obtain the solution of the optimization model (M_1); i.e. let the suppliers' scores be $s_1 \geq s_2 \geq \cdots \geq s_n$, then the solutions of the optimization model (M_1) are as follows:

(i) If $q_1 < Q_0$, then $q_1^* = Q_0$ and $q_2^* = q_3^* = \cdots = q_n^* = 0$;

(ii) If $q_1 < Q_0$ and $q_2 \leq Q_0 - q_1$, then $q_2^* = q_2$ and $q_3^* = \cdots = q_n^* = 0$;

(iii) If $q_1 < Q_0$ and $q_2 > Q_0 - q_1$, then $q_2^* = \frac{Q_0 - q_1}{q_2} Q_0$ and $q_3^* = \cdots = q_n^* = 0$;

(iv) For any $k = 3, 4, \cdots, n$, if $q_k \leq Q_0 - \sum_{i=1}^{k-1} q_i$, then $q_k^* = q_k$ and $q_{k+1}^* = q_{k+2}^* = \cdots = q_n^* = 0$;

(v) For any $k = 3, 4, \cdots, n$, if $q_k > Q_0 - \sum_{i=1}^{k-1} q_i$, then $q_k^* = \frac{Q_0 - \sum_{i=1}^{k-1} q_i}{q_k} Q_0$ and $q_{k+1}^* = q_{k+2}^* = \cdots = q_n^* = 0$.

By the given score function, $s_i = \sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i$, the score of supplier i is determined by two kinds of factors. The first kind is quantity attributes and delivery time; the score of supplier i increases with increase in the values of quantity attributes and delivery time. The other kind is price attribute; the score increases with decrease in the bid price.

According to the conclusion of Proposition 2, the values of optimal quantity attributes are invariant. Thus, every supplier only needs to consider how to choose the optimal price in his bidding. For the supplier i, his bid price must satisfy the condition that the price of electricity coal per ton, p_i, is equal to or greater than the cost of electricity coal per ton, C_{si}. Together with the conclusion of Proposition 3, we know that the greater the score of supplier i, the higher the chance of winning is and the greater the proportion of the allowable supply quantity q_i^* of supplier i and the supply quantity q_i submitted by supplier i in his bid are. Moreover, the score function, s_i, is decreasing in price, p_i; therefore, each supplier's bid price will be close to his true cost.

When the price of electricity coal per ton p_i is less than the cost of electricity coal per ton C_{si}, the score s_i increases and supplier i gets more opportunities to win the bid, but his utility is negative. Thus, the rational supplier will not submit his bid to the buyer.

From the above analysis and discussion, the multi-attribute auction mechanism of electricity coal procurement in this paper is a feasible mechanism, i.e. it satisfies the incentive compatibility condition and individual rationality condition. Thus, we can use this multi-attribute auction mechanism to procure electricity coal. In the practical auction, the buyer may announce the method of selecting winners described by model M_1 to all suppliers at the beginning of the auction. It will induce suppliers to submit their bid prices close to their true costs to improve their scores and get more chances to win the bid.

3.2. The second stage: negotiation mechanism

Based on the winners' scheme and corresponding pre-allocation results of electricity coal supply in the auction stage, we further design a negotiation mechanism which can improve the allocation efficiency and optimize the attribute combination in this section.

In the stage of negotiation, the premise condition of negotiation is that the utilities of the buyer and winners are not decreased and the allowed supply quantity for each winner is not decreased. Therefore, the result of negotiation is that values of some attributes must increase decrease and other values of some attributes decrease increase. Finally, the buyer and winners get a new equilibrium point $(p'_i, q'_i, t'_i, a'_{i1}, a'_{i2}, \cdots, a'_{i6})$; this is called a new protocol, which is the base for the final payment. But this new protocol cannot be solved directly and it is found by the method of negotiation between the buyer and winners.

Without loss of generality, here, we take three attributes (x_{i1}, x_{i2}, x_{i3}) as an example. Figure 1 describes a surface plot of equal utility for the buyer and winners, where π denotes the surface plot of equal utility for the winner i and u denotes the surface plot of equal utility for the buyer; then, the intersection of π and u is the negotiation set. Any point on the surface plot of equal utility π for the winner i can satisfy the buyer's utility value u and any point on the surface plot of equal utility u for the buyer can also satisfy the winner i's utility value π. For the buyer, his satisfactory attribute combination is $(x^*_{i1}, x^*_{i2}, x^*_{i3})$, which is shown as point B in Figure 1. This point is unknown for the winners. Thus, in the process of negotiation, the buyer will induce the winners to change their attribute combination $(x'_{i1}, x'_{i2}, x'_{i3})$ in the negotiation set. The initial point (current situation point) is denoted as point A. When the attribute combination $(x'_{i1}, x'_{i2}, x'_{i3})$ changes to point B, which is the only satisfactory attribute combination $(x^*_{i1}, x^*_{i2}, x^*_{i3})$ of the buyer, the negotiation is over and point B is the new protocol.

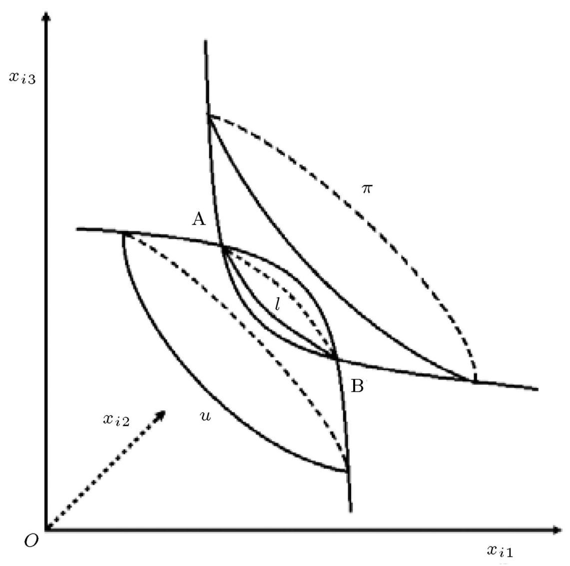

Figure 1. The surface plot of equal utility for the buyer and winners.

In the negotiation, the winners will negotiate with buyer on all attribute values and then a new protocol will be produced under the condition that utilities of the buyer and suppliers are not decreased and the allowed supply quantity for each winner is not decreased. The new protocol can be determined according to the bidding efficiency of the winners. Here, the bidding efficiency is defined as follows:

Definition 1. If the following two conditions are satisfied, then we declare that a winner's bidding has 100% bidding efficiency.

(i) To get the existing allowable supply quantity and utility, at least one attribute value of a winner is not reduced in multiple attribute values of his bidding, unless he increases the other attribute values at the same time;

(ii) Under the condition that all the existing attribute values are unchanged, the winner's allowable supply quantity and utility cannot be increased.

Definition 2. If a winner's bidding has 100% bidding efficiency, then his bidding is called an effective bidding.

In the practical application, the bidding efficiency can be calculated by using the method of Data Envelopment Analysis (DEA) [50,51] for each winner. Concretely, for the winner i, we can regard the values of price, quantity, quality (calorific value, moisture, ash, volatile matter, ash melting point, and sulfur coal classification), and the delivery time in winner i's bid as the input indicators and regard the values of winner i's allowed supply quantity and the utilities of the buyer and the winner i as the output indicators; then, we use the method of DEA to calculate the winner i's bidding efficiency. On the basis of this result, the buyer will negotiate with each winner on all attribute values and then a new protocol will be produced under the condition that all values of output indicators are not decreased.

4. The basic implementation steps of the two-stage compound mechanism

Based on the analysis and discussion in Sections 2 and 3, now, we give the specific implementation steps to show how to apply the two-stage compound mechanism in the actual procurement of electricity coal.

- **Step 1:** At the beginning of the procurement, the buyer announces some standards and rules including the score rule:

$$s_i = \sum_{j=1}^{6} w_j (a_{ij})^{\frac{1}{3}} + \frac{w_7}{t_i} - p_i,$$

the reserve price of electricity coal per ton $\bar{p}$, the reserve values of quality $\underline{a} = (\underline{a}_1, \underline{a}_2, \cdots, \underline{a}_6)$, the supplier's delivery time $t_i \leq T$ (where T is a prescribed time limit), and the limitative maximum supply quantity $\bar{q}$;

- **Step 2:** Every supplier submits a sealed bid with the form $(p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6})$ based on the standards and rules given by the buyer. Every supplier has only one chance to submit the bid;
- **Step 3:** After all suppliers submit their bids, the bidding data $p_i, q_i, t_i, a_{i1}, a_{i2}, \cdots, a_{i6}$, $i = 1, 2, \cdots, n$, and the values of Q_0, w_j, and $\bar{q}$ given by the buyer are substituted into the model M_1. By using the Lingo software to solve M_1, we can obtain the allowable supply quantity q_i^* for all suppliers. When $q_i^* > 0$, the corresponding supplier i wins the bid and becomes a winner. When $q_i^* = 0$, the corresponding supplier i loses his bid. The prepaid rules are as follows. The winner i must provide his promised quality level of the electricity coal to the buyer within the delivery time given in his bid. His received payment is different from the uniform price auction and discriminatory price auction. If the buyer chooses a discriminatory price auction, then the market clearing price is the unit price p_i in the winner i's bid and winner i obtains the allowable supply quantity q_i^* and gets the total payment $p_i q_i^*$. If the buyer chooses a uniform price auction, then the market clearing price is $p^* = \min_i p_i$, which means the winner i will supply the buyer with the electricity coal with price $p^* = \min_i p_i$ and quantity q_i^*;
- **Step 4:** Based on the winners' scheme and corresponding pre-allocation results of electricity coal supply in the auction stage, the buyer and all winners enter the negotiation stage. The premise condition of negotiation is that utilities of the buyer and winners are not decreased and the allowed supply quantity for each winner is not decreased. The result of negotiation is that the values of some attributes increase/decrease and other values of some attributes decrease/increase and at last, the buyer and each winner get a new protocol point $(p_i', q_i', t_i', a_{i1}', a_{i2}', \cdots, a_{i6}')$. The solving process of this new protocol point is as follows. For the winner i, the values of price, quantity, quality (calorific value, moisture, ash, volatile matter, ash melting point, and sulfur coal classification), and the delivery time in winner i's bid are regarded as the input indicators and the values of winner i's allowed supply quantity and the utilities of the buyer and the winner i are regarded as the output indicators; then, the method of DEA is used to calculate the winner i's bidding efficiency. Based on this result, the buyer will negotiate with each winner on all attribute values and then a new protocol will be produced under the condition that all values of output indicators are not decreased. The buyer will pay for each winner according to the new protocol.

5. Conclusions

Focusing on the decision making problem of multi-attribute and multi-source procurement of electricity coal in power industry, this paper designed a two-stage compound mechanism based on auction and negotiation. Compared with the existing procurement mechanisms of electricity coal, the contribution of this paper is as follows:

1. The existing procurement mechanisms of electricity coal are usually the methods based on the classical decision theory. It is difficult to motivate the suppliers to declare their real information in actual procurement, which may lead to an inefficient allocation result and it would be difficult to achieve effective allocation of electricity coal. Considering the fact that electricity coal is a kind of rare resource with the characters of continuity, homogeneity, and divisibility, this paper designs an incentive multi-attribute and multi-source procurement mechanism for electricity coal procurement based on multi-attribute auction theory and negotiation theory. This new procurement mechanism can induce the suppliers to announce their actual costs truthfully and improve the social allocation efficiency of electricity coal;
2. Considering the fact that demand of electricity coal in thermal power generation is great and the power generation enterprises need many different kinds of electricity coal, the supply of a single supplier is limited with regard to quantity and variety and it is often difficult to meet the needs of buyers within the specified time. This paper regarded electricity coal procurement as a kind of multi-attribute and multi-source procurement, which means the buyer could select multiple suppliers to supply the electricity coal at the same time. This paper effectively improves the method when the winner (the winning bidder) is unique, like in the existing literature. Also, the winner of the multi-attribute and multi-source procurement mechanism presented in this paper is not unique and can be one or more, and each winner can supply the buyer with multiple-quantity electricity coal;
3. For realizing the procurement operations with

higher efficiency, this paper further introduced negotiation mechanism into the multi-attribute auction mechanism and then designed a two-stage compound mechanism based on auction and negotiation. The prominent characteristics and the main difference from the previous research on this two-stage compound mechanism are that this mechanism considers the quality competition in multi-attribute and multi-source procurement of electricity coal and pays attention to the private information disclosed to the buyer and the suppliers. In the multi-attribute auction stage, the buyer will determine the winner among all suppliers and give the pre-allocated results according to the suppliers' bidding. In the negotiation stage, a new protocol will be produced under the condition that the utilities of the buyer and suppliers are not decreased and the allowed supply quantity for each winner is not decreased; thus, the allocation efficiency of procurement can further improve.

Moreover, for the two-stage compound mechanism presented in this paper, one important topic is that whether there are multiple equilibrium in it? If the equilibrium is not unique, then how to direct the auction to a desired equilibrium state? This is a research focus in our future work. In addition, another future work is that we intend to design an interactive multi-attribute and multi-source e-procurement system of electricity coal based on the two-stage compound mechanism in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 71540027, 71201064, 71371147, 61403288), the Natural Science Foundation of Hubei Province, China (No. 2014CFC1096), and the 2014 Key Project of Hubei Provincial Department of Education, China (No. D20142903).

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Biographies

Congjun Rao was born in Huanggang, China, in 1979. He received an MS degree from Wuhan University of Technology, China, in 2006, and received his PhD degree from Huazhong University of Science and Technology, China, in 2011. His research interests include supply chain management, auction theory, and decision theory and method.

Junjun Zheng was born in Songzi City in Hubei Province, China, in 1966. She received her MS and PhD degrees from Wuhan University in 1998 and 2006, respectively. She is currently a Professor in Wuhan University. Her current research interests include auction theory and management decision.

Zhuo Hu received his PhD degree from Huazhong University of Science and Technology, China, in 2012, and is now a postdoctoral fellow in the School of Public Administration at Huazhong University of Science and Technology. His research interests include supply chain management and decision making theory and method.

Mark Goh holds a PhD degree from the University of Adelaide. In the National University of Singapore, he holds the appointments of Director (Industry Research) at the Logistics Institute-Asia Pacific, a joint venture with Georgia Tech, USA, and Principal Researcher at the Centre for Transportation Research. Also, he was a Program Director of the Penn-State NUS Logistics Management Program. He is currently a Professor in the School of Business IT and Logistics at RMIT University, Australia. His current research interest is on buyer-seller relationships, performance measurement, and supply chain strategy.