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Abstract

Purpose – Coal and power generation are related upstream and downstream industries. Coal price marketization and electricity price regulation have caused the price of coal to be sensitive to the benefits of generators. The paper aims to discuss these issues.

Design/methodology/approach – As a financial tool, contracts for differences can both help balance interests and reduce risks caused by spot price fluctuation. This thesis regards coal demand as a triangular fuzzy stochastic variable while directing a levelling consideration towards risk returns for coal and power enterprises that are involved in coal generation contracts for differences. Risk and benefit measurement models were established between coal suppliers and power generators, and risk and benefit balance optimization models for contract negotiation were constructed.

Findings – A numerical example showed that the above models can be effectively used to avoid the risks of coal-electricity parties.

Originality/value – This thesis regards coal demand as a triangular fuzzy random variable while directing a levelling consideration towards the risk return to coal and power enterprises that are involved with coal generation contracts for differences. The features of this thesis are the following: demand information is regarded as a fuzzy random variable instead of a random variable. With historical data, sales experience and increasingly clear macro-economic conditions, coal and power enterprises are able to make a fuzzy decision – to a certain extent – when the transaction approaches. Accurate market information enables the supply chain system to satisfy the clients' needs better, improve the profit level or avoid severe financial damages; by developing a feasible set of contracts for different parameters, it is possible to estimate whether the price difference enables supply chain coordination, requires changes or gives accounts to all involved parties of the supply chain; and without the assumption that the traditional M-V rule is unfavourable

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to decision makers, this thesis proposes the prospect M-V rule, which involves decision makers' projections of future coal generation prices and enables wide applicability of the response method to contracts for differences.

Keywords Optimization model, Coal-electricity supply chain, Contracts for differences, Normal triangular fuzzy stochastic variable, Prospect M-V

Paper type Research paper

1. Introduction

Coal is a major energy source in China. Thermal power plants represent over 70 per cent of power plant capacity throughout the country. The alternating occurrence of coal cornering and electricity supply shortage in China that have occurred since 1985 have seriously affected the stable development of the national economy and the orderly development of a domestic coal generation market. The essential reason for this intense coal-power conflict is that the Chinese Government, due to the particularity of power products, has been exerting macro-economic control on the generation of the coal supply to stabilize the supply chain after a power system reform. This macro-economic control further restricts the generation of the market-oriented, price-forming coal generation mechanism (Wang, 2007). The Chinese Government and academic circle mainly focus on the application of and research on three methods of coal generation order convergence, coal-power price linkage and the coal generation vertical industry integration; however, all of the three measures have problems or limitations (Gui *et al.*, 2012). In recent years, the Chinese Government has, respectively, promulgated "coal-power price linkage", "coal-power production joint venture" and "coal-power industry integration" policies to mitigate the coal-power conflict, but none of these policies have succeeded in forming an effective coal generation price-forming mechanism. Therefore, these policies have not only failed in solving the coal generation conflict but have instead further disturbed the coal generation price system as intervention behaviour from the government.

Meanwhile, contracts, as an available coal generation relationship coordination solution, offer some political support and supports critical economy needs. First, the Chinese Government stated in the energy development "Twelfth Five Year Plan" that reform in critical industries such as power and coal must be advanced and that the energy price-forming mechanism must be addressed. Second, due to the reduced need for coal that has existed since 2012 caused by slowed economic growth in China, the supply demand situation in the coal market has obviously changed. The government has also implemented a complete marketization of the coal market by cancelling key coal contracts. Offering both political and economic advantages, the guiding opinions on the deepening reform of the coal market marketization, promulgated by General Office of the State Council, proposed to construct a new coal generation supply system, manage spontaneous contract conclusions and negotiations between coal and power enterprises and encourage enterprises to generate medium-and long-term contracts. Guiding opinions also requires the promotion of marketization reforms for coal generation transportation and long-term coal generation contracts for large and medium-sized coal-powered enterprises to prioritize transportation. The notifications for completing production-transportation coordination, promulgated by the NDRC, addresses the requirement of facilitating the conclusion of medium- and long-term contracts and developing stable long-term supply-demand relationships.

A group of scholars led by Qian (2013) suggests that it is currently the right time for the implementation of coal supply chain management. The National Development and Reform Commission also attaches great importance to coal logistics and supply chain management and disseminated the planning of coal transportation development at the end of 2013. Planning states that by the year of 2020, the overall operation efficiency, socialization, specialization and informatization level of the coal logistics system will be promoted and the construction of a modern coal logistics system with a developed transportation network, advanced technical equipment and an efficient transportation service will be preliminarily finished. Planning also proposes measures regarding the development of coal logistics and the supply chain system, including the construction of 11 large-scale coal storage and distribution bases, 30 logistics parks with 20 million tons of annual circulation and several coal transaction markets. In March 2015, the new power system reform scheme (several opinions on further deepening reform of power system, hereinafter referred to as the ninth file) was promulgated, which changes the "transportation-distribution separation" strategy in the fifth file to a system reform strategy that aims to promote market transactions. Therefore, China's coal market will gradually develop into a stable, developed and regulated market in the long term. The National Development and Reform Committee also indicate that the coal generation industry can develop a new type of coal-powered industrial relationship by signing a long-term contract instead of yearly contracts. In consideration of the true situation in China, the new development trend for China's coal generation industry is to sign long-term coal generation supply contracts with a validity period of five years or more (Li, 2013).

The research on long-term coal generation originates from Joskow and Rose (1985) research on transaction form selection and the long-term contract performance of coal-fired power plants. Following this study, Lopez-Bayon and Gonzalez-Diaz (2010), Kozhevnikova and Lange (2009) and Kerkvliet and Shogren (2001) conducted research on contract persistence, and Loredo and Suarez (2000) conducted research on regulations related to coal generation transactions.

Enterprise cooperation, income distribution and risk sharing are key components of supply chain management. In recent years, some scholars have begun to analyse supply chain coordination issues using evolutionary game theory. Barari *et al.* (2012) constructed an evolutionary game-based decision-making frame for green supply chains; Naini *et al.* (2011) proposed an integration performance assessment system for automobile supply chains on the basis of evolutionary game theory and balance score cards; Yu *et al.* (2009) conducted a stability analysis on suppliers' storage in supply chains; Huang analysed a two-tier supply chain system consisting of manufacturers and suppliers. Cooperation mechanisms between bounded rational manufacturers and suppliers through long-term collaborative product development have been studied on the basis of evolutionary game theory.

China has a high volume of coal production and coal consumption. Scholars have also conducted a wide range of related research on China's coal supply chain (Ma *et al.*, 2009). Li (2011) proposed eight value creation systems for the coal supply chain, and conducted research on cooperation methods and cooperative value creation in the coal generation supply chain. Li and Tan (2010) conducted research on competition and income distribution of the coal generation supply chain with the Stackberg game theory and bilevel programming, respectively. Tan *et al.* (2011) conducted research on the use of contracts for differences for risk prevention in the coal generation supply chain. Bi and Zhao (2011) conducted research on the cooperation quality management system of enterprises involved in the coal supply chain. Gui *et al.* (2012) conducted research on government-regulating coal-power relations in China. Lin (2013) discussed the influence of spatial-time constraints in choosing coal generation allocation contracts. Jiang *et al.* (2012) conducted economic measurements on the carbon emissions of the coal generation supply chain. Ye *et al.* (2012) conducted research on formation mechanisms and the reasonability of coal generation prices. Peng *et al.* (2013, 2015) conducted research on coal generation supply chain coordination under bilateral price regulation. Qian and Cao (2010) proposed that China's long-term coal generation contracts be led by market price adjustments.

Previously, contracts for differences are mainly applied in power market. Over the last few years, the Chinese scholars have conducted research on contracts for differences application in coal generation market. Li and Tan (2010) proposes the concept of optimized order rate based on risk measurement on introducing contracts for differences to power and coal enterprises. Zhang *et al.* (2013) and Tan *et al.* (2014a, b, c) propose that coal enterprises' production can increase by cooperating with power enterprises in concluding coal generation contracts for differences under intense conditions of coal generation. Tan *et al.* (2014a, b, c) develops a risk return-levelling model for contracts for differences between power enterprises and coal enterprises.

However, all existing models are developed either without consideration of the variable character of coal demand or under the assumption that coal demand is a random variable. Scholars have not taken into account the fact that coal companies and power generation companies have different supply and demand conditions and economic backgrounds and that their positions in the supply chain is different, particularly with regard to supply and demand and the economic environment, political environment, international market and the exchange rate context, in which the two sides produce a particular state of equilibrium. In fact, under supply chain cooperation, the two sides cooperate regarding the new interest-generated awareness, with profits of non-cooperation as a reference point. In addition, the risk-benefit balance of both sides has been established by previous scholars based on the model of the cost-benefit ratio of both sides, divided by profit variance coefficient. In fact, coal and power generation are upstream and downstream on the same industrial chain. The yield and profit variability are not comparable, so the risk-benefit expression made by scholars previously needs to be corrected. In real-life conditions, the demand for coal generation is both random and under the influence of many related factors, such as the economic environment, political environment, international market and exchange rate. Additionally, the demand is fuzzy. On the other hand, based on knowledge about the future, both power enterprises and coal enterprises have already developed their respective predictions about anticipated coal generation price changes when concluding contracts with one another.

In conclusion, this thesis regards coal demand as a triangular fuzzy random variable while directing a levelling consideration towards the risk return to coal and power enterprises that are involved with coal generation contracts for differences. The features of this thesis are the following: demand information is regarded as a fuzzy random variable instead of a random variable. With historical data, sales experience and increasingly clear macro-economic conditions, coal and power enterprises are able to make a fuzzy decision – to a certain extent – when the transaction approaches. Accurate market information enables the supply chain system to satisfy the clients' needs better, improve the profit level or avoid severe financial damages; by developing a feasible set of contracts for different parameters, it is possible to estimate whether the price difference enables supply chain coordination, requires changes or gives accounts to all involved parties of the supply chain; and without the assumption that the traditional M-V rule is unfavourable to decision makers, this thesis proposes the prospect M-V rule, which involves decision makers' projections of future coal generation prices and enables wide applicability of the response method to contracts for differences.

2. Preliminaries

The definition of a normal triangular fuzzy random variable, as well as the definition of its corresponding expected value and standard deviation, is as follows (Chen and Li, 2014):

Definition 1. For arbitrary r, if the membership function of $\xi(r) = [X(r) - \alpha, X(r), X(r) + \beta]$ satisfies:

$$u_{\xi(r)}(x) = \begin{cases} \frac{|x - X(r) + \alpha|}{\alpha}, & X(r) - \alpha \leqslant x \leqslant X(r) \\ \frac{|-x + X(r) - \beta|}{\beta}, & X(r) \leqslant x \leqslant X(r) + \beta] \\ 0, & otherwise. \end{cases}$$

Where $\alpha > 0$, $\beta > 0$, $X(r)$ refers to a real-valued random variable, then $\xi(r) = [X(r) - \alpha, X(r), X(r) + \beta]$ will be deemed a triangular fuzzy random variable.

Definition 2. Assuming that $\xi(r) = [X(r) - \alpha, X(r), X(r) + \beta]$ is a triangular fuzzy random variable, then the expected value of the triangular random fuzzy variable $\xi(r)$ will be:

$$E[\xi(r)] = \frac{4E[X(r)] - \alpha + \beta}{4} \tag{1}$$

Definition 3. Assuming that $\xi(r) = [X(r) - \alpha, X(r), X(r) + \beta]$ is a triangular fuzzy random variable defined within the probability space $(\Omega, \sum, \mathrm{P}r)$ with the limited expected value $E[\xi(r)]$, then the variance of the triangular fuzzy random variable $\xi(r) = [X(r) - \alpha, X(r), X(r) + \beta]$ is:

$$Var[\xi(r)] = E\left[\left(\xi(r) - E|\xi(r)|\right)^2\right] \tag{2}$$

The proposed PM-VR is based on the cost function of the prospect theory. As for the triangular fuzzy random variable, after the calculation of its expected value $E[\xi(r)]$ and variance $Var[\xi(r)]$, all three values will be transformed into the prospect effect, prospect expected value and prospect variance value, in accordance with definitions below:

Definition 4. Assume that $\xi(r)$ is a triangular fuzzy random variable with an expected value of $E[\xi(r)]$ and variance of $Var[\xi(r)]$. Reference points based on the prospect theory will be the triangular fuzzy random value $\Delta(u)$, expected value $E[\Delta(u)]$ and variance $Var[\Delta(u)]$. The expected prospect effect of the triangular fuzzy variable $\xi(r)$ will be:

$$\Delta E_{\xi(r)} = E[\xi(r)] - E[\Delta(u)] \tag{3}$$

The prospect variance effect of $\xi(r)$ is:

$$\Delta Var_{\xi(r)} = Var[\xi(r)] - Var[\Delta(u)] \tag{4}$$

$\xi(r)$ the prospect expected value cost function is:

$$v\left(\Delta E_{\xi(r)}\right) = \begin{cases} \left(\Delta E_{\xi(r)}\right)^{\alpha}, & \Delta E_{\xi(r)} > 0 \\ -\sigma\left(-\Delta E_{\xi(r)}\right)^{\beta}, & \Delta E_{\xi(r)} < 0 \end{cases} \tag{5}$$

$\xi(r)$ the prospect variance cost function is:

$$v\left(\Delta Var_{\xi(r)}\right) = \begin{cases} \left(\Delta Var_{\xi(r)}\right)^{\alpha}, & \Delta Var_{\xi(r)} > 0 \\ -\sigma\left(\Delta Var_{\xi(r)}\right)^{\beta}, & \Delta Var_{\xi(r)} < 0 \end{cases} \tag{6}$$

In accordance with Definition 4, the prospect expected value of triangular fuzzy variance $\xi(r)$ is:

$$W\left(\Delta E_{\xi(r)}\right) = h\left(p_{\xi(r)}\right)v\left(\Delta E_{\xi(r)}\right) \tag{7}$$

The prospect variance value of $\xi(r)$ is:

$$W\left(\Delta Var_{\xi(r)}\right) = h\left(p_{\xi(r)}\right)v\left(\Delta Var_{\xi(r)}\right) \tag{8}$$

where $h(p_{\xi(r)})$ refers to decision weights:

$$h\left(p_{\xi(r)}\right) = \frac{p^{\gamma}_{\xi(r)}}{\left[p^{\gamma}_{\xi(r)} + \left(1 - p^{\gamma}_{\xi(r)}\right)\right]^{\frac{1}{\gamma}}} \tag{9}$$

3. Coal generation price projection and profit referring point recognition of coal and power enterprises

The annual coal transaction amount of coal and power enterprises is Q^*. The profit expected by coal and power enterprises usually depends on their projection of the coal generation price. This thesis studies the anticipated profit of power enterprises and coal enterprises. In the past, the price anticipated by coal enterprises can be different from power enterprises due to specific national policies as well as domestic and foreign demand-supply conditions. For example, the previous coal-power interaction policy generates the projection of transferring costs and further promotes the profit level by increasing the power price. Therefore, it is reasonable to, respectively, take the actual psychological states and coal generation price projection of coal and power enterprises into consideration. Under the condition that the national government has basically released its control on the coal generation price and that coal and power enterprises' knowledge and market positions are basically the same, this thesis assumes that coal and power enterprises generate their coal generation price projections with the same measurements.

A number of scholars have conducted a large amount of research on coal generation price projection. The existing research on coal price projection can be divided into two factors: factor selection and mathematical models. With factor selection, the research can be divided into a time series model and a multivariate prediction model. Lin (2013) developed a short-term coal price prediction model with an autoregressive moving average. Ye *et al.* (2012) developed a multivariate regression model to fit the coal price fluctuation. For the mathematical model, the research can be divided into linear and non-linear fitting models. Qian and Cao (2010) predicted the coal price fluctuation in the domestic market with a non-linear ANN model.

With adequate consideration of different economic factors related to coal prices, this thesis adopts a new model-non-linear machine learning model as the vector machine support. Using a combination of feature selection and support vector regression, the thesis recognized five factors with the strongest influence on coal price: total coal production, total sales volume, total import quantity and the international oil prices and coal prices of the previous month. A model for an analysis and prediction for the coal price in Qinhuangdao is developed with a support vector machine and a genetic algorithm. With the monthly coal price in Qinhuangdao between 2006 and 2010 (with the listed price of 5.5 kcal of bituminous coal as a prediction object) as sample data, an analysis and prediction is conducted on coal price fluctuation. First, the difference in coal price is taken as an output vector of the model to mitigate the heteroscedasticity in the market coal price. After recognizing the factors with a strong influence on the coal price with the feature selection algorithm, the FS-SVM prediction model is developed with recognized factors, such as the input and coal price of the following month as output.

In conclusion, the coal generation price for the following year is predicted as P_{pri} with the methods above. Therefore, the anticipated profit of the coal enterprise and power enterprises, respectively, is:

$$\pi_{COAL(pri)} = P_{pri}Q^{*} - c_c - d_cQ^{*} \tag{10}$$

$$\pi_{ELC(pri)} = P_eQ^{*}\lambda - P_{c(pri)}Q^{*} - c_e - d_e\lambda Q^{*} \tag{11}$$

$E[\pi_{COAL(pri)}]$, $Var[\pi_{COAL(pri)}]$, $E[\pi_{ELC(pri)}]$ and $Var[\pi_{ELC(pri)}]$ can then be, respectively, calculated with $\pi_{COAL(pri)}$ and $\pi_{ELC(pri)}$, where λ refers to the conversion coefficient between coal generation and output power.

4. Coal generation contracts for the difference model establishment and expected risk return of coal enterprises

Coal generation contracts for differences refer to a type of financial coal transaction contract that aims to avoid potential risks that are generated from coal generation price differences. The contracted coal price, contracted coal transaction amount and transaction date are the critical parts of the complete coal generation contract for differences. As determined in the contracts for differences, the calculation of the coal generation price will be in compliance with the contract and real market situations, where the price difference calculation will comply with the contracted price, while the section exceeding the contracts for differences will be calculated in accordance with the general market price.

Compared to the developed market economy system in the USA, the market economy contract relationship in China's coal generation market is still developing. In considering this, both coal and power enterprises mainly generate annual coal generation contracts instead of long-term contracts with contract periods of several years or even decades. Therefore, the mid-term contract mode mentioned in this thesis adopts annual contract prices and daily calculated transaction prices.

As a result, the sales income of coal enterprises is approximately the sum of the sales income from the spot market and the sales income from the contract market. The daily sales income of coal enterprises can be expressed as the following mathematical model:

$$R_{(COAL)i} = Q_{ci}P_{ci} + \left(Q_{c0}/30\right)(P_{c0} - P_{ci}) \tag{12}$$

where $R_{(COAL)i}$ refers to the daily coal sales income of coal enterprises; Q_{c0} refers to the amount of coal transacted by contracts for differences; $Q_{c0}/30$ refers to the daily average transaction amount of the monthly coal transaction; Q_{ci} refers to the real daily transaction amount of coal enterprises (under the assumption that the production amount equals the sum of the sales income from the spot market and the sales income from the contract market); P_{c0} refers to the contracted coal price of the month; and P_{ci} refers to the market coal price of the day.

The monthly income of a coal enterprise can be expressed as:

$$R_{COAL} = Q_{c0}P_{c0} + \sum_{i=1}^{30} P_{ci}\left(Q_{ci} - Q_{c0}/30\right) \tag{13}$$

A strong correlation exists between the production costs and production amount of coal enterprises. The fixed cost is a fixed value for coal enterprises. Tan *et al.* (2011) presented the daily cost function of coal enterprises as a quadratic function. Tan believes that the variable cost will increase with the development and consumption of coal resources in the coal mine life cycle. Therefore, in its entire life cycle, the cost is a quadratic function of the output. He also believes that the daily cost function is a quadratic function. However, in this paper, we consider the daily cost function of coal enterprises rather than the cost function of the whole life cycle in this paper. Therefore, the mining depth of the mine is established on a specific day or in the short term. The author believes that the daily cost function of coal enterprises is a linear cost function. Thus, in this paper, we use a linear function to express this:

$$C_{COAL}(Q_{ci}) = c_c + d_c Q_{ci} \tag{14}$$

Judging by the practical delivery, the contracts for differences can be divided into physical contracts and financial contracts. Physical contracts require practical delivery, while financial contracts require only financial settlement. Due to the speculative character of contracts for differences, other complicated risks can be encountered while avoiding risks from coal price fluctuation. This thesis thus takes only the risk return in financial contracts into consideration.

The optimization model of variable Q_{ci} in financial contracts is as follows:

$$\begin{aligned} &(\text{P1}) \quad \max[P_{ci}Q_{ci} - c_c - d_c Q_{ci}] \\ &\text{s.t.} \quad 0 \leqslant Q_{ci} \leqslant Q_{ci\max} \end{aligned} \tag{15}$$

Meanwhile, under the assumption that the coal generation market consisted only of one coal enterprise and one power enterprise and presuming that P_{ci} is the linear function of Q_{ci}, the comparison expression between the coal price and coal production amount is $P_{ci} = -aQ_{ci} + b$. After solving the model, the optimal value $\overline{\overline{Q_{ci}}}$ of Q_{ci} can be expressed as:

$$\overline{\overline{Q_{ci}}}\left(\overline{P_{ci}}, Q_{ci}\right) = \begin{cases} Q_{ciMAX} & Q_{ci} \leqslant (b - d_c)/2a \\ (b - d_c)/2a & Q_{ci} > (b - d_c)/2a \end{cases} \tag{16}$$

where $\overline{P_{ci}}$, refers to a random vector, $\overline{P_{ci}} = (P_{c1}, P_{c2}, \cdots P_{c30})^T$.

Coal enterprises' production costs, given the optimal production amount, can be expressed as:

$$C_{COALi}\left(\overline{P_{ci}}\right) = c_c + d_c Q_{ci}\left(\overline{P_{ci}}\right) \tag{17}$$

The real monthly profit of coal enterprises can be expressed as:

$$\pi_{COAL}\left(\overline{P_{ci}}, P_{c0}, Q_{c0}\right) = P_{c0}Q_{c0} + \sum_{i=1}^{30} P_{ci}\left(\overline{Q_{ci}}\left(\overline{P_{ci}}\right) - Q_{c0}/30\right) - \sum_{i=1}^{30}\left[c_c + d_c Q_{ci}\left(\overline{P_{ci}}\right)\right] \tag{18}$$

On the one hand, this thesis adopts the profit rate of cost (Tan *et al.*, 2011) as a profit measurement, i.e., dividing the expected value of cost by the profit. The formula is:

$$B_{coal}(P_{c0}, Q_{c0}) = E\left\{\frac{\pi_{COAL}\left(\overline{P_{ci}}, P_{c0}, Q_{c0}\right)}{C_{coal}\left(\overline{P_{ci}}\right)}\middle|\overline{P_{ci}} \in S_{\overline{P_{ci}}}\right\} \tag{19}$$

In consideration of the prospect theory, this formula is modified as follows in this thesis:

$$B'_{coal}(P_{c0}, Q_{c0}) = E\left\{\frac{\pi_{COAL}\left(\overline{P_{ci}}, P_{c0}, Q_{c0}\right) - \pi_{COAL(pri)}}{C_{coal}\left(\overline{P_{ci}}\right)}\middle|\overline{P_{ci}} \in S_{\overline{P_{ci}}}\right\} \tag{20}$$

On the other hand, Tan Zhongfu used the M-V rule in the risk description, i.e., dividing the expected profit by the standard deviation of the profit. According to his theory, the risk measurement function for coal enterprises will be:

$$L_{coal}(P_{c0}, Q_{c0}) = \frac{\sigma_{coal}(P_{c0}, Q_{c0})}{E_{coal}(P_{c0}, Q_{c0})} \tag{21}$$

This formula is based on Definitions 1-4 of Chen and Li (2014) and assumes that the coal sales amount complies with the normal triangular fuzzy stochastic variable. Under the M-V prospect rule of coal enterprises and considering that the sales amount complies with the triangular fuzzy stochastic variable, the risk measurement calculation will be:

Step 1: utilize Equations (1) and (2) to calculate $E[\xi(\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0}))]$ and $Var[\xi(\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0}))]$ of the normal triangular fuzzy stochastic variable $\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0})$.

Step 2: calculate the expected value $E[\Delta(u)]$ and the variance $Var[\Delta(u)]$ of the reference point $\pi_{COAL(pri)}$.

Step 3: utilize Equations (3) and (4) to calculate the expected prospect effect $\Delta E_{\xi(r)}$ and the prospect variance effect $\Delta Var_{\xi(r)}$ against the reference point $\pi_{COAL(pri)}$.

Step 4: utilize Equations (5), (6) and (9) to calculate prospect expected value function $v(\Delta E_{\xi(r)})$, the prospect variance value function $v(\Delta Var_{\xi(r)})$ and the decision weights $h(p_{\xi(r)})$ of $\xi(r)$.

Step 5: utilize Equations (7) and (8) to calculate the prospect expected value $W(\Delta E_{\xi(r)})$ and the prospect variance value $W(\Delta Var_{\xi(r)})$.

Step 6: we defined Equation (22) to obtain the risk measure equation of the normal triangular fuzzy stochastic variable $\xi(\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0}))$ against the reference point $\pi_{COAL(pri)}$:

$$L'_{coal}(P_{c0}, Q_{c0}) = \frac{\sqrt{W\left(\Delta Var_{\xi(r)}\right)}}{W\left(\Delta E_{\xi(r)}\right)} \tag{22}$$

In conclusion, with coal enterprises regarding price as a normal triangular fuzzy stochastic variable $\xi(\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0}))$, the model to measure the risk and benefit balance against the reference point $\pi_{COAL(pri)}$ was defined as follows based on the prospect theory:

$$\eta_{COAL} = \frac{B'_{coal}(P_{c0}, Q_{c0})}{L'_{coal}(P_{c0}, Q_{c0})} \tag{23}$$

5. Risk and profit measurement model for power enterprises

Presently, the price of power in China is mainly regulated by the government instead of through bidding. The contracts for the differences mode adopted in the Eastern China stimulation power market is a type of transitional model. The monthly sales income of power enterprises under the partial contracts for differences mode can be expressed as:

$$R_{(elc)i} = Q_{e0}P_{e0} + \sum_{d=1}^{30}\sum_{t=1}^{24} P_{eit}(Q_{eit} - Q_{ecit}) \tag{24}$$

where Q_{e0} and P_{e0}, respectively, refer to the optimal production amount and price after the price bidding reform with the cooperation of coal and power enterprises. P_{eit} refers to the clearing price by the tth hour of the ith day; Q_{eit} refers to real generated energy of power enterprises' plants by the tth hour of the ith day. Due to the hour time unit, Q_{eit} also refers to the real generated energy of power enterprises' plants. The predictive estimated value is fixed: Q_{ecit} refers to contracted generated energy by the tth hour of the ith day that the power transaction centre distributed to the power enterprise:

$$\sum_{d=1}^{30}\sum_{t=1}^{24} Q_{ecit} = Q_{e0}, \quad Q_{ecit} > Q_{e\min} \tag{25}$$

where $Q_{e\min}$ refers to the least generated energy in the power enterprise's plant (assuming that every power enterprise owns only one power plant).

Assuming that the coal consumption rate of the power plant is β and the monthly coal consumption amount of power enterprises equals their coal purchase volumes, then:

$$\beta\sum_{i=1}^{30}\sum_{t=1}^{24} Q_{eit} = Q_{ci}P_{ci} + \sum_{i=1}^{30} P_{ci}\overline{\overline{Q_{ci}}}(P_{ci}) \tag{26}$$

The left side of the formula above refers to the monthly coal consumption amount of power enterprises; the right side of the formula refers to the monthly coal purchase volume of power enterprises in the contract market and spot market.

Therefore, as with the coal enterprises, the cost function and production amount of power enterprises will become a linear relationship on a certain day. The optimization model for variable Q_{eit} is further constructed:

$$\begin{aligned} &(\text{P2}) \quad \max[P_{eit}Q_{eit} - (a_e + b_eQ_{ecit}) \\ &\text{s.t.} \quad Q_{ecit} < Q_{eit} < Q_{e\max} \end{aligned} \tag{27}$$

where $Q_{e\max}$ refers to the highest generation energy level of the power plant. As above, assuming that P_{ei} is a linear function of Q_{ei}, the comparison expression between the power price and the coal production amount is $P_{ci} = -aQ_{ci} + b$. By solving this model, the optimal value, $\overline{\overline{Q_{eit}}}$ of Q_{eit}, may be expressed as (under the assumption that a negative linear relationship exists between the demand function Q and p):

$$\overline{\overline{Q_{eit}}}\left(\overline{P_e}, \overline{Q_{ec}}, \overline{P_{ci}}, P_{c0}, Q_{c0}\right) = \begin{cases} Q_{ciMAX} & Q_{ci} \leqslant (b-d_c)/2a \\ (b-d_c)/2a & Q_{ci} > (b-d_c)/2a \end{cases} \tag{28}$$

Formula (15) indicates that $\overline{P_e}$ and $\overline{Q_{ec}}$ in the contract influence the real generated energy of power enterprises.

The profit of power enterprise can be expressed as:

$$\pi_E\left(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0}\right) = P_{e0}Q_{e0} + \sum_{d=1}^{30}\sum_{t=1}^{24} P_{eit}\left(\overline{\overline{Q_{eit}}}\left(\overline{P_e}, \overline{Q_{ec}}, \overline{P_{ci}}, P_{c0}, Q_{c0}\right) - Q_{ecit}\right) - P_{c0}Q_{c0}$$
$$- \sum_{i=1}^{30} P_{c0}\left[\beta \sum_{t=1}^{24} \overline{\overline{Q_{eit}}}\left(\overline{P_e}, \overline{Q_{ec}}, \overline{P_{ci}}, P_{c0}, Q_{c0}\right) - Q_{c0}/30\right] \tag{29}$$

As with coal enterprises, the profit measurement function of power enterprises can be expressed as:

$$B_E^{'}(P_{c0}, Q_{c0}) = E\left\{\frac{\pi_E\left(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0}\right) - \pi_{ELC(pri)}}{Q_{c0}P_{c0} + \sum_{i=1}^{30} P_{ci}(Q_{ci} - Q_{c0})}\middle| \overline{P_{ci}} \in S_{\overline{P_{ci}}}, \overline{P_e} \in S_{\overline{P_e}}\right\} \tag{30}$$

Similar to coal enterprises, power enterprises regard price as a normal triangular fuzzy stochastic variable $\xi(\pi_{ELC}(\overline{P_{ci}}, P_{c0}, Q_{c0}))$, and the risk measurement calculation of power enterprises will be:

Step 1: utilize Equations (1) and (2) to calculate the $E[\xi(\pi_E(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0}))]$ and $Var[\xi(\pi_E(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0}))]$ of the normal triangular fuzzy stochastic variable $\pi_E(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0})$.

Step 2: calculate the expected value $E[\Delta(u)]$ and the variance $Var[\Delta(u)]$ of the reference point $\pi_{ELC(pri)}$.

Step 3: utilize Equations (3) and (4) to calculate the expected prospect effect $\Delta E_{\xi(r)}$ and the prospect variance effect $\Delta Var_{\xi(r)}$ against the reference point $\pi_{ELC(pri)}$.

Step 4: utilize Equations (5), (6), (9) to calculate the prospect expected value function $v(\Delta E_{\xi(r)})$, the prospect variance value function $v(\Delta Var_{\xi(r)})$ and the decision weights $h(p_{\xi(r)})$ of $\xi(r)$ $(\xi(\pi_E(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0})))$.

Step 5: utilize Equations (7) and (8) to calculate the prospect expected value $W(\Delta E_{\xi(r)})$ and the prospect variance value $W(\Delta Var_{\xi(r)})$.

Step 6: we defined Equation (22) to obtain the risk measure equation of the normal triangular fuzzy stochastic variable $\pi_E(\overline{P_{ci}}, P_e, P_{c0}, Q_{c0})$ against the reference point $\pi_{ELC(pri)}$:

$$L'_{ELC}(P_{c0}, Q_{c0}) = \frac{\sqrt{W\left(\Delta Var_{\xi(r)}\right)}}{W\left(\Delta E_{\xi(r)}\right)} \tag{31}$$

In conclusion, the set price of power enterprises will be the normal triangular fuzzy stochastic variable $\xi(\pi_{COAL}(\overline{P_{ci}}, P_{c0}, Q_{c0}))$. Additionally, the risk return measurement model, based on the prospect theory and reference point $\pi_{COAL(pri)}$, will be:

$$\eta_{COAL} = \frac{B'_{ELC}(P_{c0}, Q_{c0})}{L'_{ELC}(P_{c0}, Q_{c0})} \tag{32}$$

6. Risk and benefit balance optimization models for contract negotiation between coal suppliers and power generators

6.1 Model construction

Contracts for differences can help market subjects – coal and power enterprises – avoid risks, but its performance can be poor given inappropriate application. The competition mechanism can be restricted and can further influence social effect promotion with excessively large contract amounts. Incorrect contract amounts enable coal enterprises to manipulate the market and push coal prices with market power. Therefore, identifying the method to confirm the proper contract prices and contract amounts is an important issue in this thesis.

Considering the objective function least unit risk return difference between coal and power enterprises and the largest bearable risk and expected least cost-benefit of coal and power enterprises, the following is a contract negotiation optimization model for coal and power enterprises:

$$\begin{aligned}
(P3)\ \min & \left| \frac{B'_{coal}(P_{c0}, Q_{c0})}{L'_{coal}(P_{c0}, Q_{c0})} - \frac{B'_{ELC}(P_{c0}, Q_{c0})}{L'_{ELC}(P_{c0}, Q_{c0})} \right| \\
s.t.\quad & 0 \leqslant Q_{ci} \leqslant Q_{ci\max} \\
& L_{coal}(P_{c0}, Q_{c0}) \leqslant L_{coal}^{\max} \\
& B_{coal}^{\min} \leqslant B_{coal}(P_{c0}, Q_{c0}) \\
& L_e(P_{c0}, Q_{c0}) \leqslant L_e^{\max} \\
& B_e^{\min} \leqslant B_e(P_{c0}, Q_{c0})
\end{aligned}$$

where $L_{coal}^{\max}$ and $L_e^{\max}$, respectively, refer to the bearable largest risk of coal enterprise and power enterprises and $B_{coal}^{\min}$ and $B_e^{\min}$, respectively, refer to the least unit cost-benefit of coal and power enterprises.

6.2 Model solving steps

The negotiation solution steps for model (P4) are as follows:

(1) The coal enterprise and power enterprise, respectively, submit contract coal price P_{c0bid} and P_{e0bid} at the beginning of each month. If $\{P_{c0bid}, P_{e0bid}\} = \varnothing$, the two enterprises will be required to submit new contract prices until $\{P_{c0bid}, P_{e0bid}\} \neq \varnothing$.

(2) The coal enterprise and power enterprise will, respectively, submit their largest bearable risk value $L_{coal}^{\max}$ and $L_e^{\max}$, as well as their least expected cost-benefits, $B_{coal}^{\min}$ and $B_e^{\min}$.

(3) Use lingo programming software to optimize the model after calculating the quoted price scope [P_{c0bid}, P_{e0bid}] of the two enterprises into the constraint condition, and the optimal solution P^*_{ci}, Q^*_{ci} is acquired.

(4) If (P4) is insoluble, it is possible to decrease P_{c0bid} and increase P_{e0bid} by a certain rate, increase the largest bearable risk above or decrease the least expected cost-benefit of the two enterprises and repeat the process until the formula becomes solvable.

7. Example and result analysis

Assume that the installed capacity of a thermal power generation enterprise is 40,150 MW; the annual average operation hour of the enterprise is 5,500 h; the average coal consumption rate is 360 g/k Wh; the annual coal consumption of the generator engine is 475.12 million tons; and the pool purchase price is 0.135 yuan/k Wh. The enterprise adopts the integration of spot and contracts for difference mode and concluded contracts for differences with a coal enterprise in fuel procurement process to diversify the risks in the coal generation market. The maximum daily production of the coal enterprise is 150t. The production cost function is Ccoal = 1,000+2.2 Qd. The contracted price is 445 yuan/t. The monthly transaction cycle and daily settlement method. Spot coal generation is mainly purchased from adjacent large coal transaction ports. The maximum working hour of the power enterprise is 21 h/d. The power enterprise is regulated by the government to supply power at a contract price of 50,000 MWh/month and a contract price of 360 yuan/MWh. Other power supplies are directly purchased from the spot market. Assume that the maximum bearable risk to the coal supplier and power enterprise in a contract negotiation is 15 per cent and that the minimum acceptable cost-benefit rate to coal suppliers and power enterprises is 10 per cent.

A coal generation price scatter diagram is generated in accordance with the stimulated coal generation price fluctuation data from 1 June 2013 to 1 July 2015. It is shown that the points refer to the average coal generation price decrease in certain areas. Within 108 weeks, the coal generation price fluctuates within the scope of [390, 500] (yuan/t). Thus, it is reasonable to assume that the price complies with the normal triangular fuzzy distribution within the area. The points shown in the coal transaction amount-price scatter diagram for the 108 weeks mainly fall along the same line. The scatter diagram for the average coal generation price within the 108 weeks is drawn with SPSS.

The related coefficient is calculated after conducting a linear regression on the coal transaction amount-price scatter diagram: $a = 247.56$, $b = 130{,}576.4$. Therefore, the correlation between the exact weekly coal generation transaction amount and the average weekly coal generation price at a large coal transaction port is shown in the following formula:

$$Q_{c(p)} = 247.56a + 130{,}576.4 \quad (33)$$

Research on the electricity price in the power market of Zhejiang Province indicates that the pool purchase price is in approximate compliance with the normal distribution under a small load and a non-intense supply demand relationship. Here, assume that the pool purchase price complies with the normal distribution (mean 395, standard deviation 40).

The following are the specific calculation steps:

Step 1: according to the calculation results of model (P1), the optimized daily production of the coal supplier is $\overline{\overline{Q_{ci}}} = 2.3P_{ci}-3.8$.

Step 2: substitute the known conditions into model (P2), assuming that the primary contract prices submitted by the coal supplier and power enterprise is, respectively, $P_{c0bid} = 332$ yuan/t and $P_{e0bid} = 478$ yuan/t. Substitute the offering of the two parties into the constraint condition of the model, i.e., $332 < P < 478$.

Step 3: we adopt Lingo because the model is related to the discrete non-linear optimization issue. The optimal solutions outputted by the software programming are $P_{ci}^{*} = 408.55$ yuan/MWh, $Q_{ci}^{*} = 20{,}579.24$t.

The transaction between the coal supplier and power enterprise will be completed in the spot market if no contracts for difference are involved. Table I shows a comparison of profit/ risk to the coal supplier and power enterprise before and after the application of contracts for differences, where the risk value refers to the risk level.

Under the condition that the market coal price and coal production remain the same, the application of contracts for differences increases the coal supplier's monthly profit to 900 thousand yuan, which is 18 per cent higher than before the application of the contracts for differences. Meanwhile, the application increases the power enterprise's purchase costs and reduces the profit by 10 per cent. In the specific environment of China's coal price marketization, the mitigation of the risk to both the coal supplier and power enterprise proves that the application of contracts for differences is an effective solution for avoiding risks to coal and power enterprises that are caused by market coal price fluctuation.

Table II shows a comparison of risk factors in different quotation interval of coal suppliers and power suppliers. It can be clearly seen that the risk of coal suppliers and power suppliers gradually increase with the narrowing interval based on range (332, 478). If both coal and power suppliers' initial quotation interval are too small, the negotiation space for optimization will be affected and the global optimal solution can not be obtained. Thus, both sides need to give a reasonable initial coal quotation after fully weighing their production costs and expected benefits. This conclusion suits the reality of Chinese coal and power suppliers, and have consistency with previous studies.

Table I. Profit and risk of coal and power enterprises in situations before and after the contracts of difference

	Coal enterprises		Power enterprises	
	Profit/thousand yuan	Risk	Coal dealer	Power enterprises
Before COF	45,786	0.055	10,557.6	0.048
After COF	53,192	0.014	9,651.2	0.012

Table II. Effect of different price strategies for coal and power enterprises

Price range (P_{c0bid}, P_{e0bid})	Coal enterprises	Power enterprises
(332, 478)	0.013	0.011
(350, 454)	0.016	0.014
(375, 420)	0.020	0.016

Conclusions

Compared with past research, in consideration of risk, the model of this thesis improves upon Tan Zhongfu and other scholars' risk-benefit functions to resolve the status and consultations of power enterprises and coal enterprises in the coal generation supply chain. In this model, the coal demand is regarded as a triangular fuzzy variable, which is closer to reality. Therefore, this thesis has good applicability. Otherwise, the triangular fuzzy variable in the thesis can be applied to situations of market equilibrium, when the supply is less than or exceeds the demand, and the thesis has the same conclusion as other papers when market equilibrium is present, which shows that this method is useful. The M-V prospect theory in the thesis takes into account the extreme situation of oversupply and over-demand, which is realistic when signing contracts for difference. However, compared to Tan Zhongfu and other scholars, the computation is more complex because of the triangular fuzzy variable.

This thesis uses the M-V prospect theory and considers the demand triangular fuzzy variable to establish a contract for difference model. Future research can be conducted based on the following aspects:

(1) identify the relationship between the parameters of contracts for difference (contract transition amount and prices in contracts of difference) and the coal sales volume;

(2) assume that the value functions of coal and power enterprises are linear or non-linear and comprise the parameters of contracts of difference;

(3) under the economic environment of the coal supply exceeding the demand, research the proper value function and parameter design for coal and power enterprises through behavioural experiments; and

(4) in an economic environment in which the coal supply is less than the demand, research the proper value function for coal and power enterprises by behavioural experiments further to enrich the contracts for difference.

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