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DEA MODELS FOR TWO DECISION MAKERS WITH CONFLICTS: THE PRINCIPAL-AGENT PROBLEM

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Abstract. This paper studies the impact of two decision makers' interaction with conflicts on the efficiencies of the system. We start with a general principal-agent framework where the principal and the agent make decisions independently and the principal has a contradictive objective to that of the agent. We develop data envelopment analysis (DEA) models in the principal's and the agent's perspectives respectively. Non-cooperation between the principal and the agent is discussed to illustrate how one decision maker affects the other and the corresponding efficiency and incentive contract of the system. In addition, cooperation of the two parties is also analyzed to better derive how the performance of the system is influenced by the parties and their interactions as well. Then, this study illustrates the proposed models and effective incentive contracts by applying them to the efficiency evaluations of 22 China listed electric power companies.

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1. Introduction

In complex operations practices, there are often various managerial problems involving two decision makers coupled with conflicting interests. In a stylish principal-agent framework, a principal has a primary stake in the performance of an operational system, *i.e.* a firm, and an agent is delegated to have an operational control of the system with his professional knowledge and skills. Similarly, in a service platform such as amazon.com, ctrip.com, the .com firms act as service providers and their members can book various services, *e.g.* hotels, tickets, vacations, from service suppliers as the hotels, airlines and tourist attractions which provide customized service to the member. In these examples, the participant parties engage in an identical business relationship and their interests are usually not perfectly aligned [15]. The performance of the system is influenced significantly by the resources provided by one party, *i.e.* investment by the principal, service resource and effort by the hotel, airline etc., and the efforts by another party, *i.e.* efforts by the agent, customer base and promotion effort by the .com firm. In addition, information asymmetry, *i.e.* the agent may have private information or his response cannot be observed by the principal, further exacerbates the conflicting tension between them.

Keywords. Data envelopment analysis, two decision makers, conflict, principal-agent problem.

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Recently, a significant body of researches has accumulated in the context of principal-agent paradigm. A basic idea of these studies is to derive a short/long-term contract between the parties with the purpose to maximize the principal's expected payoff and to ensure best response of the agent to his choice of the utility. In an attempt to better model hidden action (the agent's response cannot be observed by the principal) and hidden information (the agent has private information unobservable by the principal), economists study single-period principal-agent models with complex information structures (see [13, 22]) and multi-period models with simplified information structures (see [3, 14, 20]). In addition, multi-period models with dynamic information structures are also investigated by various researchers. For example, Zhang and Zenios [26] studied a model with Markov decision process with hidden information.

However, less is understood on how the performance of the system is influenced by the parties and their interactions as well. Since two parties make distinct decisions independently and the decisions of both parties can affect each other, the impacts of their decisions on the system's performance are complex and are not easy to characterize in an explicit way. For example, although the primary stake of the principal may have a technical effect on the system's performance, the effort and private information of the agent can exert a managerial impact on the performance of the system. In addition, the performances of the agent and the principal can also influence each other. In an effort to better describe the complex relationship between the parties and their impacts on the performance of the system, this paper attempt to model this issue from performance perspective using data envelopment analysis (DEA).

Initiated by Charnes *et al.* [5], DEA proves itself to be an effective programming for measuring the relative performance of peer decision making units with multiple inputs and multiple outputs. Recently, a significant body of researches in DEA context has been developed concerning with better modeling of different production scenarios from a theoretical perspective and applies them in various issues [10], such as bank branch efficiency (see [6, 7, 23, 24]), R&D project evaluation (see [9]), productivity evaluation on research institution (see [1, 21]), Olympic achievements study (see [17]), environmental efficiency research (see [2, 25]) as well. More detailed application examples can be seen in (see [8]). The use of DEA can bring a new flavor to the principal-agent problem, because it is possible to measure organizational effectiveness and obtain ex post evaluation of the relative efficiency of management accomplishments (see [4]). In conventional DEA models, it is generally assumed that a higher output level and a lower input level are preferred in principal perspective. Therefore, one decision making unit (DMU) is deemed more efficient than another if the DMU produces larger amounts of outputs using the same amounts of inputs, or produces the same amounts of outputs using smaller amounts of inputs. Unfortunately, little research takes into account how the agent behaves and the influence on the system's performance. Especially, since the agent has a contradictive interest to the principal, what is the impact of such conflict between two decision makers on the performance of the system?

The motivation of this paper is to build a bridge between the principal-agent problem and DEA, focusing our attention on the interactions between two parties and the evaluation of the system's performance. We assume that the principal invests the inputs to a system and the agent is delegated to control the system and produce the outputs with his knowledge and ability. The agent obtains a stake from the principal and decides his effort level. The principal cannot directly observe the agent's knowledge and effort. In order to address the conflict between the principal and agent, two decision makers with independent decision making, we begin with two traditional DEA models in both the principal's and the agent's perspectives, and provide efficiency scores for both individual parties. Significant characteristics of the models are discussed to well illustrate the differences from each other. Non-cooperative and cooperative situations are discussed respectively to investigate the influence of the principal to the agent or vise versa. Numerical analysis demonstrates the feasibility and appropriateness of our proposed models.

The remainder of the paper is organized as follows. Section 2 presents basic DEA models for the principal-agent problem. Sections 3 and 4 are devoted to the development of three models by extending the non-cooperative and cooperative games. Section 5 discusses the efficiencies of the principal and the agent and their corresponding actions. In Section 6, the proposed models, efficiency measures, effective incentive contracts are illustrated by

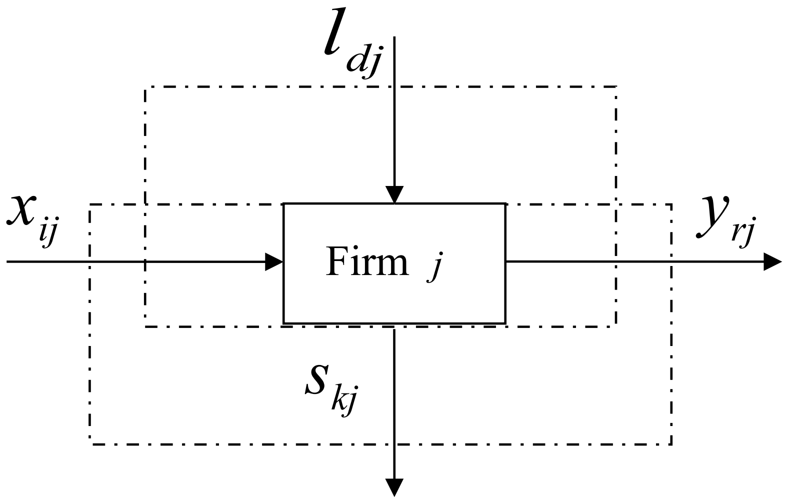

FIGURE 1. Principal-agent structure.

an application to the efficiency evaluation of 22 China listed electric power companies. Concluding remarks are provided in Section 7.

2. Basic models of principal-agent problem

Figure 1 depicts the principal-agent situation, where the firm (Principal) invests inputs $x_{ij}(i = 1, ..., m)$ and hires a manager (Agent) with motivated payments $s_{kj}(k = 1, ..., K)$. Hereafter we use "he" to refer to the agent and use "she" to refer to the principal. The manager provides managerial labors $l_{dj}(d = 1, ..., D)$ and generates outputs $y_{rj}(r = 1, ..., R)$. Each party acts as a decision maker who makes decisions independently.

In conventional economic context, the firm's performance is measured as the ratio of weighted outputs to weighted inputs, while ignoring the existence of the agent and his influence on the performance. However, such situation is not reasonable because the ability and effort of the agent can have a significant influence on the performance of the system. That is, the system's performance is affected by the principal and the agent simultaneously.

From the principal's perspective, her performance is affected by the levels of her inputs (investment, stake, payment) and the outputs of the system. From the agents perspective, his performance is affected by the levels of his inputs (knowledge, ability, effort) and the outputs (stake, payment). That is, the stake and payment are viewed as inputs and outputs from various perspectives, which construct a contradictive interest between the principal and the agent. In this regard, as independent decision makers, the principal/agent makes decision based on the inputs/outputs of another. Consequently, the performance of one party is influenced by another. For example, as the inputs of the agent, his knowledge and effort affect the performance of the principal. Similarly, the payment of the principal affects that of the agent.

The characteristics of a principal-agent paradigm can be depicted as follows:

1) The principal and the agent act as two independent decision makers.
2) The effort of the agent is unobservable by the principal. That is, the information is asymmetric.
3) The effort of the agent is difficult to measure.
4) The principal has a contradictive objective to that of the agent. That is, the principal is to optimize the efficiency by maximizing her output whereas holding the payment to the agent constant. It implies that the

agent is suggested to maximize his effort. Contrarily, the agent desires to maximize his payment holding his current effort constant or minimize his effort holding his payment from the principal constant.

In an effort to better describe the performances of the principal and the agent within the framework of DEA, we assume that each system (firm) acts as a decision making unit (DMU), which is co-decided by a principal and an agent. The inputs and outputs vector of DMU_j are $x_{ij}(i = 1, ..., m)$ and $y_{rj}(r = 1, ..., R)$, respectively. The agent exerts efforts $l_{dj}(d = 1, ..., D)$ and receives the motivated payments $s_{kj}(k = 1, ..., K)$.

2.1. In the principal's perspective

In the principal's perspective, the motivated payments $s_{kj}(k = 1, ..., K)$ are viewed as one of the classifications of the inputs. Correspondingly, the efficiency of the principal can be estimated by traditional DEA model as follows.

$$
\begin{aligned}
&\max\ \phi \\
&\text{s.t.} \\
&\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{i0} \quad (i = 1, ..., m) \quad (2.1\text{a}) \\
&\sum_{j=1}^{n} \lambda_j s_{kj} \leq s_{k0} \quad (k = 1, ..., K) \quad (2.1\text{b}) \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \geq \phi y_{r0} \quad (r = 1, ..., R) \quad (2.1\text{c}) \\
&\lambda_j \geq 0, \quad j = 1, 2, ..., n
\end{aligned} \tag{2.1}
$$

As constraint (2.1b) depicts, s_{kj} is one of the classifications of the inputs in the view of the principal. Given the inputs remain constant, the objective of model (2.1) is to optimize ϕ, a proportion of the outputs which can be maximized possibly.

Suppose ϕ^* is the optimal solution of model (2.1) and the efficiency of the system in principal's perspective is defined as $e^p = \frac{1}{\phi^*}$. If $\phi^* = 1$, then the evaluated DMU is efficient and the outputs cannot be improved without an increase of the inputs. Otherwise, if $\phi^* > 1$, then the evaluated DMU is inefficient and the outputs have the potential to be improved.

It is worth noting that model (2.1) investigates the efficiency of the system in the principal's perspective. She seeks to maximize her outputs for a given level of regular inputs and motivated payments. It may not be enough while taking no account the influence of the agent. We will discuss the agent's impact on the system's performance in Section 3.

2.2. In the agent's perspective

In traditional DEA model or principal-oriented model, the interests of the principal are emphasized. However, the interests of the agent are ignored and little research makes a considerable discussion on how the agent optimizes his efforts while ensuring the payments are guaranteed. Motivated by such consideration, our current study desires to propose a model assessing the performance of the system in the agent's perspective.

In the agent's perspective, he devotes his self-knowledge and effort $l_{dj}(d = 1, ..., D)$ to earn the payments $s_{kj}(k = 1, ..., K)$ from the principal. His objective is to optimize his effort $l_{dj}(d = 1, ..., D)$ while keeping the payments at the current levels. His efficiency can be modeled as follows:

$$
\begin{aligned}
&\min \theta \\
&\text{s.t.} \\
&\sum_{j=1}^{n} \mu_j l_{dj} \leq \theta l_{d0} \quad (d = 1, ..., D) \quad \text{(2.2a)} \\
&\sum_{j=1}^{n} \mu_j s_{kj} \geq s_{k0} \quad (k = 1, ..., K) \quad \text{(2.2b)} \\
&\mu_j \geq 0, \quad j = 1, 2, ..., n
\end{aligned}
\tag{2.2}
$$

Model (2.2) differs from model (2.1) in the following aspects. First, the objective of model (2.2) is to minimum possible proportion of efforts of the agent, θ, by maintaining a given level of the payments. This implies that the agent subjectively thinks that he has exerted enough effort. Second, s_{kj} is viewed as one of the classifications of the outputs, which is depicted as constraint (2.2b).

Suppose θ^* is the optimal solution of model (2.2), and the efficiency of the system in the agent's perspective is defined as $e^a = \theta^*$. $\theta^* = 1$ implies that the DMU under evaluation is efficient and the efforts reach a minimization in the agent's perspective. Otherwise, the evaluated DMU is inefficient and has a potential to decrease the efforts. Intrinsically, the agent has the inner incentive to seek possible reasons and adjust his behavior in future control of the system.

In model (2.2), we consider the effort of the agent as a specified classification of the inputs. However, the effort of the agent is difficult to measure in principal-agent problem. Various researches have addressed the issue of the manager's effort from different perspectives (see [11, 15, 16, 19]). Generally, some explicit signals, such as the performance of the firm, are suggested to identify the effort level of the agents. However, on account of the external influence of contextual factors, such as the market, public policies, industrial environment and other competitors, any signals cannot fully reflect the information of the agent's effort. In this regard, Hölmstrom [15] proposes the theory of relative performance evaluation (RPE) to estimate the agent's effort in an objective way by referring to the performances of other agents in an industry or a market. Thus, the performance of the evaluated firm is adjusted accordingly and the "noise" affecting the agent's performance is filtered. Feng and Li [12] extends the RPE theory to binary relative performance evaluation by incorporating DEA approach. The relative performances of other firms (as a measure of the conditional context) in previous period are viewed as an input and the performance of the firm under evaluation in current period as an output. The binary relative performance of the firm is obtained by using the output-oriented CCR model. In this way, the impact of external environment on the firm's performance is eliminated and the performance of the firm can truly reflect the results of the operational and managerial efforts of the agent, which can be a better reflection of the agent's effort level. In this study, we adopt the Feng and Li [12]'s approach to evaluate the effort level of the agent by identifying the economic benefit derived from the agent's operational management.

3. Modeling non-cooperation of the principal and the agent

In this section, we model two independent decision makers (principal and agent) who have heterogeneous or contradictive objectives in the context of non-cooperative game. For example, suppose a DMU consists of a manufacturer and a retailer. In such a setting, traditionally the manufacturer holds manipulative power and acts as a leader, and the retailer is treated as a follower in modeling non-cooperative supply chains. In a similar manner, our non-cooperative approach assumes that one of the parties is the leader that seeks to optimize her outputs or optimize his efforts while ensuring the motivated payments are accepted by both parties. Now, we introduce $\tilde{s}_{kj}(k = 1, ..., K)$ as a decision variable representing the payments expectation of the agent. Then the other party (the follower) is suggested to accept the new motivated payments. In other word, the leader's benefits can be viewed as being more important than the other party.

Next, we consider non-cooperative situations where the principal and the agent dominate the system, respectively.

3.1. The principal as the leader

When the principal dominates the system, the primary objective of the system is to maximum the outputs of the principal while considering the influence of the agent. Then, the efficiency of the system is proposed as follows:

$$\begin{aligned}
&\max\ \phi \\
&\text{s.t.} \\
&\text{(the principal)} \\
&\sum_{j=1}^{n} \lambda_j x_{ij} \le x_{i0} \quad (i = 1, ..., m) && \text{(3.1a)} \\
&\sum_{j=1}^{n} \lambda_j s_{kj} \le \tilde{s}_{k0} \quad (k = 1, ..., K) && \text{(3.1b)} \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi y_{r0} \quad (r = 1, ..., R) && \text{(3.1c)} \\
&\lambda_j \ge 0, \quad j = 1, 2, ..., n \\
&\text{(the agent)} \\
&\sum_{j=1}^{n} \mu_j l_{dj} \le l_{d0} \quad (d = 1, ..., D) && \text{(3.1d)} \\
&\sum_{j=1}^{n} \mu_j s_{kj} \ge \tilde{s}_{k0} \quad (k = 1, ..., K) && \text{(3.1e)} \\
&\mu_j \ge 0, \quad j = 1, 2, ..., n
\end{aligned} \tag{3.1}$$

In model (3.1), the constraint (3.1b) treats $\tilde{s}_{k0}$ as an "output" of the principal, and the constraint (3.1e) treats $\tilde{s}_{k0}$ as an "input" of the agent. The objective of model (3.1) is to maximize the outputs of the principal while ensuring that the optimal motivated payments $\tilde{s}_{k0}(k = 1, ..., K)$ are accepted by both parties.

Model (3.1) assumes that the return to scale (RTS) is constant and can be extended to variable return to scale (VRS) by adding additional constraints, $\sum_{j=1}^{n} \lambda_j = 1$ and $\sum_{j=1}^{n} \mu_j = 1$ into the model.

Since the objective of the system is to maximize the principal's outputs, the principal has to propose an incentive contract based on the payments to the agent and expected effort from him. Define $e^{ps} = \frac{1}{\phi^*}$ as the efficiency of the system in such situation. $\phi^* = 1$ implies that the system under evaluation is efficient and the outputs reach a maximization. Otherwise, the evaluated system is inefficient and has a potential to obtain more outputs.

Corollary 3.1. *A system must be a frontier point in the principal's perspective with respect to* $x_{i0}(i = 1, ..., m)$, $\tilde{s}^*_{k0}(k = 1, ..., K)$, $l_{d0}(d = 1, ..., D)$ *and* $\phi^* y_{r0}(k = 1, ..., K)$.

Then, we consider the following linear program:

$$
\begin{aligned}
&\max\ \phi\\
&\text{s.t.}\\
&\sum_{j=1}^{n}\lambda_j x_{ij}\le x_{i0}\quad (i=1,...,m)\\
&\sum_{j=1}^{n}\lambda_j y_{rj}\ge \phi y_{r0}\quad (r=1,...,R)\\
&\sum_{j=1}^{n}\mu_j l_{dj}\le l_{d0}\quad (d=1,...,D)\\
&\sum_{j=1}^{n}(\mu_j-\lambda_j)s_{kj}\ge 0\quad (k=1,...,K)\\
&\lambda_j,\mu_j\ge 0,\quad j=1,2,...,n
\end{aligned}\tag{3.2}
$$

Theorem 3.2. *The optimal solutions of model* (3.2) *are equivalent to those of model* (3.1).

Proof. Suppose ϕ^*, λ_j^*, ${\mu_j}^*$, $\tilde{s}_{k0}^*$ are optimal solutions of model (3.1), and ϕ'^*, λ'^*, μ'^* are optimal solutions of model (3.2). It is worth noting that the feasible region of model (3.2) contains that of model (3.1). Thus, $\phi'^*\ge\phi^*$, and $\sum_{j=1}^{n}\mu'_{j^*}s_{kj}\ge\tilde{s}'_{k0^*}\ge\sum_{j=1}^{n}\lambda'_{j^*}s_{kj}$. Therefore, ϕ'^*, λ'^*, μ'^*,$\tilde{s}'_{k0^*}$ are feasible in model (3.1). Thus, ϕ'^*, λ'^*, μ'^* must be optimal in model (3.1) with $\phi'^*=\phi^*$. □

3.2. The agent as the leader

Model (3.1) illustrates a situation where the principal dominates the system. That is, the primary objective of the system is to design reasonable incentive contract to maximize the outputs of the principal. Similarly, if the agent dominates the system, then the primary objective of the system is to design appropriate incentive contract to minimize the efforts of the agent. The efficiency of the system is proposed as follows:

$$
\begin{aligned}
&\min\ \theta\\
&\text{s.t.}\\
&\text{(the principal)}\\
&\sum_{j=1}^{n}\lambda_j x_{ij}\le x_{i0}\quad (i=1,...,m) &&(3.3\text{a})\\
&\sum_{j=1}^{n}\lambda_j s_{kj}\le \tilde{s}_{k0}\quad (k=1,...,K) &&(3.3\text{b})\\
&\sum_{j=1}^{n}\lambda_j y_{rj}\ge y_{r0}\quad (r=1,...,R) &&(3.3\text{c})\\
&\lambda_j\ge 0, j=1,2,...,n\\
&\text{(the agent)}\\
&\sum_{j=1}^{n}\mu_j l_{dj}\le \theta l_{d0}\quad (d=1,...,D) &&(3.3\text{d})
\end{aligned}
$$

$$\sum_{j=1}^{n} \mu_j s_{kj} \geq \tilde{s}_{k0} \quad (k = 1, ..., K) \tag{3.3e}$$

$$\mu_j \geq 0, \quad j = 1, 2, ..., n \tag{3.3}$$

The objective of model (3.3) is to minimize the efforts of the agent while ensuring that the optimal motivated payments are accepted by both parties. An explicit connection is suggested to better illustrate how both parties affect the performance of the system. We assume that the payments have been adjusted to an optimal level, $\tilde{s}^*_{k0}(k = 1, ..., K)$, which is depicted in the constraints (3.3b) and (3.3e). Given the inputs and optimized payments, the agent can have the potential to decrease his efforts with a proportion, θ. In this way, the efficiency of the system is obtained.

Model (3.3) attempts to decrease the amount of efforts as much as possible when the agent dominates the system. Define $e^{as} = \theta^*$ as the efficiency of the system. θ^* implies that the system is efficient and the efforts reach its frontier. Otherwise, the system is inefficient and the efforts have the potential to be reduced. Model (3.3) yields a set of new payments and efforts that render the DMU efficient.

Corollary 3.3. *A system must be a frontier point in the agent's perspective with respect to* $x_{i0}(i = 1, ..., m)$, $\tilde{s}^*_{k0}(k = 1, ..., K)$, $\theta^* l^*_{d0}(d = 1, ..., D)$ *and* $y_{r0}(r = 1, ..., R)$.

Similar to model (3.2), we can show that in the input-oriented case, model (3.3) is equivalent to the following model.

$$\begin{aligned}
&\min \ \theta \\
&\text{s.t.} \\
&\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{i0} \quad (i = 1, ..., m) \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{r0} \quad (r = 1, ..., R) \\
&\sum_{j=1}^{n} \mu_j l_{dj} \leq \theta l_{d0} \quad (d = 1, ..., D) \\
&\sum_{j=1}^{n} (\mu_j - \lambda_j) s_{kj} \geq 0 \quad (k = 1, ..., K) \\
&\lambda_j, \mu_j \geq 0, \quad j = 1, 2, ..., n
\end{aligned} \tag{3.4}$$

4. Modeling cooperation of the principal and the agent

In previous section, we discuss two situations where the principal and agent independently dominate the system, respectively. In such situations, one of the parties desires to optimize his efforts/her outputs separately, the parties work together with a non-cooperative manner. However in practice, cooperation can also exist between the parties in that they work in coordination and have an identical objective to optimize the overall efficiency of the system.

In a cooperative environment, the principal and the agent cooperate with each other to control the system. In addition, the principal invests an effective composition of the inputs to optimize the technical performance of the system and motivates the agent with a favorable payment. Simultaneously, the agent optimizes his efforts to improve the managerial performance. In this regard, the overall efficiency of the system can be optimized from both technical and managerial perspective.

An alternative approach is proposed to determine optimal ϕ and θ with the desire to optimize outputs and efforts simultaneously. The proposed model in a cooperative perspective is as follows:

$$\begin{aligned}
&\min\ w_1\theta - w_2\phi \\
&\text{s.t.} \\
&\text{(the principal)} \\
&\sum_{j=1}^{n}\lambda_j x_{ij} \le x_{i0} \quad (i=1,...,m) && \text{(4.1a)} \\
&\sum_{j=1}^{n}\lambda_j s_{kj} \le \tilde{s}_{k0} (k=1,...,K) && \text{(4.1b)} \\
&\sum_{j=1}^{n}\lambda_j y_{rj} \ge \phi y_{r0} (r=1,...,R) && \text{(4.1c)} \\
&\lambda_j \ge 0, \quad j=1,2,...,n \\
&\text{(the agent)} \\
&\sum_{j=1}^{n}\mu_j l_{dj} \le \theta l_{d0} \quad (d=1,...,D) && \text{(4.1d)} \\
&\sum_{j=1}^{n}\mu_j s_{kj} \ge \tilde{s}_{k0} \quad (k=1,...,K) && \text{(4.1e)} \\
&\mu_j \ge 0, \quad j=1,2,...,n
\end{aligned} \tag{4.1}$$

where w_1 and w_2 are the weights illustrating the importance of the two parties or preference information of the system. Originally, we assume that both parties are equally important and w_1 and w_2 are set to be the same as 1.

The objective function of model (4.1) means that the system seeks to maximize ϕ and minimize θ simultaneously. ϕ illustrates possible increase of the proportion of the outputs, and θ illustrates possible decrease of the proportion of the efforts. The constraints (4.1b), (4.1c), (4.1d) and (4.1e) form an envelopment of production possible set of the payments, the efforts and the outputs, respectively.

Model (4.1) assumes that the RTS is constant and can be extended to VRS by adding additional constraints, $\sum_{j=1}^{n}\lambda_j = 1$ and $\sum_{j=1}^{n}\mu_j = 1$ into the model.

Theorem 4.1. *If $\theta^*=\phi^*=1$, there must exist an optimal solution such that $\lambda_j^* = \mu_j^* = 1$.*

Proof. Note that $\theta^*=\phi^*=1$, $\sum_{j=1}^{n}\mu_j = 1$, and $\tilde{s}_{k0}^* = \tilde{s}_{k0}$ are feasible solutions in model (4.1). □

Theorem (4.1) indicates that the system is efficient if $\theta^*=\phi^*=1$. Similarly, the proposed also holds under the assumption of VRS. We can get corresponding theorem.

Corollary 4.2. *A system must be a frontier point in both parties with respect to $x_{i0}(i=1,...,m)$, $\tilde{s}_{k0}^*(k=1,...,K)$, $\theta^* l_{d0}^*(d=1,...,D)$ and $y_{r0}(r=1,...,R)$.*

Model (4.1) provides not only an efficiency index, but also optimal values on the motivated payments with which the two parties are efficient. Based upon Corollary 4.2, model (4.1) yields directions for achieving the DEA frontier of this two-decision maker situation.

Note that in model (4.1), the motivated payments for a specific DMU_0 under evaluation are set as unknown decision variables. As a result, additional constraints can be imposed on the motivated payments. This constitutes an important contribution to DEA modeling, because no additional constraints on the inputs/outputs can be added into the conventional DEA model.

When w_1 and w_2 are set to be the same as 1, similar to models (3.2) and (3.4), model (4.1) is equivalent to the following model.

$$\begin{aligned}
&\min\ \theta - \phi \\
&\text{s.t.} \\
&\sum_{j=1}^{n} \lambda_j x_{ij} \le x_{i0} \quad (i = 1, ..., m) \\
&\sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi y_{r0} \quad (r = 1, ..., R) \\
&\sum_{j=1}^{n} \mu_j l_{dj} \le \theta l_{d0} \quad (d = 1, ..., D) \\
&\sum_{j=1}^{n} (\mu_j - \lambda_j) s_{kj} \ge 0 \quad (k = 1, ..., K) \\
&\lambda_j, \mu_j \ge 0, \quad j = 1, 2, ..., n
\end{aligned} \tag{4.2}$$

Let $\lambda'_j = \frac{\lambda_j}{\theta}$, $\mu'_j = \frac{\mu_j}{\theta}$ and $\alpha = \frac{\phi}{\theta}$, then model (4.2) becomes

$$\begin{aligned}
&\max\ \theta(\alpha - 1) \\
&\text{s.t.} \\
&\sum_{j=1}^{n} {\lambda'}_j x_{ij} \le \frac{1}{\theta} x_{i0} \quad (i = 1, ..., m) \\
&\sum_{j=1}^{n} {\lambda'}_j y_{rj} \ge \alpha y_{r0} \quad (r = 1, ..., R) \\
&\sum_{j=1}^{n} {\mu'}_j l_{dj} \le l_{d0} \quad (d = 1, ..., D) \\
&\sum_{j=1}^{n} ({\mu'}_j - {\lambda'}_j) s_{kj} \ge 0 \quad (k = 1, ..., K) \\
&\alpha\theta \ge 1;\ {\lambda'}_j, {\mu'}_j \ge 0, \quad j = 1, 2, ..., n
\end{aligned} \tag{4.3}$$

Now, we consider the following model

$$\begin{aligned}
&\max\ \theta(\alpha - 1) \\
&\text{s.t.} \\
&\sum_{j=1}^{n} {\lambda'}_j x_{ij} \le \frac{1}{\theta} x_{i0} \quad (i = 1, ..., m) \\
&\sum_{j=1}^{n} {\lambda'}_j y_{rj} \ge \alpha y_{r0} \quad (r = 1, ..., R)
\end{aligned}$$

$$\sum_{j=1}^{n} \mu'_j l_{dj} \leq l_{d0} \quad (d = 1, ..., D)$$
$$\sum_{j=1}^{n} (\mu'_j - \lambda'_j) s_{kj} \geq 0 \quad (k = 1, ..., K)$$
$$\alpha \geq 1;\ \lambda'_j, \mu'_j \geq 0, \quad j = 1, 2, ..., n \tag{4.4}$$

The only difference between models (4.3) and (4.4) is that model (4.4) sets $\theta = 1$ in the constraint of $\alpha\theta \geq 1$ in model (4.3).

Theorem 4.3. *The optimal solutions of model* (4.4) *are equivalent to those of model* (4.3).

Proof. Suppose λ'_j, μ'_j, α and θ are the feasible solutions of model (4.3), then $\alpha \geq \frac{1}{\theta} \geq 1$. Thus, λ'_j, μ'_j, α and θ are also feasible in model (4.4). This indicates that the feasible region of model (4.4) contains that of model (4.3). □

Let λ'_{j^1}, μ'_{j^1}, α^1, θ^1 and λ'_{j^2}, μ'_{j^2}, α^2, θ^2 are the optimal solutions of models (4.3) and (4.4), respectively. Then we have $\theta^2(\alpha^2 - 1) \geq \theta^1(\alpha^1 - 1)$. Suppose $\alpha^2\theta^2 < 1$. Since $\alpha^2 \geq 1$ in model (4.4), then an θ'^2 such that $\frac{1}{\alpha^2} \leq \theta'^2 \leq 1$ can be found, we have $\theta'^2\alpha^2 \geq 1 > \theta^2\alpha^2$, $1 \geq \theta'^2 > \theta^2$, this indicates that λ'_{j^2}, μ'_{j^2}, α^2, θ'^2 are feasible in model (4.4) and $\theta'^2(\alpha^2 - 1) > \theta^2(\alpha^2 - 1)$. A contradiction to the fact that λ'_{j^2}, μ'_{j^2}, α^2, θ^2 are optimal. Thus, $\alpha^2\theta^2 \geq 1$.

Therefore, λ'_{j^2}, μ'_{j^2}, α^2, θ^2 are feasible in model (4.3), moreover, $\theta^2(\alpha^2 - 1) \geq \theta^1(\alpha^1 - 1)$, thus, λ'_{j^2}, μ'_{j^2}, α^2, θ^2 are optimal in model (4.3). And at optimality, $\theta^* = 1$, model (4.4) is equivalent to the following linear program

$$\max \alpha$$
$$\text{s.t.}$$
$$\sum_{j=1}^{n} \lambda'_j x_{ij} \leq x_{i0} (i = 1, ..., m)$$
$$\sum_{j=1}^{n} \lambda'_j y_{rj} \geq \alpha y_{r0} (r = 1, ..., R)$$
$$\sum_{j=1}^{n} \mu'_j l_{dj} \leq l_{d0} (d = 1, ..., D)$$
$$\sum_{j=1}^{n} (\mu'_j - \lambda'_j) s_{kj} \geq 0 (k = 1, ..., K)$$
$$\alpha \geq 1;\ \lambda'_j, \mu'_j \geq 0, j = 1, 2, ..., n \tag{4.5}$$

Theorem 4.4. *At optimality $\theta^* = 1$ and $\phi^* = \alpha^*$, where θ^* and ϕ^* are optimal values of θ and ϕ in model* (4.1) *and α^* is the optimal value of α in model* (4.5).

5. Further discussion

5.1. In the principal's and the agent's perspectives

First, we discuss the efficiency of a system in the principal's and the agent's perspectives and corresponding actions.

1) For a specific DMU_0, if $e_0^p = 1$ and $e_0^a = 1$, this means that the principal achieves output optimization and the agent achieves effort optimization.
2) For a specific DMU_0, if $e_0^p = 1$, $e_0^a < 1$ or $e_0^p < 1$, $e_0^a = 1$, this means that the principal or the agent is efficient, while the other party is inefficient. Consequently, she may request for additional outputs or he may reduce the efforts.
3) For a specific DMU_0, if $e_0^p < 1$ and $e_0^a < 1$, this means that the principal does not achieve output optimization and the agent does not achieve effort optimization. The principal believes that her output can be increase and the agent also believes that his effort can be decrease. At this point, the principal and the agent may cooperate to optimize output and effort, or sign a new contract about the effort, payment and outputs for better coordination alternatively.

5.2. The principal dominates the system

Next, we discuss the efficiency of the system and corresponding actions when the principal dominates the system.

1) For a specific DMU_0, if $e_0^{ps} = 1$ and $\tilde{s}_{k0} = \tilde{s}_{k0}^*$, this means that the system achieves the principal's output maximization goal and both parties accept the motivated payments $\tilde{s}_{k0}^*(k = 1, ..., K)$. At this point, both parties satisfy to this equilibrium.
2) When a specific DMU_0 is inefficient to the principal ($i.e.$ $\phi^* > 1$) and $\tilde{s}_{k0} = \tilde{s}_{k0}^*$, this means that the principal does not achieve output maximization goal. Under such situation, the principal may require outputs to be $\phi_0^* y_{r0}(r = 1, ..., R)$, and both parties satisfy to motivated payments with $\tilde{s}_{k0}^*(k = 1, ..., K)$.

5.3. The agent dominates the system

In this sub-section, we discuss the efficiency of the system and corresponding actions when the agent dominates the system.

1) When a specific DMU_0 is efficient to the agent ($i.e.$ $e_0^{as} = \theta_0^* = 1$) and $\tilde{s}_{k0} = \tilde{s}_{k0}^*$, this means that the system achieves the agent's effort minimum goal and both parties accept the motivated payments $\tilde{s}_{k0}^*(k = 1, ..., K)$. At this point, both parties satisfy to this equilibrium.
2) When a specific DMU_0 is inefficient to the agent ($i.e.$ $e_0^{as} = \theta_0^* < 1$) and $\tilde{s}_{k0} = \tilde{s}_{k0}^*$, this means that the system does not achieve the agent's effort minimum goal. Under such situation, the agent believes that his effort can be decreased to $\theta_0^* l_{d0}$, and both parties satisfy to motivated payments with $\tilde{s}_{k0}^*(k = 1, ..., K)$.

5.4. In cooperative perspective

Further, we discuss the efficiencies of the system and corresponding actions in cooperative perspective.

1) For a specific DMU_0, if $e_0^{cp} = \frac{1}{\phi_0^*} = 1$, $e_0^{ca} = \theta_0^* = 1$ and $\tilde{s}_{k0} = \tilde{s}_{k0}^*$, this means that the principal achieves output optimization and the agent achieves effort optimization. At this point, both parties satisfy to this equilibrium.
2) When a specific DMU_0 is efficient to the principal ($i.e.$ $e_0^{cp} = \frac{1}{\phi_0^*} = 1$) and inefficient to the agent ($i.e.$ $e_0^{ca} = \theta_0^* < 1$), this means that the principal achieves output optimization and the agent does not achieve effort optimization. In cooperative perspective, the agent may require reducing the effort by consulting with the principal. Contrarily, when a specific DMU_0 is inefficient to the principal ($i.e.$ $e_0^{cp} = \frac{1}{\phi_0^*} < 1$) and efficient to the agent ($i.e.$ $e_0^{ca} = \theta_0^* = 1$), this means that the agent achieves effort optimization and the principal does not achieve output optimization. In cooperative perspective, the principal can request for additional output by consulting with the agent.
3) When a specific DMU_0 is inefficient from both the principal's and the agent's perspective ($i.e.$ $e_0^{cp} = \frac{1}{\phi_0^*} < 1$ and $e_0^{ca} = \theta_0^* < 1$), this means that the principal does not achieve output optimization and the agent does not achieve effort optimization. In cooperative perspective, the principal and the agent can consult with each other to achieve a win-win situation.

6. Empirical study

In this section, we illustrate the feasibility and appropriateness of our approach. Due to the availability of the data, we collect the data of 22 electric power companies in China from the 2010, 2011 Chinese listing Corporation financial reporting database, Chinese listing Corporation financial ratios database and Chinese listing Corporation governance structure database provided by the CSMAR.

6.1. Case description

The principal invests the inputs, such as asset (millions), equity (millions) and numbers of employees to produce the output, net profit (millions). It is worth mentioning that, these input and output indexes have been used in the studies, such as Seiford and Zhu [23] and Liang *et al.* [18]. She also hires the agent by providing the motivated payments, *e.g.* annual salary of management (ASM, millions). The agent devotes efforts to earn the payments from the principal. Following Feng and Li [12]'s method, the relative performances of the firms in 2010 and 2011 are viewed as the inputs and outputs respectively. The binary relative performances of the firms are calculated by applying the output-oriented CCR model and are viewed as the effort level of the agents. The descriptive statistics is provided in Table 1.

Table 1. The descriptive statistics for the data set (2011).

Variables		Max	Min	Mean	Std. Dev.
x_1	Asset (millions)	254365.4	1566.592	36508.3	65849.91
x_2	Equity (millions)	58159.86	853.7812	9824.767	14657.69
x_3	Numbers of employees	35903	172	8962.591	10985.38
l	Effort level	1.0000	0.2692	0.5123	0.1804
s	Annual salary of management (millions)	2.7821	0.502	1.5835	0.6197
y	Net profit (millions)	4498.217	38.2742	756.9488	1024.112

6.2. Computational results

We first depict the efficiencies of the system in the principal's and the agent's perspectives derived from models (1) and (2). Table 2 reports the computational results.

From Table 2, we find that,

1) The efficiencies of the system in the principal's perspective are distinctly different from that in the agent's perspective. Since the principal intends to increase the organizational outputs whereas the agent has the incentive to increase the motivated payments, the efficiencies depict the extents the two parties prefer to optimize self-benefits. Consequently, the differences clearly indicate the conflicts of the two parties. Take the efficient DMUs in the principal's perspective for examples. The efficiencies of corresponding DMUs in the agent's perspective are lower than 1, which implies that the agent intends to obtain more motivated payment from the principal or has incentive to reduce his own effort level.
2) Only the DMU GDDL is efficient in both perspectives, and sixteen DMUs are inefficient in both perspective. It clearly indicates the conflict of principal and the agent, *i.e.*, the principal has incentive to increase her output and the agent has incentive to reduce his effort level.
3) Six DMUs are efficient in the principal's perspective whereas only one DMU is efficient in the agent's perspective. It implies that the agent has the incentive to reduce the effort level.

To illustrate the interactions between the principal and the agent, Table 3 reports the efficiencies and motivated payments of system in different scenarios (the principal as the leader or the agent as the leader).

TABLE 2. The efficiencies of the system.

DMUs	Model (1)		Model (2)
	ϕ^*	$e^p = \frac{1}{\phi^*}$	$\theta^* = e^a$
HNGJ	4.0896	0.2445	0.8658
GCHDT	1.0000	1.0000	0.3992
GZHB	1.0619	0.9417	0.4916
TBDG	1.5822	0.6320	0.7635
MXDL	1.3416	0.7454	0.3843
SXSHL	4.3091	0.2321	0.3716
ZHZHMD	2.6315	0.3800	0.3344
CHCHDG	6.7716	0.1477	0.1012
GGDL	2.8163	0.3551	0.7437
GDNZ	2.6597	0.3760	0.4263
JLDL	2.9227	0.3421	0.2167
GDDL	3.9736	0.2517	0.3850
XCDL	1.0000	1.0000	0.3775
SHHNY	1.0000	1.0000	0.5198
TFRD	1.0000	1.0000	0.1031
JNRD	2.4348	0.4107	0.5079
SHNGF	1.0000	1.0000	0.4202
LSHDL	2.8353	0.3527	0.4799
TBNY	1.4958	0.6685	0.1084
GDDL	1.0000	1.0000	1.0000
HTGF	1.6178	0.6181	0.5439
GTDL	3.2480	0.3079	0.5267

From Table 3, we find that

1) In model (3), when the principal as leader and dominates the system, the motivated payments are increased ($\tilde{s}^*_{k0} \geq s_{k0}$) for the most DMUs except DMUs SXSHL and LSHDL. It implies that the principal may take the benefits of the agent into consideration if she prefers to maximize self-benefits.
2) In model (3), the motivated payments of DMUs SXSHL and LSHDL are decreased ($\tilde{s}^*_{k0} < s_{k0}$). The reason may be that the efficiencies of the principals in model (3) are equal to those in model (1). This indicates that if the increment of the principal's output when taking the agent into account is identical to that not taking the agent into account, the principal may intend to reduce the motivated payments.
3) The potential increments of principals' outputs in model (3) are larger than those in model (1). Correspondingly, the efficiencies of the principals in model (3) are less than those in model (1). It implies that when the principal as the leader and takes the benefits of the agent into consideration, there is greater room for her to improve self-benefits compared with the scenario where evaluating the systems efficiency only in her own perspective.
4) The potential decrements of the most agents' effort levels in model (5) are significantly less than that in model (2) except DMUs GCHDT, XCDL, SHHNY, TFRD, GDDL and TBNY. It implies that the most agents have obvious incentive to reduce effort levels. The potential decrements of DMUs GCHDT, XCDL, SHHNY, TFRD and GDDL in model (5) are greater than those in model (2). The reason may be that the efficiencies of these DMUs are equal to 1 in model (1), the principals have great influence in the principal-agent relationship and the agents could not reduce effort levels optionally.
5) In model (5), the motivate payments become smaller compared with the original ones s_{k0}. It implies that if the agent reduces his effort level, the principal may decrease the motivated payments. Constrained by the motivated payment, the agent may not reduce his effort level optionally.

TABLE 3. The efficiencies of the system.

DMUs	Model (3)				Model (5)	
	ϕ^*	$e^{ps} = \frac{1}{\phi^*}$	$\tilde{s}_{k0}^*$	s_{k0}	$e^{as} = \theta^*$	$\tilde{s}_{k0}^*$
HNGJ	4.4420	0.2251	2.9546	2.5582	0.2117	0.6255
GCHDT	1.0000	1.0000	1.9217	1.7450	0.5906	1.7450
GZHB	1.3851	0.7220	3.5160	1.7283	0.4744	1.4017
TBDG	1.7975	0.5563	3.3958	2.5927	0.3143	0.9288
MXDL	1.3906	0.7191	1.8431	1.2505	0.0978	0.2890
SXSHL	4.3091	0.2321	0.9226	0.9734	0.0090	0.0266
ZHZHMD	2.6315	0.3800	1.9429	1.6170	0.0282	0.0833
CHCHDG	7.0738	0.1414	1.6890	0.5020	0.0059	0.0175
GGDL	3.2925	0.3037	2.0600	1.5319	0.0482	0.1424
GDNZ	2.6797	0.3732	2.4301	1.6842	0.0624	0.1844
JLDL	2.9227	0.3421	2.0543	1.3988	0.0155	0.0458
GDDL	4.0255	0.2484	1.9031	1.0538	0.0189	0.0560
XCDL	1.0000	1.0000	1.5552	1.3189	0.4464	1.3189
SHHNY	1.0000	1.0000	2.3032	2.1367	0.7232	2.1367
TFRD	1.3792	0.7250	2.0078	0.5160	0.1746	0.5160
JNRD	2.8208	0.3545	1.8452	1.3885	0.0589	0.1740
SHNGF	1.0000	1.0000	1.9564	1.8500	0.6261	1.8500
LSHDL	2.8353	0.3527	0.9725	1.3448	0.0142	0.0418
TBNY	1.9306	0.5180	4.3056	0.8291	0.1345	0.3974
GDDL	1.0000	1.0000	2.0625	2.0625	0.6981	2.0625
HTGF	1.6792	0.5955	3.6894	2.7821	0.1191	0.3518
GTDL	4.1270	0.2423	3.7466	1.9732	0.1043	0.3083

Table 4 reports the efficiencies of the principal and the agent in cooperation situation.
Table 4 has the following interesting findings:

1) When the principal and the agent cooperate with each other, 6 principals are efficient, 4 agents are efficient. Only DMU GDDL is efficient in both parties. It implies that there is great room for the principal and the agent to improve both parties' interests by cooperating and consulting with each other.
2) When the efficiencies of the principals in model (7) are less than those in model (1), the motivated payments are increased ($\tilde{s}_{k0}^* > s_{k0}$).Whereas, when the efficiencies of the principals in model (7) are no less than those in model (1), the motivated payments are no increased ($\tilde{s}_{k0}^* \leq s_{k0}$). These indicate that the principal may adjust the motivated payment in cooperation situation to maximize her own benefits and avoid the agent's hidden actions.)]
3) In model (7), the efficiencies of the principals in model are no less than those in model (3). It implies that the increments of the principals' outputs are no greater than those in model (3) because of taking the benefits of the agents into consideration in cooperation situation. The efficiencies of the agents are greater than those in model (5) except DMUs GCHDT, TBDG, XCDL, SHHNY and SHNGF. It implies that the decrements of these agents' effort levels are less than those in model (5) because of taking the principals' benefits into account in cooperation situation. The decrements of the effort levels of DMUs GCHDT, GZHB, XCDL, SHHNY and SHNGF are less than those in model (5). The reason may be that the principals of these DMUs are efficient in model (7), and they may take the agents' benefits into account and allow the agents to reduce effort levels appropriately in cooperation situation. In addition, four principals of these DMUs keep the original motivated payments and only one principal (DMU GZHB) reduce the motivated payment.
4) The optimized motivated payment when both parties cooperate with each other is no less than that when the principal as the leader and no greater than that when the agent as the leader. In addition, the efficiency

Table 4. The efficiencies of the system.

DMUs	Model (7)			
	ϕ^*	$e^{cp}=\frac{1}{\phi^*}$	$e^{ca}=\theta^*$	$\tilde{s}^*_{k0}$
HNGJ	4.4420	0.2251	1.0000	2.9546
GCHDT	1.0000	1.0000	0.3992	1.7450
GZHB	1.0000	1.0000	0.3987	1.4017
TBDG	1.3494	0.7411	0.5077	1.7241
MXDL	1.2560	0.7962	0.1484	0.4828
SXSHL	4.3091	0.2321	0.2021	0.5294
ZHZHMD	2.6315	0.3800	0.1998	0.9662
CHCHDG	7.0738	0.1414	0.1849	0.9176
GGDL	3.2925	0.3037	1.0000	2.0600
GDNZ	2.6499	0.3774	0.3468	1.3703
JLDL	2.9227	0.3421	0.0256	0.1650
GDDL	3.9681	0.2520	0.3542	0.9694
XCDL	1.0000	1.0000	0.3775	1.3189
SHHNY	1.0000	1.0000	0.5198	2.1367
TFRD	1.3792	0.7250	0.2331	1.1662
JNRD	2.8208	0.3545	0.6624	1.8110
SHNGF	1.0000	1.0000	0.4202	1.8500
LSHDL	2.8353	0.3527	0.1954	0.5474
TBNY	1.8706	0.5346	0.1676	1.2820
GDDL	1.0000	1.0000	1.0000	2.0625
HTGF	1.4552	0.6872	0.1580	0.8082
GTDL	4.1270	0.2423	1.0000	3.7466

of the principal when both parties cooperate with each other is greater than that when the principal as the leader. All these may imply that both parties may prefer to cooperate with each other. Thus, the potential increment of the principal's output is not so many, the potential decrement of the agent's effort level is not so much, and both parties are relatively satisfied with the optimized motivated payment.

7. Conclusions

In many DEA situations, each DMU has a decision maker. However, many interesting managerial problems involve two decision makers in a complex environment coupling with conflicting interests, which can well illustrated by the principal-agent problem. It has been recognized that existing DEA approaches, including conventional DEA models, do not appropriately address such issue. This paper presents alternative ways to address the conflicts between two decision makers in a system caused by various factors such as inconsistent goals and unobservable effort, and at the same time provides efficiency scores and corresponding actions for both individual parties and the organization. Our non-cooperative approach shows that the principal and the agent desire to increase her outputs/decrease his effort level, while is not willing to increase the other's payments/outputs. Contrarily, the cooperative approach illustrates that both the principal and the agent have the incentive to take the interests of the other into consideration.

Since the effort and other factors of the agent, such as experience, knowledge and ability which affect the system's outputs are hard to measure, we adopt Feng and Li [12]'s method and give an explicit illustration of them in the models. It is possible to explore whether and how other factors influence the organizational performance from the perspective of human capital or organizational behavior. It urges us to make further investigation on such issues.

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