The Co-development Performance Evaluation of Complex Equipment Based on Two-Stage Network DEA Method

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Abstract: Based on the co-development model of "main manufacturer-suppliers" complex equipment with suppliers' participation, we consider a three-echelon supply chain of complex equipment products, a two-stage network DEA performance evaluation model is constructed to evaluate the performance of manufacturer and suppliers reasonably. Subunits efficiency are optimized by the reverse efficiency value method of the whole supply chain, and be evaluated in the envelope surface projection to determine different input to improve value of the optimization of the supplier and the main manufacturers, as well as the coordinated development of operational efficiency of the whole supply chain, suppliers, main manufacturer, evaluate the coordinated development of the whole project operation level. Compared with the traditional DEA results, the simulation results show that the two-stage DEA performance evaluation model can evaluate the efficiency of main manufacturer and suppliers more accurately and comprehensively, so as to provide scientific decision-making and improvement basis for suppliers and manufacturer.

1 Introduction

The development of large complex equipment is a complex system engineering based on high and new technology, the product quality requirements, production technology intensity and technology added value are very high. Companies which involves complicated equipment in order to win competitive advantage in the fierce market competition, "main manufacturer-supplier" collaborative development mode has gradually become the main production mode of complex equipment development. Main manufacturer and suppliers of coordinated development is not simple addition of each main body innovation achievements, there are many different kinds of exchanges between the companies and have a strong uncertainty, the course of the development of risk occurrence node, each production node dynamic complex logical relations, social influence and social efficiency, therefore, manager must understand the current collaborative development and efficiency of individual and whole supply chain network operation conditions, to evaluate and analysis the coordinated development of the current performance comprehensively.

The performance evaluation of the cooperative development network of complex equipment is a typical multi-index comprehensive evaluation problem. DEA method can evaluate the relative effectiveness of DMU, and is applicable to the performance evaluation of R&D projects with multiple inputs and outputs. DEA method can be used to evaluate the performance of collaborative development network more comprehensively, and to calculate and compare the performance of different suppliers, main manufacturers and the whole supply chain, so as to provide more concrete decision basis for the overall optimization of the project. Fare [1] proposed the network DEA model for the first time, which can penetrate into the internal operation process of the evaluated system and make more accurate evaluation on the decision-making unit when evaluating the overall efficiency of the decision-making unit. Zhang [2] evaluated the R&D projects efficiency based on
the three-stage DEA method. Liu [3] established a DEA evaluation model of DEA coordination preference on the basis of analyzing the equivalence of DEA effective solution and Pareto solution of multi-objective programming. Chen et al. [4] constructed two levels of influencing factors at the organizational level and the project level, and combined the system dynamics DEA and super-efficiency DEA to rank the project efficiency. Chen lei et al. [5] measured and decomposed environmental efficiency based on two-stage DEA model of cooperative game. Cook [6] and Kao[7] divided the existing network DEA models into nine models and the structure of network DEA into seven structures. Peter [8] established a dynamic network DEA model to deal with the internal relationship between major accounting indicators and financial indicators. Yang et al. [9] constructed the evaluation model of class variance coordination based on the DEA of association network. Liu et al. [10] divided the network DEA model into two stages considering the non-expected output, evaluated the production efficiency and environmental efficiency of the sample port, and analyzed the containerization efficiency of the sample port. Sha [11] established a network DEA model to evaluate the efficiency of supply chain. Peter et al. [12] used network DEA method to evaluate the strategic fit of South African Banks' behaviors.

Scholars have done a lot of research on the efficiency evaluation of R & D projects, but there are few researches on the overall performance of complex equipment "main manufacturer supplier" collaborative R&D projects, the performance of suppliers, main manufacturers, and the relationship between them by using network DEA method. This paper establishes a two-stage network DEA linear programming model to comprehensively evaluate the performance of each supplier and main manufacturer, as well as the whole supply chain.

2. Network DEA performance evaluation model

The multi-level "main manufacturer-suppliers" collaborative development supply chain network is dominated by the main manufacturer, including primary suppliers and secondary suppliers. In order to gain more profits, the main manufacturer manufactures some important parts and outsources some parts to suppliers. The main manufacturer assembles the parts of the products and finally transports the products into the market. The primary supplier plays an important role as a link in the supply chain. It not only provides the technology and products required by the main manufacturer in a certain production, but also undertakes the responsibility of managing the subordinate suppliers and coordinating the supply chain.

2.1 Basic model

DEA method needs to use the above model to calculate the optimal weight of each decision-making unit, and then get the efficiency value of the decision-making unit under the optimal weight, the efficiency is relative. This paper calculates several linear programming models as the decision-making units. According to the dual theory of linear programming, the dual model of the above model can be obtained as model 1:

\[
\begin{align*}
\text{min} & \quad \sum_{j=1}^{n} \lambda_j x_j \\
\text{st} & \quad \sum_{i=1}^{m} \lambda_i y_i \leq \theta y_n \\
& \quad \sum_{j=1}^{n} \lambda_j \leq \theta x_n \\
& \quad \lambda_j \geq 0, \quad j = 1, 2, \ldots, n
\end{align*}
\]

Where, \( \theta \) is the effective value of the DMU, that is, the evaluation efficiency, and the weight coefficient \( \lambda_j \) is the contribution of the DMU\(_j\) in the evaluation of DMU\(_0\). When \( \theta = 1 \), the DMU is DEA effective. If \( \theta \neq 1 \), the DMU is non-DEA effective.

This paper based on C\( ^2 \)R model as model (1), evaluate the performance of "the main manufacturer-suppliers" supply chain (manufacture, suppliers, the whole supply chain). The first DMU is "primary supplier-secondary supplier" dominated by primary supplier, the second DMU is "main manufacturer-primary supplier" dominated by the main manufacturer, evaluate and analysis the individual and overall performance by the DEA model, the specific model is shown in figure 1:
Among the supply chain, sub-supplier R will input multiple resources $X_R$ for production, and the produced parts $Y_R$ will be provided to primary supplier $S$.

2.2 Two-stage network DEA model

Suppose a collaborative development network model with $n$ supply chains shown in Figure 1, that is, there are $2n$ decision making units (DMU), each of which includes 2 sub-decision making units (SDMU). $DMU_j^p (j = 1, 2, 3, ..., n)$ represents the "primary supplier-secondary supplier" decision-making unit of the $j$ supply chain within the $n$ supply chain; $DMU_j^m (j = 1, 2, 3, ..., n)$ represents the "main manufacturer-primary supplier" decision-making unit of the $j$ supply chain within $n$ supply chains, and $j_0$ represents the decision-making unit to be evaluated. In the network DEA model, the following variables and parameters are defined: $X_i^m (i=1,2,3, ..., m)$ represents that sub-supplier R has $m$ initial inputs; $X_h^s (h=1,2,3, ..., n)$ represents that primary supplier S has $n$ initial inputs; $X_k^M (k=1,2,3, ..., h)$ represents that master manufacturer M has $h$ initial inputs; $Y_l^R (l=1,2,3, ..., p)$ represents $p$ outputs of subordinate supplier R, intermediate inputs of primary supplier S; $Y_r^S (r=1,2,3, ..., q)$ represents $p$ outputs of the primary supplier S, intermediate inputs of the main manufacturer M; $Y_s^M (s=1,2,3, ..., s)$ represents that the master manufacturer has $s$ final outputs; $\lambda^R, \lambda^S, \lambda^M$ represent the weight coefficients of supplier R, primary supplier S and main manufacturer M respectively, and is the variable to be solved in DEA model; $\theta^R, \theta^S, \theta^M$ represent the relative efficiency values of sub-supplier R, primary supplier S and main manufacturer M respectively.

(1) DEA model of "primary supplier - secondary supplier"

According to model (1), the solution of DEA relative efficiency value of secondary supplier R in DMU$_j$ ($DMU_j$) is shown in model (2):

$$
\min \theta^s \\
\text{s.t.} \sum_{i=1}^{m} \lambda^s_i x^s_i \leq \theta^s_{x^s_{i}}, i = 1,2,3, ..., m \\
\sum_{i=1}^{m} \lambda^s_i y^s_l \geq y^s_l, l = 1,2,3, ..., p \\
\lambda^s_j \geq 0, j = 1,2,3, ..., n
$$

For the relative efficiency value of primary supplier S, the DEA linear programming solution model is shown in model (3):

$$
\min \theta^s \\
\text{s.t.} \sum_{i=1}^{m} \lambda^s_i x^s_i \leq \theta^s_{x^s_{i}}, j = 1,2,3, ..., n \\
\sum_{i=1}^{m} \lambda^s_i y^s_l \geq y^s_l, l = 1,2,3, ..., p \\
\sum_{r=1}^{s} \lambda^s_r y^s_r \geq y^s_r, r = 1,2,3, ..., s \\
\lambda^s_j \geq 0, j = 1,2,3, ..., n
$$

By solving the models (2) and (3), the relative efficiency values of the suppliers in the DMU of "primary supplier - secondary supplier" can be obtained respectively as $\theta^R, \theta^S, \theta^M$, and the weight factor as $\lambda^R, \lambda^S$.  

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The DEA model of "main manufacturer - primary supplier" and the overall efficiency of different supply chains in the collaborative development network as the model 3. Through the projection of variables, the minimum intermediate input required by the primary supplier S and the manufacturer M is determined when the final output of the primary supplier S and the manufacturer M remain unchanged. Take "main manufacturer - primary supplier" as an example, use \( y_{0i}^S \) as the least intermediate input by master manufacturer M:

\[
\sum_{j=1}^{n} \lambda_{ij} y_{0j}^S = x_{0i}^S
\]

Replace the original output value of primary supplier S with \( y_{0i}^S \), and the reference set is still the reference set of primary supplier solved for the first time. At this time, the relative efficiency value \( \theta^S \) and weight coefficient of primary supplier \( \lambda_{ij}^S \) are solved. DEA projection method is used to solve the minimum initial input required by the primary supplier to keep the intermediate output unchanged at this time, expressed as:

\[
\sum_{j=1}^{n} \lambda_{ij}^S x_{0j}^S = x_{0i}^S
\]

The ratio between the initial input with the least consumption and the actual initial input of primary supplier S is used to represent the overall DEA efficiency of DMU in the collaborative development network with the final output unchanged:

\[
\theta_h = \max_{i=1,2,...,m} \left( \frac{x_{0i}^S}{x_{0i}} \right)
\]

Through the network DEA model to calculate the performance of different parts, also can further reflect the supplier at a lower level, the level of supplier and the manufacturer's performance impact on the overall efficiency of the supply chain, and more intuitive to find "the main manufacturer - supplier" coordinated development of the deep-seated reasons for low efficiency of supply chain network.

### 3 Numerical Simulation

#### 3.1 Solution and analysis of network DEA efficiency value

This paper selects a "main manufacturer-suppliers" collaborative development supply chain composed of 6 secondary suppliers, 3 primary suppliers and main manufacturers, as shown in figure 1. Input-output data of different enterprises in a certain period are shown in table 1 and table 2. Suppliers' input includes production cost of raw materials, transportation cost, inventory cost, fixed cost, opportunity cost, etc. Manufacturers' input includes production cost, variable cost, assembly cost, storage cost, transportation cost.

**Table 1. Input-output data table of "primary supplier - secondary supplier".**

| Secondary suppliers - primary suppliers | Secondary suppliers R | Input (million) | Output (million) | Input (million) | Output (million) |
|----------------------------------------|----------------------|----------------|-----------------|----------------|-----------------|
| 1                                      | 70                   | 100            | 350             | 208            | 440             |
| 2                                      | 88                   | 108            | 405             | 204            | 580             |
| 3                                      | 93                   | 111            | 480             | 217            | 470             |
| 4                                      | 78                   | 93             | 480             | 217            | 470             |
| 5                                      | 90                   | 122            | 480             | 217            | 470             |
| 6                                      | 81                   | 95             | 480             | 217            | 470             |

**Table 2. Input-output data of "master manufacturer - primary supplier".**

| Manufacturer - primary suppliers | Primary suppliers S | Input (million) | Output (million) | Input (million) | Output (million) |
|----------------------------------|---------------------|----------------|-----------------|----------------|-----------------|
| 1                                | 350                 | 440            | 1000            | 1490           | 1568            |
| 2                                | 405                 | 580            | 1000            | 1490           | 1568            |
| 3                                | 480                 | 470            | 1000            | 1490           | 1568            |

The input and output data of table 1 to the performance evaluation of two-stage network DEA model, calculated by using linear programming software Lingo. Efficiency values of secondary suppliers and primary suppliers, as well as the overall network DEA efficiency values of "primary supplier-secondary suppliers" and their ranking are shown in table 3:
Table 3. Network DEA efficiency values of "primary supplier - secondary supplier".

| SC | secondary supplier | rank | primary supplier | rank | Minimum input | middle input | Minimum initial input | efficiency value | rank |
|----|-------------------|------|-----------------|------|----------------|--------------|---------------------|----------------|------|
| 1  | 1                 | 1    | 1               | 1    | 0.877 83      | 2            | 154.754 4          | 0.758 82        | 3    |
| 2  | 0.859 09          | 3    | 0.877 83        | 2    | 119.893 56    | 154.754 4    | 0.758 82           | 3              |
| 3  | 0.835 48          | 4    | 1               | 1    | 204           | 133          | 0.777 78           | 2              |
| 4  | 0.834 62          | 5    | 1               | 1    | 133           | 133          | 0.777 78           | 2              |
| 5  | 0.948 89          | 2    | 0.761 80        | 3    | 165.301 2     | 138.560 3    | 0.810 29           | 1              |
| 6  | 0.820 99          | 6    | 0.761 80        | 3    | 165.301 2     | 138.560 3    | 0.810 29           | 1              |

Enter the input and output data of table 2 network DEA evaluation model of two phase, calculated by using linear programming software Lingo, including: level 1 supplier efficiency value calculated by the model (4), income, the main manufacturers of efficiency value calculated by the model (5), income, collaborative supply chain in the development of the network overall efficiency value calculated by the model (9). The efficiency value of level-1 supplier, the overall network DEA efficiency value of "master manufactor-level-1 supplier" and its ranking are shown in table 4:

Table 4. Network DEA efficiency values of "main manufacturer - primary supplier".

| SC | primary supplier | rank | manufacturer | Minimum input | middle input | efficiency value |
|----|-----------------|------|--------------|----------------|--------------|----------------|
| 1  | 0.877 83        | 2    |              | 0.7147 31      | 1 193.832 7  | 0.801 23       |
| 2  | 0.834 62        | 5    |              | 0.810 29       | 138.560 3    | 0.810 29       |

The difference between "main manufacturers-primary suppliers "network DEA efficiency value and efficiency of the main manufacturers, is due to the different level of suppliers with different operational efficiency, the main manufacturers in the supply chain of the terminal, the efficiency value is slightly lower than the SC network DEA efficiency value, suggests that the management of the main manufacturers should be improved, and strengthen the management of the various manufacturing module and optimization.

3.2 Improvement of production units

Suppose that the input and output vectors of DMU$_j$ are $X_j$ and $Y_j$, the efficiency value of DEA is $\theta_j$, and the corresponding relaxation variables of input and output vectors are $S_j^-, S_j^+$ respectively:

$$\tilde{X}_j = \theta_j X_j - S_j^-$$
$$\tilde{Y}_j = Y_j + S_j^+$$

Then vector $(\tilde{X}_j, \tilde{Y}_j)$ is the projection value of DMU$_j$ corresponding to $(X_j, Y_j)$ on the production front surface.

According to equations (6) and (7), the projection values of each DMU of suppliers reaching DEA effectiveness can be obtained, as shown in table 5:

Table 5. DEA improvement values of input of secondary suppliers.

| supplier | efficiency value | input | projection value of input | projection value of SC |
|----------|------------------|-------|---------------------------|------------------------|
| 1        | 0.877 83         | 70    | 66.510 3                  |                        |
| 2        | 0.859 09         | 88    | 75.599 9                  |                        |
| 3        | 0.835 48         | 93    | 77.699 6                  |                        |
| 4        | 0.834 62         | 78    | 65.100 4                  | 75.33                  |
| 5        | 0.948 89         | 90    | 85.400 1                  | 79.356 8              |
| 6        | 0.820 99         | 81    | 66.500 2                  | 74.706 9              |

According to the input projection results in table 5, managers of secondary suppliers can improve their production system management to make management decisions more targeted. In addition, the managers should pay more attention to inefficient node enterprise strategic target adjustment and business process improvement, as well as the exchange of information between the main manufacturers and their suppliers and monitoring, targeted to take corresponding measures to improve the performance of nodal enterprises of the supply chain, make suppliers have good
communication between the main manufacturers, avoid information asymmetry which lead to low corporate performance, so as to improve the overall performance of collaborative development.

4 Conclusion

In the process of the development of complex equipment, the collaborative development network structure composed of suppliers and manufacturers is a complex system with multiple objectives, multiple resource inputs and multiple value outputs. Network DEA method is a kind of internal operation process can be precisely formulated and simulation system of evaluation methods, to open the "black box" of internal evaluation system of process, analyse the overall effectiveness of the factors that influence the system low efficiency problem. For enterprises on the supply chain, it is necessary to regularly evaluate the performance of node enterprises, so that problems can be found in time and optimized management can be carried out. From the numerical simulation of this paper, DEA method is introduced into the network performance evaluation of complex equipment coordinated development is reasonable, the network DEA method can not only get the evaluation results more scientific, but also provide direction and amplitude adjustment in improving the efficiency, offer the decision basis for managers to improve the overall efficiency. Complex equipment research and development enterprises can formulate reasonable policies according to the status of input and output, so as to adjust the input of different departments or improve the utilization rate of resources, to better cope with future risks and achieve the optimization of input and output. Help managers to find faster recognition coordination board in the development of the supply chain network, improve the efficiency for the enterprise to provide the improvement direction. However, as the development of complex equipment is a complex system engineering, and the structure of the cooperative development network of "main manufacturer-supplier" is also extremely complex, there are few evaluation indicators selected in this paper. How to comprehensively and effectively select performance evaluation indicators can be further discussed in detail. In addition, the concept of product quality and green is increasingly valued by consumers, and the quality loss of products and green indicators can be included in the scope of performance evaluation for further modeling.

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