A Multi-Stage Network DEA Modelling Approach for Logistics Systems with Multi-Process Decision Making

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Abstract: A comprehensive efficiency evaluation is very important for a logistics system. To get a flexible framework for its evaluation, a new multi-stage network DEA model is proposed, which considers the corresponding process characteristics and integrate the strategic and the tactical levels. Comparing with the existing methods, the method in this paper can be extended directly to deal with many more complex operational environments. It applies intermediate variables to handle the complex interactions of many sub-processes and estimates the direct and hidden efficiencies caused by various processes. In order implement the model efficiently, the corresponding solution algorithm is put forward. Finally, a computational example is provided to verify the usefulness and advantages of the proposed method.

Keywords: Multi-process decision-making, Logistics system, Multi-stage network DEA, Efficiency

1. Introduction

During the past decades, logistics has been playing a fundamental role on a country or region’s development. A logistics system always needs to maximize the operational efficiency by facilitating greater collaboration and coordination with all processes. It is very important and meaningful to keep track and manage the overall efficiency of the system, which requires evaluating not only the performance of every individual process but also the performance of the overall system.

As addressed by Sivasubramaniam et al. [1], the evaluation methods of a logistics system can probably be summarized as benchmarking, analysis and simulation models. However, the benchmarking model is based on realistic statistics to know all the relevant capacities of input and output and to build the best productivity frontier, and it reveals the inadequacies of relatively inefficient nodes. Data envelopment analysis (DEA) is a very common form of quantitative analysis used in benchmarking. It was proposed by Charnes and Cooper in 1978, which has been widely used to reflect the relative efficiency of evaluation objects. The basic model can be extended and applied to many practical problems. Since numerous models were developed by use of the DEA technique, it has become a popular tool for decision-making. Hackman and Frazelle developed an input-output model of a warehouse system to assess operational efficiency by using and extending the DEA method [3]. Talluri and Baker used a multi-phase data envelopment analysis to design and evaluate an effective supply chain [4]. McGinnis applied the DEA method to permit the self-assessment or benchmarking of individual warehouses [5]. Chen constructed a network-DEA model with new efficiency measures to systematically cope with the dynamic effect within a production network [6]. Falsini et al. combined analytical hierarchy process, DEA and linear programming to evaluate the third party logistics service providers [7]. With the further research and expansion of DEA studies, people begin to pay much attention to the research of Decision Making Unit’s (DMU) internal structure and characteristics.

In this paper, a flexible framework for evaluating the overall logistics system is initially introduced. It involves multiple stages and various processes to form a ‘network flow’ characterized by a set of inputs and some related outputs. For a logistics system, construction, storage and distribution are its most important business stages. To get the overall feedback of the design and operation, construction stage should be considered in its efficiency evaluation. Gu et al. made a comprehensive analysis of the logistics system and summarizes major operational issues into three parts which are the design, operation and performance evaluation [8]. Many decisions have been made during the construction stage of logistics facilities. Once the construction is finished or the facilities are bought, many decisions will be difficult to change. However, only a few studies have applied those evaluation models to explore its overall efficiency.

To evaluate the relative efficiency of a logistics system with internal and external factors mentioned above, several papers have attempted to take into account the network structure in the DEA model. Castelli et al. put forward to a DEA-like model to evaluate the efficiency of a number of interdependent sub-units within a larger system [9]. A small amount of research attempted to take into account the internal structure in the DEA model [10-12]. Lu et al. analyzed the data collected from the logistics industry and proposed a process-oriented DEA model [13]. In brief, the operation functions of a logistics system become the interaction result of various internal and external factors, so the entire system need to be analyzed and evaluated comprehensively. The existing research seldom starts from its internal structure to estimate the cumulative inputs or costs caused by various processes.

To get a comprehensive understanding of the efficiency of a logistics system, this paper will construct a multi-stage network DEA model considering the corresponding characteristics of processes, which involves both the strategic level and the tactical level, and analyze survey data collected from the logistics industry in China to make evaluation. The model can be extended directly to more complex operational environments. Considering the operation mechanisms of a logistics system, the related sub-processes will be analyzed and an intermediate variable that is the output of one process and also the input of another process to deal with the complex interactions will be used. The rest of this paper is organized as follows. In section 2, a multi-stage network DEA model which can fully reflect the internal structure of measure efficiency is proposed. Then several models for characterizing and measuring the efficiency of the logistics system are developed, and the related solution algorithms are presented as well. Computational examples and their results are given for illustration in Section 3. Meanwhile, an efficiency analysis is conducted and some management insights are put forward. Conclusions are provided in the last section.

2. Multi-stage network DEA model for logistics systems

A logistics system is an organic whole which has specific functions and whose internal factors have organic links with each other. The general pattern consists of three elements which are the external environment input (such as labors, resources, energy and information), transformation function in the system itself and outputting (e.g., finished goods, etc.). Although the traditional DEA approaches focus on the system inputs and outputs as well as the relative efficiency, the transformation process between the input and output is handled as a black box and the mutual influence within the system on the performance is unknown.

Furthermore, the logistics system has obvious collective, relative and hierarchical features, because each sub-process of manufacturing operations has a direct influence on the entire process. Only some differences between sub-processes may lead to the overall low efficiency. Therefore, the network DEA is an extension of the traditional DEA, which can further understand the operation processes and enhance performance evaluations of various sub-processes and ultimately draw more convincing decision-making information.
Thus, a multi-stage network DEA model which will fully reflect the internal structure of measure efficiency of the logistics system is constructed. Suppose the $n$ same logistics systems to be $DMU_{1}$, $DMU_{2}$, $DMU_{3}$, ... , $DMU_{n}$. Each $DMU$ can be divided into $R$ sub-processes and an arbitrary sub-process $r$ followed by a certain sequence along the material flow direction. For sub-process $r$ of an arbitrary $DMU_{j0}$, its input-oriented DEA model can be expressed as follows.

$$
\begin{align*}
\min & \quad E_{ij0} \\
\text{s.t.} & \quad \sum_{j=1}^{n} \lambda_{j} X_{ij0} \leq \sum_{j=1}^{n} E_{ij0} X_{ij0} \\
& \quad \sum_{j=1}^{n} \lambda_{j} X_{ij0} \geq \sum_{j=1}^{n} M_{ij0} \\
& \quad \sum_{j=1}^{n} \lambda_{j} Y_{ij0} \geq Y_{ij0} \\
& \quad \delta_{1} \cdot \sum_{j=1}^{n} \lambda_{j} M_{ij0} + \delta_{2} \cdot (1-\delta_{1}) \cdot \lambda_{j} Y_{ij0} = \delta_{1} \\
& \quad \lambda_{j} \geq 0, j = 1, 2, \ldots, n, i = 0, 0+1, 0+2, \ldots, n+1, E_{ij0} \geq 0 \\
\end{align*}
$$

In the model, $Y_{ij0}$ represents level of output $k$ produced by sub-process $r$ in $DMU_{j}$. Define $E_{ij0}$, $\lambda_{ij0}$ and $X_{ij0}$ as the relative efficiency of sub-process $r$ in $DMU_{j}$, the weight placed on sub-process $r$ in $DMU_{j}$ by sub-process $r$ in $DMU_{j}$ and level of input $h$ consumed by sub-process $r$ in $DMU_{j}$, respectively. $M_{ij0}$ represents level of intermediate product $l$ produced by sub-process $r$ and consumed by sub-process $r$ in $DMU_{j}$. $\delta_{1}$, $\delta_{2}$ and $\delta_{3}$ are the parameters whose value is 0 or 1. The meanings of the above optimization model can be explained as follows.

The general DEA model can be divided into input orientation and output orientation. The above evaluation models are input orientation, in which the decision-makers seek to decrease inputs without decreasing outputs. If consider the condition in which the decision-makers hope to increase the output, the evaluation model for output orientation can also be established according to its features. More importantly, it allows the complex relationship between sub-processes and each sub-process can use reversed variables, which will better reflect the real organization’s structure.

Different DEA models of each sub-process can be gotten according to the three conditions of the $DMU$ which are decreasing, constant and increasing. The differences between them depend on the production possibility set determined by the parameters $\delta_{1}$, $\delta_{2}$ and $\delta_{3}$. When $\delta_{1}=0$, the model is a C$^R$R model of input orientation, which belongs to the constant scale-profit model and meets the conditions of convexity, invalidity, minimum and cone. When $\delta_{1}=1$ and $\delta_{3}=0$, it is an input-oriented BC model which belongs to a changeable scale-profit model and meets the conditions of convexity, invalidity, expansion and minimum and is a non-decreasing scale-profit model.

$M_{ij0}$ and $N_{ij0}$ are intermediate variables. They are the output of one sub-process and also the input of another sub-process, reflecting the mutual influence of sub-processes. According to the ideas proposed in Chen and Yan or Lewis and Sexton, based on the optimum value of the output of intermediate product $M_{ij0}$, each of the input-oriented sub-process evaluation model can be solved reversely.

A logistics system involves a series of operational processes, which start from suppliers, pass through other service providers and finally provide the goods to the customers. The projects and processes it covers are sometimes different, but the basic processes are the same. Without loss of generality, its operation processes as construction process, storage process, distribution and delivery process are summarized. From the perspective of operational processes, it is necessary and reasonable to evaluate the efficiency of the logistics system. That is because the nature of the overall efficiency of the logistics system is made up of the efficiency of each of the major processes. This paper will evaluate the unit logistics efficiency based on the process. You can further dig out the specific information of the logistics system efficiency to provide a more clear direction for improving the overall efficiency.

According to the operation process of the logistics system, it is necessary to figure out the corresponding evaluation indexes. Let $CC$ denote construction cost. Generally speaking, the construction cost of the logistics facilities includes land costs and construction costs which involve the construction of internal infrastructure, storage facilities, goods yards and auxiliary buildings. Suppose that $WS$ denote warehousing storage area. Let $AD$ denote availability of delivering, which reflects the ability that the logistics facilities arrive at the customer. The calculation of $AD$ is based on the effective distance starting from the origination to the destination. Let EC denote equipment cost. The better use of equipment input can improve the efficiency of satisfying customers. Equipment cost includes the capital investment of storage systems and distribution systems, which are EC1 and EC2 respectively. Suppose that LT denote the labor time. The better use of labor time can improve the efficiency. According to the operation process, it is necessary to calculate the corresponding evaluation indexes.
Based on those mentioned above, a corresponding multi-stage network DEA model will be constructed as follows. Let $i$ be the investment and construction process, $k$ the storage process, and $l$ the distribution delivery process. The internal structure of a logistics system’s multi-stage network DEA model is shown in Figure 2.

Figure 2 The internal structure of multi-stage network DEA model for a logistics system

Suppose that there are $n$ DMUs, and each DMU has $R=3$ sub-processes, $i$, $k$ and $l$ respectively. To the $j$th decision-making unit $DMU_j$, the input and output vectors of its sub-systems are as follows.

\[
\begin{align*}
X_i^j &= \left(x_{ij}, \ldots, x_{ij}^{m_i}\right)^T > 0 \\
Y_i^j &= \left(y_{ij}, \ldots, y_{ij}^{s_i}\right)^T > 0 \\
X_k^j &= \left(x_{kj}, \ldots, x_{kj}^{m_k}\right)^T > 0 \\
Y_k^j &= \left(y_{kj}, \ldots, y_{kj}^{s_k}\right)^T > 0 \\
X_l^j &= \left(x_{lj}, \ldots, x_{lj}^{m_l}\right)^T > 0 \\
Y_l^j &= \left(y_{lj}, \ldots, y_{lj}^{s_l}\right)^T > 0
\end{align*}
\]

where, $X_i^j$, $X_k^j$, and $X_l^j$ represent input vectors of sub-process $i$, $k$, and $l$ of the $j$th decision-making unit respectively, and have $m_i$, $m_k$, and $m_l$ input respectively. $Y_i^j$, $Y_k^j$, and $Y_l^j$ denote output vector of sub-process $i$, $k$, and $l$ of the $j$th decision-making unit respectively, and have $s_i$, $s_k$, and $s_l$ input respectively. The $j$th decision-making unit $DMU_j$ is evaluated decision-making unit. For simplicity, let $DMU_0$ denote $DMU_{j_0}$. Its input and output vectors are $X_0$ and $Y_0$ respectively. For simplicity, let $X_0$ and $Y_0$ denote $X_{j_0}$ and $Y_{j_0}$ respectively. In accordance with the operating characteristics of logistics system, output-oriented models will be considered. That is, maintaining the input unchanged, they strive to achieve the maximum of the output and get high efficiency. In summary, the multi-stage network DEA models shown in Figure 2 are constructed as follows.

Construction sub-process. According to the results of the previous indicators, the construction sub-process has an input variable that is the construction costs, and two output intermediate product variables that are the warehousing storage area and availability of delivering. The latter two belong to the reverse variables. When its factors production factors change with the same percentage, the percentage of the output level is incremented or decremented. There is a threshold in these different states. It is essential to consider the situation that the production possibility set meets the variable scale income. Therefore, the evaluation problem is equivalent to solving the following programming models.

\[
\begin{align*}
\max \quad & \sum_{j=1}^{n} \lambda_j \cdot E_{i0} \\
\text{s.t.} \quad & \sum_{j=1}^{n} \lambda_j \cdot CC_j \leq CC_0 \\
& \sum_{j=1}^{n} \lambda_j \cdot WS_j \geq E_{i0} \cdot WS_0 \\
& \sum_{j=1}^{n} \lambda_j \cdot AD_j \leq Z_{i0} \cdot AD_0 \\
& E_{i0} \cdot Z_{i0} = 1 \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda_j \geq 0; \quad j = 1, 2, ..., n \\
& Z_{i0}, E_{i0} \geq 0
\end{align*}
\]

Storage sub-process. There are 3 input variables in the storage sub-process, namely, storage area, equipment costs, and labor time. The first is an input variable as an intermediate product. There are two output variables which are the warehousing storage area and availability of delivering. When its factors production factors change with the same percentage, the percentage of the output level is incremented or decremented. There is a threshold in these different states. It has to consider the situation that the production possibility set meets the variable scale income. Therefore, this problem is equivalent to solving the following optimization models.
max $E_{i0}$

s.t. $\sum_{j=1}^{n} \lambda_{j0}^* \cdot WS_j \leq WS_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot ECI_j \leq ECI_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot LT_j \leq LT_{10}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot SI_j \geq E_{k0} \cdot SI_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot TQ_j \geq E_{l0} \cdot TQ_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* = 1$

$\lambda_{j0}^* \geq 0; j = 1, 2, ..., n$

$E_{i0} \geq 0$  \hspace{2cm} (3)

Distribution and delivery sub-process. For the distribution and delivery’s sub-process, there are four input variables. Besides the equipment costs, labor time, there are two intermediate products as input variables, namely cargo turnover and availability of delivering. The latter belongs to the reverse variable. In practice, distribution and delivery costs tends to increase with the increase of logistics quantity, while the marginal cost decreases with the increase of logistics quantity. It is essential to consider the situation that the production possibility set meet the increasing scale income. Accordingly, it can establish the following planning model.

max $E_{i0}$

s.t. $\sum_{j=1}^{n} \lambda_{j0}^* \cdot TQ_j \leq TQ_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot AD_j \geq AD_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot ECI_j \leq ECI_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot LT_j \leq LT_{20}$

$\sum_{j=1}^{n} \lambda_{j0}^* \cdot DI_j \geq E_{i0} \cdot DI_{0}$

$\sum_{j=1}^{n} \lambda_{j0}^* \geq 1$

$\lambda_{j0}^* \geq 0; j = 1, 2, ..., n$

$E_{i0} \geq 0$  \hspace{2cm} (4)

Since the evaluation models of the three sub-processes are output-oriented, the intermediate products’ output of the last sub-process is the intermediate products’ input of the next sub-process. The intermediate product is the connection of the whole process. Thus, in order to solve the general overall efficiency of each DMU values, the solution process needs iteration in a certain order. In summary, this paper solves the problems by the following steps.

Step 1. At first, solve the programming model of the construction sub-process. It can get the optimal value $\lambda_{j0}^*$ and determine whether the sub-process of the unit being evaluated has an effective hypothesis decision-making unit combination. Thus, when the evaluation of this unit is effective, there are two intermediate products’ quantities $WS_{0} = \sum_{j=1}^{n} \lambda_{j0}^* \cdot WS_j$, and $AD_{0} = \sum_{j=1}^{n} \lambda_{j0}^* \cdot AD_j$.

Step 2. When the programming model of the constructing sub-process is solved, the optimal value $\lambda_{j0}^*$ will be known. According to a related effective assumed DMU combination, $SI^*$, and $TQ^*$ can be obtained. Then, the optimal value $WS_{0}$ needs to be used when solving the programming model of the storage sub-processes. When the other input variables are constant, it can get the optimal value $\lambda_{j0}^*$. On the condition that the aforementioned sub-process is effective, it can determine the effective assumed DMU combination. Thus, it can get the quantity of the output products when the unit evaluated is effective $SI^* = \sum_{j=1}^{n} \lambda_{j0}^* \cdot SI_j$ and the intermediate products quantity $TQ^* = \sum_{j=1}^{n} \lambda_{j0}^* \cdot TQ_j$.

Step 3. Similarly, it can get $DI^*$, and use $DI^*$ and $TQ^*$ to solve the programming model of the distribution and delivery sub-process. When other input variables also remain unchanged, it can get the optimal value $\lambda_{j0}^*$. It can determine the sub-process of the unit being
evaluated and has an effective hypothesis decision-making unit combination. Then, when the unit evaluated is effective, the number of output products is \( \sum_{j=1}^{n} \lambda_{j}^{*} \cdot D_{j} \). The overall efficiency reference unit value can be calculated by \( \frac{D_{j}^{*}}{D_{j}} \).

Step 4. The above steps can be followed to obtain the overall efficiency of each decision-making unit's value \( E_{j} \), \( j=1,2,\ldots,n \).

3. Empirical analysis

According to the models mentioned above, this paper took 20 logistics enterprises in Hunan province of China as Decision Making Units. They are A-T enterprises or, of which, B, H, K, L, M, P, R belong to large logistics enterprises. The total number of samples exceeds twice the variables of the sum of each sub-process's input and output. The data used in the computing are listed in Table 1. MATLAB7.1 was used to write the programming code and solve the model. The relative efficiency and organizational efficiency of its sub-processes will analyzed and evaluated as shown in Table 2.

<p>| Table 1 The Computational data of the multi-stage network DEA model |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>DMU</th>
<th>CC</th>
<th>WS</th>
<th>AD</th>
<th>LT1</th>
<th>EC1</th>
<th>TQ</th>
<th>LT2</th>
<th>EC2</th>
<th>SI</th>
<th>DI</th>
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<td>4,000</td>
<td>10.6</td>
<td>2,816</td>
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<td>24,130</td>
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<td>24,130</td>
<td>34,946</td>
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<td>7,209,000</td>
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<td>5,693,200</td>
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<tr>
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Table 2 shows the average of the overall efficiency of all of the enterprises is 1.7619. The overall efficiency value of D, F, G, H is 1, which indicates that all of the 20 companies are relatively operating in a better condition, so they are relatively effective. Thus, they belong to the first class. The overall efficiency of the other 16 companies is bigger than 1, indicating that their output is low for investment. Their operating conditions are the less ideal so that they are relatively ineffective. Through some improvement and perfection in some aspects, it is easy to make these companies become leaders in this industry sector. So they are put in the fifth class.

<p>| Table 2 The evaluation results of the multi-stage network DEA model |
|-----------------|----------------|----------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>DMU</th>
<th>Organization</th>
<th>Sub-DMU 1</th>
<th>Sub-DMU 2</th>
<th>Sub-DMU 3</th>
<th>Ranking</th>
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The overall efficiency values can't represent the management level of the company or organization and marketing capabilities. Different input conditions and requirements will lead to differences in efficiency, and this paper analyzes the specific sub-process' efficiency to reveal the "black box". For sub-process 1, the average efficiency of all the sample enterprises is 1.5012. The standard deviation is 0.3337. The efficiency levels are quite different. I, J and S’s performances are relatively the best. Their efficiency values are all 1. Enterprise R’s efficiency is the lowest, which is 2.0525. This indicates that there are obvious serious problems or reciprocity compared with their rivals in sub-process1. For sub-process 2, the average efficiency of all the sample enterprises was 1.057298. The standard deviation is 0.1316. Compared to other sub-processes, the gap of the efficiency level of the sub-process 2 is not large. This matches the practical situation in our area, which is the logistics service differentiation is not enough and operational level of automation is low. For sub-process 3, the average efficiency of all the sample enterprises is 1.188165. The standard deviation is 0.1948. The differences of the efficiency levels are moderate.

Through the above analysis, the network DEA gives us more comprehensive evaluation of information, not only including the situation whether the decision-making unit is efficient or not but also including the factors to make it inefficient. The operating time of each segment can be reflected. The invalid condition of each sub-process eventually leads to the overall failure. Even if the overall efficiency performance is relatively effective, further improvements in the segment and sub-processes can still be reflected, such as enterprise H, while the overall efficiency value is 1, its sub-process1 is still relatively invalid. Multi-stage network DEA undoubtedly enables us to know more about their economic problems.

4. Conclusion

With the development of society and the requirements of logistics development, planning and management practices have higher requirements for the performance evaluation of the logistics industry. This paper must find the crux of the failure in the internal decision-making unit. Moreover, there are different conditions and individual aspects in a logistics system. This requires us to find a new way to reveal the "black box", through the perspective of which, the internal reason of the performance of the logistics system output efficiency can be got clearly. To solve these problems, this paper proposes a multi-stage network DEA model with chain and parallel form relationships. Taking operating and strategic decisions into account, this paper makes further extensions for these models and gives basic steps and solution algorithms for the measurement of the efficiency. It also uses case analysis to reflect the practicality and advantages of the method, especially which can detect inefficiencies that the standard DEA Model misses.

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