Measuring performance of supply chain by relational network DEA: A game theory approach

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Abstract

An appropriate performance measurement system is an important requirement for the effective management of a supply chain. Because of the existence of the intermediate measures connecting the supply chain members, conventional data envelopment analysis (DEA) cannot be utilized directly to measure the performance of supply chain and its members. This paper evaluated the performance of supply chain under cooperative and non-cooperative games by utilizing relational network DEA. Relational network DEA model considers the interrelationship of the members within the supply chain, to measure the efficiency of the supply chain and those of the members at the same time. The non-cooperative game is based on the Stackelberg strategy solution concept. In non- cooperative game, it is considered that some parts in supply chain have more power in marketing competition (leaders) and the other parts of the supply chain repetition of supply chain are the followers. In the leader-follower structure (Stackelberg model), the leaders efficiency, first evaluated by using the relational network DEA in parallel situation, and then the followers efficiency is evaluated, using information related to the leader's efficiency. In cooperative game it is assumed that all parts of supply chain cooperate to each other in order to achieve higher efficiency.

Keywords: Supply chain, Relational network DEA, Efficiency, Game theory

Introduction

During the recent years, severe competition among various business companies has made supply chain management (SCM) a very essential requirement for the companies to maintain their competitive position in the trade. It is then causing the SCM to become a favorite subject for studies and researches in various academic levels.

According to reports by Consulting (1999), from now on the companies will compete together through their supply chains. This report is based on studies carried out over 200 manufacturers and distributors in the United States and Canada which involved various industries such as aerospace, automotive, consumer's products, and high-tech productions and so on. As an example, mobile phone industry has been considered. At this case, Nokia (the producer) and Symbian (software retailer) have formed a supply chain which compete with another supply chain of HTC (producer) and Microsoft (software retailer) (Xiao & Yang, 2008).

Any disorder or lack of harmony and coordination among various parts and departments within a supply chain, will result in damages and financial losses. There comes the importance of continuous evaluation of supply chain within an organization, and its key role for continuous improvement ,and detection and treatment of lose links for final success. There are various methods for evaluating the performance of supply chain, among which DEA has been most utilized in academic studies. DEA is a suitable mean to measure the performance of the supply chain ,because it deals with multiple inputs and outputs.

Most of the studies about supply chain evaluation with DEA were confined to survey the supply chain members individually such as evaluation of distributors performance (Ross & Droge, 2002), purchasers performance (Hatami-Marbini *et al.*, 2011), vendor`s performance (Talluri *et al.*, 2006)

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and etc. They all considered the supply chain as a "black box", whereas the supply chains usually involves two or more stages which the output of one stage is the input of the next one. So, it cannot be treated merely as a black box. Also, these stages are very much related and interconnected together. Consider a supply chain with two stages in which manufacturers are at the first stage and the retailers are at the second stage. In this system, if retailers achieve maximum efficiency in conflict with the manufacturers which do not, it is reasonable that the manufacturers would try to increase their outputs in order to achieve maximum efficiency. However, a rise in the manufacturer's outputs causes a build-up in the retailer's inputs, because the outputs of the first stage are the inputs of second stage. Such issues cannot be tackled by the classical DEA models. The problems and deficiencies associated with classical DEA system caused the researchers to have more concentration and studies on the internal processes and structure of DMUs. Hatami-Marbini *et al*. (2011) classified these researches into four groups: standard DEA; efficiency decomposition; network DEA; and game theory approach.

Network DEA is classified into three groups by Kao and Hwang (2010).Among them, the relational network DEA is the most suitable method to measure the efficiency of the supply chain. In the relational methodology, a single mathematical program is used to calculate the system and process efficiencies. Through the constraints of the mathematical program, the relationship between the system efficiency and process efficiencies is obtained. The relational approach and methodology was introducedfot the first timebyKao and Hwang (2008)in order to evaluate a system which had two sub-processes connected in series. (Kao, 2009a) then further expended the two stage model by adding more sub-processes in series and parallel. They used their model as a case study to evaluate the efficiency of non-life insurance firms in Taiwan. Kao and Hwang (2010) expanded this model for evaluation of all types of network structures. They applied the model to assess the impact of information technology on firm performance in a banking industry. Chen and Yan (2011) used the network DEA to evaluate the efficiency of a supply chain ,consisting of one supplier and two manufacturers in three approaches of centralized, decentralized ,and mixed. All of these papersconsidered, that the sub-systems in the system have equal power, and no one can enforce her strategy to the others. Game theory approach is utilized, when members have unequal power.

Using game theory approach in DEA with 2 stages originates from the work of Liang *et al*. (2006). They use standard DEA and Stackelberg game (or leader-follower) to measure the performance of supply chains with two members. In Liang *et al*. (2006), first the efficiency of leader is evaluated, and then the efficiency of follower is measured by using the information related to efficiency of leader. By using similar modeling principle as in (Liang *et al*., 2008; Liang *et al*., 2006) provide detailed models for the two-stage process. The resulting models suggest, efficiency decomposition, where the overall efficiency of the two-stage process is a product of the efficiencies of the two sub-processes. Hatami-Marbini *et al*. (2011) show that by using the efficiency decomposition of (Kao & Hwang, 2008) and (Liang *et al*., 2006) approach, the model of (Liang *et al*., 2008) will be obtained. All above-mentioned papershave applied game theory approach in a supply chain with two stages,whereas supply chains usually involve more than two stages.

In this paper, contrary to the previous studies in game theory approach ,a supply chain with more than two stages (five suppliers, two manufactures, one distribution) are used, which the outputs of one member are inputs of other members. This paper evaluated the performance of supply chain under cooperative and non-cooperative games. In cooperative game, it assumes that all parts of supply chain cooperate to each other to achieve higher efficiency. The relational network DEA of Kao and Hwang (2010) is used to find the efficiency of the supply chain.

In the non-cooperative game, the concept of a leader-follower structure is used. Usually in supply chains one or more members have unequal power and they have their own strategy to achieve efficiency, so that one or more members can act as Stackelberg leaders. For example in supply chain, there may be a set of suppliers who have initiatives and can enforce their strategy on the other participants. In other words such suppliers act as leader and the other parts act s as follower. This paper finds the efficiency of supply chain when some sets of members in supply chain have more power than the other participants. For this purpose, first the efficiency of leader parts is calculated by using the relational network DEA. Then, by using the efficiency of these parts, the efficiency of the whole supply chain is obtained.

Models

In real world the structure of supply chain are not same because number of members in chain will be different. This paper, utilized a perfect supply chain which consists of five suppliers, two manufactures and one distribution which is described in Fig 1.

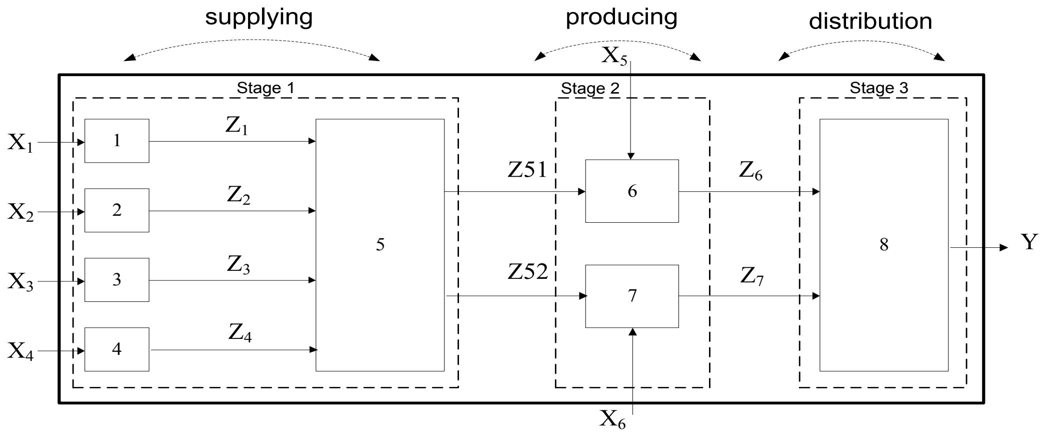

Figure 1. The structure of the supply chain

As it can be seen in figure 1, supply chain has four parallel stages. In stage one, Processes 1 to 4 use inputs X_1, X_2, X_3 and X_4 to produce Intermediate Products Z_1, Z_2, Z_3 and Z_4, respectively. In stage two, process 5 uses intermediate products Z_1, Z_2, Z_3 and Z_4, produced by Processes 1 to 4, respectively, to produce intermediate Products Z_5 and Z_6. In stage 3, Process 6 uses intermediate Products Z_5 and Process 7 uses intermediate Products $Z_{6,}$ produced by Process 5, to produce intermediate Product Z_6 and$Z_{7,}$ respectively. Finally, in stage 4, Process 8 uses intermediate Products Z_6 and $Z_{7,}$ to produced final output Y.

The non-cooperative Stackelberg game

This section considers the relationship of supply chain member's by using the non-cooperative structure. Specifically, we will regard the interaction between stages as a Stackelberg game, where one of the stages, the leader, has the initiative and can enforce her strategy on the other stages, the follower. Each of the members in the stages can cooperate to each other in order to have more power in supply chain. For example, we consider that the members of stage one cooperate to each other in order to have higher efficiency. The leader (first stage) makes the first move then the follower responds by playing the best move with available information. This idea for Stackelberg is used in various papers, see, e.g. (Edirisinghe *et al.*, 2011; Esmaeili *et al.*, 2009;Liang *et al.*, 2006).

Kao (2009b) presented relational DEA for parallel systems. By using the Kao (2009b) model, the efficiency of the stage one calculated as follows:

$$
\begin{aligned}
& E_k^{S1} = \max w_1 Z_{1k} + w_2 Z_{2k} + w_3 Z_{3k} + w_4 Z_{4k} \\
& v_1 X_{1k} + v_2 X_{2k} + v_3 X_{3k} + v_4 X_{4k} = 1, \\
& (w_1 Z_{1j} + w_2 Z_{2j} + w_3 Z_{3j} + w_4 Z_{4j}) - (v_1 X_{1j} + v_2 X_{2j} + v_3 X_{3j} + v_4 X_{4j}) \le 0, j = 1,\dots,n \\
& w_1 Z_{1j} - v_1 X_{1j} \le 0, \qquad j = 1,\dots,n \\
& w_2 Z_{2j} - v_2 X_{2j} \le 0, \qquad j = 1,\dots,n \\
& w_3 Z_{3j} - v_3 X_{3j} \le 0, \qquad j = 1,\dots,n \\
& w_4 Z_{4j} - v_4 X_{4j} \le 0, \qquad j = 1,\dots,n
\end{aligned} \tag{1}
$$

The second constrain is related to the efficiency of stage one, and the third to sixth constrains are related to supplier one to four, respectively. The efficiencies and effectiveness of suppliers 1 to 4 are calculated as follows:

$$
E_k^{(1)} = \frac{w_1^* Z_{1k}}{v_1^* X_{1k}} \qquad E_k^{(3)} = \frac{w_3^* Z_{3k}}{v_3^* X_{3k}}
$$
$$
E_k^{(2)} = \frac{w_2^* Z_{2k}}{v_2^* X_{2k}} \qquad E_k^{(4)} = \frac{w_4^* Z_{4k}}{v_4^* X_{4k}} \tag{2}
$$

Where E_k^1, E_k^2, E_k^3, E_k^4, u_r^*, v_i^* and w_q^* represent the optimal multipliers of the mathematical model. Now the follower (supply chain) efficiency is computed subject to the requirement that the efficiency of the members of stage one, suppliers 1 to 4, is to stay fixed. By using the rational network DEA and the optimal efficiency of suppliers 1 to 4, the efficiency of supply chain calculated in mode l (3): Note that in model (3), the efficiency of the suppliers 1, 2, 3 and 4 is equal to E_k^1, E_k^2, E_k^3 and E_k^4, respectively. Model (3) is the efficiency of the supply chain when the members into stage one have more power (members in stage one acts as leader). In similar manner, the efficiency of the supply chain when other stages act as leader can obtain.

$$
\begin{aligned}
& E_k = \max uY_k \\
& s.t. \\
& v_1X_{1k} + v_2X_{2k} + v_3X_{3k} + v_4X_{4k} + v_5X_{5k} + v_6X_{6k} = 1, \\
& uY_j - (v_1X_{1j} + v_2X_{2j} + v_3X_{3j} + v_4X_{4j} + v_5X_{5j} + v_6X_{6j}) \le 0, \quad j = 1,\dots,n \\
& w_1Z_{1k} = E_k^{(1)}(v_1X_{1k}), \\
& w_2Z_{2k} = E_k^{(2)}(v_2X_{2k}), \\
& w_3Z_{3k} = E_k^{(3)}(v_3X_{3k}), \\
& w_4Z_{4k} = E_k^{(4)}(v_4X_{4k}), \\
& w_1Z_{1j} - v_1X_{1j} \le 0, && j = 1,\dots,n, j \ne k \\
& w_2Z_{2j} - v_2X_{2j} \le 0, && j = 1,\dots,n, j \ne k \\
& w_3Z_{3j} - v_3X_{3j} \le 0, && j = 1,\dots,n, j \ne k \\
& w_4Z_{4j} - v_4X_{4j} \le 0, && j = 1,\dots,n, j \ne k \\
& w_{51}Z_{51j} + w_{52}Z_{52j} - (w_1Z_{1j} + w_2Z_{2j} + w_3Z_{3j} + w_4Z_{4j}) \le 0, && j = 1,\dots,n \\
& w_6Z_{6j} - (w_{51}Z_{51j} + v_5X_{5j}) \le 0, && j = 1,\dots,n \\
& w_7Z_{7j} - (w_{52}Z_{52j} + v_6X_{6j}) \le 0, && j = 1,\dots,n \\
& uY_j - (w_6Z_{6j} + w_7Z_{7j}) \le 0, && j = 1,\dots,n
\end{aligned}
\tag{3}
$$

The cooperative game

In this section, cooperative game approach is used for determining the efficiency of the supply chain. In this case the members of the supply chain jointly determine a set of optimal weights of multipliers in order to achieve the highest efficiency in the supply chain. The relational network which is presented by (Kao & Hwang, 2010) determines the efficiency of the system and the members in a single mathematical model. In fact it calculates the multiplayer of the system in way to increase the efficiency of the whole system. In other words, the sub-systems are coordinating to each other to increase the efficiency of the entire system. Therefore, it is acting like the cooperative game.By using the relational network DEA, the efficiency of supply chain in cooperative case calculated in model (4).The second constrain is related to the efficiency of supply chain of given shipping firm, and the third to seventh constrains are related to its suppliers. Constrains number eight and nine are related to producers and the tenth constrain is related to disturber.

$$
\begin{aligned}
& E_k = \max uY_k \\
& s.t. \\
& v_1X_{1k} + v_2X_{2k} + v_3X_{3k} + v_4X_{4k} + v_5X_{5k} + v_6X_{6k} = 1, \\
& uY_j - (v_1X_{1j} + v_2X_{2j} + v_3X_{3j} + v_4X_{4j} + v_5X_{5j} + v_6X_{6j}) \le 0, && j = 1,\dots,n \\
& w_1Z_{1j} - v_1X_{1j} \le 0, && j = 1,\dots,n \\
& w_2Z_{2j} - v_2X_{2j} \le 0, && j = 1,\dots,n \\
& w_3Z_{3j} - v_3X_{3j} \le 0, && j = 1,\dots,n \\
& w_4Z_{4j} - v_4X_{4j} \le 0, && j = 1,\dots,n \\
& w_{51}Z_{51j} + w_{52}Z_{52j} - (w_1Z_{1j} + w_2Z_{2j} + w_3Z_{3j} + w_4Z_{4j}) \le 0, && j = 1,\dots,n \\
& w_6Z_{6j} - (w_{51}Z_{51j} + v_5X_{5j}) \le 0, && j = 1,\dots,n \\
& w_7Z_{7j} - (w_{52}Z_{52j} + v_6X_{6j}) \le 0, && j = 1,\dots,n \\
& uY_j - (w_6Z_{6j} + w_7Z_{7j}) \le 0, && j = 1,\dots,n
\end{aligned}
\tag{4}
$$

The efficiencies and effectiveness of supply chain members are calculated as follows:

$$
\begin{aligned}
&E_k^{(1)} = \frac{w_1^* Z_{1k}}{v_1^* X_{1k}} \qquad E_k^{(2)} = \frac{w_2^* Z_{2k}}{v_2^* X_{2k}} \\
&E_k^{(3)} = \frac{w_3^* Z_{3k}}{v_3^* X_{3k}} \qquad E_k^{(4)} = \frac{w_4^* Z_{4k}}{v_4^* X_{4k}} \\
&E_k^{(5)} = \frac{w_{51}^* Z_{51k} + w_{52}^* Z_{52k}}{w_1^* Z_{1k} + w_2^* Z_{2k} + w_3^* Z_{3k} + w_4^* Z_{4k}} \\
&E_k^{(6)} = \frac{w_6^* Z_{6k}}{w_{51}^* Z_{51k} + v_5^* X_{5k}} \\
&E_k^{(7)} = \frac{w_7^* Z_{7k}}{w_{52}^* Z_{52k} + v_6^* X_{6k}} \\
&E_k^{(8)} = \frac{u^* Y_k}{w_6^* Z_{6k} + w_7^* Z_{7k}}
\end{aligned}
\qquad (5)
$$

Conclusion

The current paper develops relational network DEA models for measuring the performance of a supply chain and its members in 2 scenarios. In first scenario, we consider that some parts in the supply chain have more power in marketing competition (the leaders) and the other parts of the supply chain are the followers. The non-cooperative model is modeled as a leader-follower structure, where in our case, the leaders are first calculated by the relational network DEA model, and then the followers are evaluated using the leaders-optimized efficiency. In second scenario, the cooperative model tries to maximize the joint efficiency of the whole supply chain. The relational network DEA is utilized to measure the performance of the supply chain.

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