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Fuzzy revenue efficiency in sustainable supply chains

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Abstract The performance assessment of supply chains including sustainability dimensions of economic, environmental and social is a significant aspect for managers and decision makers. Furthermore, imprecise data are presented in many real world applications. Therefore, the current paper proposes an approach based on data envelopment analysis (DEA) to analyze the revenue efficiency of sustainable supply chains when fuzzy measures are present. Actually, a fully fuzzy DEA approach is proposed to measure the revenue efficiency of sustainable supply chains and their members. A numerical example is used to illustrate the introduced approach.

Keyword: Data Envelopment Analysis, Revenue Efficiency, Fuzzy Data, Sustainable Supply Chains.

1 Introduction

The uncertainty is present in many real-life problems. Furthermore, the performance measurement of sustainable supply chains (SSCs) is a significant topic for management. Due to the importance of revenue efficiency analysis in organizations, the current paper proposes a data envelopment analysis (DEA) approach to assess the revenue efficiency of sustainable supply chains with two components, supplier and manufacturer while imprecise data are presented.

DEA, firstly proposed by Charnes et al. [1], is a popular approach to evaluate the relative efficiency of firms. Traditional DEA models consider each decision making unit (DMU) as a black box while all measures are deemed precise and crisp. Nevertheless, there are many systems with network structures such as supply chains that their performance must be determined. Moreover, fuzzy factors are present in many real world applications. In the DEA literature, there are different studies such as [2, 3] to deal with network structures. Chen et al. [2] provided a DEA model to identify DEA projections and to measure the efficiency of two-stage processes. Afterwards, Zhu [3] extended it for evaluating the relative efficiency of supply chains with four components. Banihashem et al [4] concerned cost, revenue and profit efficiency of supply chains with crisp measures. Also, different approaches can be found in the DEA context to analyze the efficiency of DMUs with fuzzy data. Puri and Yadav [5] presented a fully fuzzy DEA approach to measure cost and revenue efficiency in the presence

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of undesirable outputs. Hatami-Marbini et al. [6] proposed a DEA-based approach to assess fuzzy efficiency using lexicographic multiobjective approach.

Because of the key role of taking different dimensions of sustainability into account in the performance analysis, the current paper extends Tone's approach [7] to measure the revenue efficiency of sustainable supply chains when fuzzy measures are available. To illustrate, a fully fuzzy DEA approach is proposed to analyze the revenue efficiency of sustainable supply chains and their members.

The rest of this paper is organized as follows: In Section 2, we review the basic concepts and related models. Section 3 introduces a fuzzy DEA-based approach to analyze the revenue efficiency of SSCs. A numerical example is given in Section 4 to illustrate the proposed approach. Conclusions are discussed in Section 5.

2 Preliminaries

In this section, some basic models and definitions are presented that are essential to explain the approach introduced herein.

2.1 Revenue efficiency

Consider n DMUs, $DMU_j\ (j=1,...,n)$, with m inputs $x_{ij}(i=1,...,m)$ and s outputs $y_{rj}(r=1,...,s)$. $P_j=(p_{1j},p_{2j},...,p_{rj})$ is used to show non-negative price vectors of outputs. Tone [7] proposed the following model to assess the maximum revenue of the unit under evaluation, DMU_o:

$$
\begin{aligned}
\Omega_o^* = Max \quad & \sum_{r=1}^{s} \bar{y}_r^o \\
s.t. \quad & \sum_{j=1}^{n} \lambda_j x_{ij} \le x_{ijo},\ i=1,...,m, \\
& \sum_{j=1}^{n} \lambda_j \bar{y}_{rj} \ge \bar{y}_r^o, \quad r=1,...,s, \\
& \lambda_j \ge 0.
\end{aligned}
\tag{1}
$$

in which $\lambda_j(j=1,...,n)$ are intensity variables and $\bar{y}_{rj}=p_{rj}\times y_{rj}$, $\bar{y}_r^o\ (r=1,...,s)$ is the optimal solution obtained from model (1).

The revenue efficiency of DMU_o can be defined as $RE=\sum_{r=1}^{s}\bar{y}_{ro}/\sum_{r=1}^{s}\bar{y}_r^o$.

2.2 Hatami-Marbini et al.'s fuzzy model [6]

In this subsection, the fuzzy model proposed by Hatami-Marbini et al. [6] is briefly explained.

Suppose there are n DMUs, $DMU_j\ (j=1,...,n)$, with m inputs $\tilde{x}_{ij}\ \ (i=1,...,m)$ and s outputs $\tilde{y}_{rj}\ (r=1,...,s)$. Fuzzy inputs and outputs are shown by trapezoidal fuzzy numbers, $\tilde{x}_{ij}=(x_{ij1},x_{ij2},x_{ij3},x_{ij4})$, and $\tilde{y}_{rj}=(y_{rj1},y_{rj2},y_{rj3},y_{rj4})$, respectively. Moreover, all variables are taken into account as fuzzy numbers. This means $\tilde{\theta}_o=(\theta_{o1},\theta_{o2},\theta_{o3},\theta_{o4})$ and $\tilde{\lambda}_j=(\lambda_{j1},\lambda_{j2},\lambda_{j3},\lambda_{j4})$. Hatami-Marbini et al. [6] suggested the following model to evaluate the relative efficiency of DMUs:

$$
\begin{aligned}
& Min\ \tilde{\theta}_o \\
& s.t. \sum_{j=1}^{n}\lambda_{jk}x_{ijk}\leq\theta_{ok}x_{iok}, \quad i=1,...,m, k=1,2,3,4, \\
& \quad \sum_{j=1}^{n}\lambda_{jk}y_{rjk}\geq y_{rok}, \quad r=1,...,s, k=1,2,3,4, \\
& \quad \lambda_{j1}\geq 0, \lambda_{j2}-\lambda_{j1}\geq 0, \lambda_{j3}-\lambda_{j2}\geq 0, \lambda_{j4}-\lambda_{j3}\geq 0, \ j=1,2,...,n, \\
& \quad \theta_{o2}-\theta_{o1}\geq 0, \theta_{o3}-\theta_{o2}\geq 0, \theta_{o4}-\theta_{o3}\geq 0.
\end{aligned}
\tag{2}
$$

As can be seen, model (2) contains the fuzzy decision variable, $\tilde{\theta}_o$, with four variable parameters $(\theta_{o1},\theta_{o2},\theta_{o3},\theta_{o4})$ For computing model (2), Hatami-Marbini et al. [6] used a lexicographic multi-objective approach. To illustrate, they considered the problem as a multi-objective model to find the relative fuzzy efficiency of DMU_o and first optimized one of the objectives (θ_{o4}), then, maintaining the optimal value of that variable, optimized a second objective (θ_{o3}), and then, following the same procedure, successively, optimized the third (θ_{o2}) and fourth (θ_{o1}) objective functions.

In the next section, by following Hatami-Marbini et al. [6] and Puri and Yadav [5], a DEA-based approach is introduced to evaluate the fuzzy revenue efficiency of sustainable supply chains.

3 Fuzzy revenue efficiency in sustainable supply chains

We consider n supply chains, $SC_j\ (j=1,...,n)$, with trapezoidal fuzzy inputs $\tilde{x}_{ij}=(x_{ij1},x_{ij2},x_{ij3},x_{ij4})$, trapezoidal fuzzy outputs $\tilde{y}_{rj}=(y_{rj1},y_{rj2},y_{rj3},y_{rj4})$ and trapezoidal fuzzy intermediate measures $\tilde{z}_{kj}=\ (z_{kj1},z_{kj2},z_{kj3},z_{kj4})$. Two components, supplier and manufacturer, are taken for each supply chain. The structure under evaluation can be seen in Figure 1. Fuzzy prices of output r for each member of supply chain j is indicated by $\tilde{p}_{rj}=(p_{rj1},p_{rj2},p_{rj3},p_{rj4})$ that $r\in O^s\cup O^M$. O^s and O^M show the output subscript sets of supplier and manufacturer members. Similarly, the input subscript sets of supplier and manufacturer members are denoted by I^s and I^M.

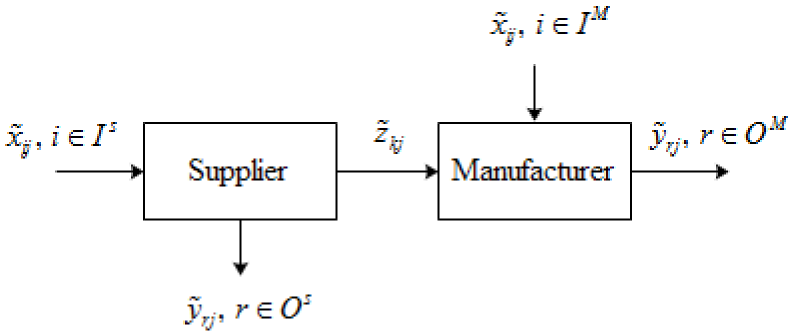

Fig. 1 Sustainable supply chain network under evaluation

The following model is proposed for measuring the maximum revenue of the whole SSC and each member:

$$
\begin{aligned}
\Omega_o^* = Max \quad & \sum_{r \in O^s} \tilde{\bar{y}}_r + \sum_{r \in O^M} \tilde{\bar{y}}_r \\
s.t. \quad & Supplier \\
& \sum_{j=1}^{n} \tilde{\lambda}_j \tilde{\bar{x}}_{ij} \le \tilde{x}_{io}, \ \ \forall i \in I^s, \\
& \sum_{j=1}^{n} \tilde{\lambda}_j \tilde{y}_{rj} \ge \tilde{\bar{y}}_r, \quad \forall r \in O^s, \\
& \sum_{j=1}^{n} \tilde{\lambda}_j \tilde{z}_{kj} \ge \tilde{z}'_{ko}, \quad \forall k \in K, \\
& \tilde{\lambda}_j \ge \tilde{0}, \forall j, \\
& Manufacturer \\
& \sum_{j=1}^{n} \tilde{\beta}_j \tilde{\bar{x}}_{ij} \le \tilde{x}_{io}, \ \ \forall i \in I^M, \\
& \sum_{j=1}^{n} \tilde{\beta}_j \tilde{y}_{rj} \ge \tilde{\bar{y}}_r, \quad \forall r \in O^M, \\
& \sum_{j=1}^{n} \tilde{\beta}_j \tilde{z}_{kj} \le \tilde{z}'_{ko}, \quad \forall k \in K, \\
& \tilde{\beta}_j \ge \tilde{0}, \forall j.
\end{aligned}
\tag{3}
$$

in which $\tilde{\bar{y}}_{rj} = \tilde{p}_{rj} \times \tilde{y}_{rj}$ and $\tilde{\bar{y}}_r = (\bar{y}_{r1}, \bar{y}_{r2}, \bar{y}_{r3}.\bar{y}_{r4})$ $r \in O^s \cup O^M$. Also, $\tilde{\lambda}_j = (\lambda_{j1}, \lambda_{j2}, \lambda_{j3}, \lambda_{j4})$, $\tilde{\beta}_j = (\beta_{j1}, \beta_{j2}, \beta_{j3}, \beta_{j4})$ are fuzzy intensity variables for supplier and manufacturer components, respectively.

Definition 3.1. The fuzzy revenue efficiency scores of the whole supply chain under evaluation, SC_o , and its components are obtained by:

$$\tilde{E}_o^{SC*} = \frac{\sum_{r\in O^s \cup O^M} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^s \cup O^M} \tilde{\bar{y}}_r^*}\ ,\ \tilde{E}_o^{Supplier*} = \frac{\sum_{r\in O^s} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^s} \tilde{\bar{y}}_r^*},\ \text{and}\ \tilde{E}_o^{Manufacturer*} = \frac{\sum_{r\in O^M} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^M} \tilde{\bar{y}}_r^*} \tag{4}$$

As can be seen, model (3) is a fully fuzzy linear programming. Also, each formula of (4) is fully fuzzy. Model (3) can be replaced by a linear programming problem following Hatami-Marbini et al. [6]. Thus, we have

$$\begin{aligned}
&\Omega_o^* = Max \quad 1/4(\sum_{f=1}^{4} \sum_{r\in O^s \cup O^M} \bar{y}_{rf}) \\
&s.t. \quad \sum_{j=1}^{n} \lambda_{jf} x_{ijf} \le x_{iof},\ i \in I^s,\ f=1,...,4, \\
&\sum_{j=1}^{n} \lambda_{jf} \bar{y}_{rjf} \ge \bar{y}_{rf},\quad r \in O^s,\ f=1,...,4, \\
&\sum_{j=1}^{n} \lambda_{jf} z_{kjf} \ge z'_{kof},\quad \forall k \in K,\ f=1,...,4, \\
&\lambda_{j1} \ge 0, \lambda_{j2} - \lambda_{j1} \ge 0, \lambda_{j3} - \lambda_{j2} \ge 0, \lambda_{j4} - \lambda_{j3} \ge 0, \forall j, \\
&\sum_{j=1}^{n} \beta_{jf} x_{ijf} \le x_{iof},\ i \in I^M,\ f=1,...,4, \\
&\sum_{j=1}^{n} \beta_{jf} \bar{y}_{rjf} \ge \bar{y}_{rf},\quad r \in O^M,\ f=1,...,4, \\
&\sum_{j=1}^{n} \beta_{jf} z_{kjf} \le z'_{kof},\quad \forall k \in K,\ f=1,...,4, \\
&\beta_{j1} \ge 0, \beta_{j2} - \beta_{j1} \ge 0, \beta_{j3} - \beta_{j2} \ge 0, \beta_{j4} - \beta_{j3} \ge 0 \quad \forall j, \\
&\bar{y}_{r1} \ge 0, \bar{y}_{r2} - \bar{y}_{r1} \ge 0, \bar{y}_{r3} - \bar{y}_{r2} \ge 0, \bar{y}_{r4} - \bar{y}_{r3} \ge 0 \forall r \in O^s \cup O^M.
\end{aligned} \tag{5}$$

Notice that the approach used for difuzzifying the objective function differs from Hatami-Marbini et al.'s [6].

The fuzzy revenue efficiency scores are also calculated as follows:

$$\tilde{E}_o^{SC*} = \frac{\sum_{r\in O^s \cup O^M} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^s \cup O^M} \tilde{\bar{y}}_r^*} = \frac{(\sum_{r\in O^s \cup O^M} \bar{y}_{ro1}, \sum_{r\in O^s \cup O^M} \bar{y}_{ro2}, \sum_{r\in O^s \cup O^M} \bar{y}_{ro3}, \sum_{r\in O^s \cup O^M} \bar{y}_{ro4})}{(\sum_{r\in O^s \cup O^M} \bar{y}_{r1}^*, \sum_{r\in O^s \cup O^M} \bar{y}_{r2}^*, \sum_{r\in O^s \cup O^M} \bar{y}_{r3}^*, \sum_{r\in O^s \cup O^M} \bar{y}_{r4}^*)} = \tag{6}$$

$$\left(\frac{\sum_{r\in O^s \cup O^M} \bar{y}_{ro1}}{\sum_{r\in O^s \cup O^M} \bar{y}_{r4}^*}, \frac{\sum_{r\in O^s \cup O^M} \bar{y}_{ro2}}{\sum_{r\in O^s \cup O^M} \bar{y}_{r3}^*}, \frac{\sum_{r\in O^s \cup O^M} \bar{y}_{ro3}}{\sum_{r\in O^s \cup O^M} \bar{y}_{r2}^*}, \frac{\sum_{r\in O^s \cup O^M} \bar{y}_{ro4}}{\sum_{r\in O^s \cup O^M} \bar{y}_{r1}^*}\right)$$

$$\tilde{E}_o^{Supplier*} = \tilde{E}_o^{SC*} = \frac{\sum_{r\in O^s} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^s} \tilde{\bar{y}}_r^*} = \frac{(\sum_{r\in O^s} \bar{y}_{ro1}, \sum_{r\in O^s} \bar{y}_{ro2}, \sum_{r\in O^s} \bar{y}_{ro3}, \sum_{r\in O^s} \bar{y}_{ro4})}{(\sum_{r\in O^s} \bar{y}_{r1}^*, \sum_{r\in O^s} \bar{y}_{r2}^*, \sum_{r\in O^s} \bar{y}_{r3}^*, \sum_{r\in O^s} \bar{y}_{r4}^*)} \quad (7)$$

$$= (\frac{\sum_{r\in O^s} \bar{y}_{ro1}}{\sum_{r\in O^s} \bar{y}_{r4}^*}, \frac{\sum_{r\in O^s} \bar{y}_{ro2}}{\sum_{r\in O^s} \bar{y}_{r3}^*}, \frac{\sum_{r\in O^s} \bar{y}_{ro3}}{\sum_{r\in O^s} \bar{y}_{r2}^*}, \frac{\sum_{r\in O^s} \bar{y}_{ro4}}{\sum_{r\in O^s} \bar{y}_{r1}^*})$$

$$\tilde{E}_o^{manufacturer*} = \frac{\sum_{r\in O^M} \tilde{\bar{y}}_{ro}}{\sum_{r\in O^M} \tilde{\bar{y}}_r^*} = \frac{(\sum_{r\in O^M} \bar{y}_{ro1}, \sum_{r\in O^M} \bar{y}_{ro2}, \sum_{r\in O^M} \bar{y}_{ro3}, \sum_{r\in O^M} \bar{y}_{ro4})}{(\sum_{r\in O^M} \bar{y}_{r1}^*, \sum_{r\in O^M} \bar{y}_{r2}^*, \sum_{r\in O^M} \bar{y}_{r3}^*, \sum_{r\in O^M} \bar{y}_{r4}^*)} = \quad (8)$$

$$(\frac{\sum_{r\in O^M} \bar{y}_{ro1}}{\sum_{r\in O^M} \bar{y}_{r4}^*}, \frac{\sum_{r\in O^M} \bar{y}_{ro2}}{\sum_{r\in O^M} \bar{y}_{r3}^*}, \frac{\sum_{r\in O^M} \bar{y}_{ro3}}{\sum_{r\in O^M} \bar{y}_{r2}^*}, \frac{\sum_{r\in O^M} \bar{y}_{ro4}}{\sum_{r\in O^M} \bar{y}_{r1}^*})$$

Definition 3.2. The whole supply chain under evaluation, SC_o is said to be revenue efficient if and only if $\sum_{r\in O^s\cup O^M} \tilde{\bar{y}}_{ro} = \sum_{r\in O^s\cup O^M} \tilde{\bar{y}}_r^*$. Furthermore, supplier and manufacturer components are said to be revenue efficient if and only if we have $\sum_{r\in O^s} \tilde{\bar{y}}_{ro} = \sum_{r\in O^s} \tilde{\bar{y}}_r^*$ and $\sum_{r\in O^M} \tilde{\bar{y}}_{ro} = \sum_{r\in O^M} \tilde{\bar{y}}_r^*$, respectively.

It is clear that the deterministic overall revenue efficiency of sustainable supply chains can be calculated by:

$$E_o^{SC*} = \frac{1/4(\sum_{f=1}^{4} \sum_{r\in O^s\cup O^M} \bar{y}_{rof})}{1/4(\sum_{f=1}^{4} \sum_{r\in O^s\cup O^M} \bar{y}_{rf}^*)} \quad (9)$$

4 A numerical example

In this section, 5 SSCs with two members, supplier and manufacturer, are considered. As can be seen in Table 1, there are economic (EC), environmental (EN) and social (SO) factors in this example. The linguistic terms are shown as the following trapezoidal fuzzy numbers because of uncertainty about factors: Very Low (VL): (0.1, 0.2, 0.3, 0.4), Low (L): (0.2, 0.3, 0.4, 0.5), Medium Low (ML): (0.3, 0.4, 0.5, 0.6), Medium (M): (0.4, 0.5, 0.6, 0.7), Medium High (MH): (0.5, 0.6, 0.7, 0.8), High (H): (0.6, 0.7, 0.8, 0.9) and Very High (VH): (0.7, 0.8, 0.9, 1.0). Data have also been given in Table 1. The proposed approach is used to estimate the overall and component revenue efficiencies of SSCs. The results are revealed in Table 2. As can be seen, SSC 4 has better performance in contrast to others in the supplier component.

The last column of Table 2 shows the deterministic overall revenue efficiency. As can be found, SSc 4 has the best overall revenue efficiency. Actually, it is overall efficient as shown in Table 3. Observed fuzzy revenue and maximum fuzzy revenue of supplier and manufacturer components are also provided in Table 4. As shown, SSC 4 is efficient in the supplier component, while SSCs 2 and 4 are efficient in the manufacturer component.

Table 1. Sustainable supply chain data

SSC	Supplier (S)		Manufacturer (M)					S-M	Prices		
	Input	Output	Input	Input	Input	Output	Output				
	Operating costs (EC)	Diversity (SO)	Electricity consumption (EN)	Water consumption (EN)	Health and safety costs of labor (SO)	Income (EC)	Green products (EN)	Productions from S to M (EC)	Diversity	Income	Green products
1	ML	L	ML	L	ML	MH	ML	H	H	1	H
2	MH	ML	M	ML	M	H	H	L	MH	1	VH
3	H	H	M	M	M	VH	H	ML	ML	1	MH
4	L	MH	MH	ML	ML	H	MH	MH	M	1	MH
5	VH	H	H	MH	L	MH	ML	VL	H	1	M

Table 2. Revenue efficiency results

SSC	Revenue efficiency			Deterministic overall revenue efficiency
	Supplier	Manufacturer	Overall	
1	(0.1786, 0.4167, 0.8889, 1.8750)	(0.4533, 0.7237, 1.1640, 1.9706)	(0.3683, 0.6337, 1.0881, 1.9457)	0.8337
2	(0.1674, 0.3571, 0.7292, 1.5000)	(0.5667, 0.8289, 1.2063, 1.7647)	(0.4340, 0.6843, 1.0747, 1.7015)	0.8559
3	(0.1786, 0.3704, 0.7407, 1.5000)	(0.5556, 0.8026, 1.1587, 1.6863)	(0.4202, 0.6591, 1.0333, 1.6377)	0.8228
4	(0.3571, 0.7143, 1.4000, 2.8000)	(0.5519, 0.8217, 1.2170, 1.8118)	(0.5000, 0.7953, 1.2574, 2.0000)	1
5	(0.3214, 0.5833, 1.0667, 2.0250)	(0.4831, 0.7752, 1.2579, 2.1529)	(0.4078, 0.6891, 1.1756, 2.1000)	0.895

Table 3. SSC Results

SSC	Overall	
	Observed fuzzy revenue	Maximum fuzzy revenue
1	(0.8000, 1.0900, 1.4200, 1.7900)	(0.9200, 1.3050, 1.7200, 2.1720)
2	(1.1700, 1.5000, 1.8700, 2.2800)	(1.3400, 1.7400, 2.1920, 2.6960)
3	(1.1800, 1.5000, 1.8600, 2.2600)	(1.3800, 1.8000, 2.2760, 2.8080)
4	(1.0500, 1.3600, 1.7100, 2.1000)	(1.0500, 1.3600, 1.7100, 2.1000)
5	(0.9800, 1.2900, 1.6400, 2.0300)	(0.9667, 1.3950, 1.8720, 2.4034)

Table 4. Components Results

SSC	Supplier		Manufacturer	
	Observed fuzzy revenue	Maximum fuzzy revenue	Observed fuzzy revenue	Maximum fuzzy revenue
1	(0.1200, 0.2100, 0.3200 0.4500)	(0.2400, 0.3600, 0.5040, 0.6720)	(0.6800, 0.8800, 1.1000, 1.3400)	(0.6800, 0.9450, 1.2160, 1.5000)
2	(0.1500, 0.2400, 0.3500, 0.4800)	(0.3200, 0.4800, 0.6720, 0.8960)	(1.0200, 1.2600, 1.5200, 1.8000)	(1.0200, 1.2600, 1.5200, 1.8000)
3	(0.1800, 0.2800, 0.4000, 0.5400)	(0.3600, 0.5400, 0.7560, 1.0080)	(1.0000, 1.2200, 1.4600, 1.7200)	(1.0200, 1.2600, 1.5200, 1.8000)
4	(0.2000, 0.3000, 0.4200, 0.5600)	(0.2000, 0.3000, 0.4200, 0.5600)	(0.8500, 1.0600, 1.2900, 1.5400)	(0.8500, 1.0600, 1.2900, 1.5400)
5	(0.3600, 0.4900, 0.6400, 0.8100)	(0.4000, 0.6000, 0.8400, 1.1200)	(0.6200, 0.8000, 1.0000, 1.2200)	(0.5667, 0.7950, 1.0320, 1.2834)

6 Conclusions

In this paper, we introduced a fuzzy DEA approach to evaluate the revenue efficiency of sustainable supply chains. To illustrate, the overall revenue efficiency of sustainable supply chains and the revenue efficiency of each component have been estimated while fuzzy measures are presented. A numerical example has been applied to clarify the introduced approach.

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