Evaluating and Selecting Recycling Centers in Lead-Acid Battery Supply Chain using DEA: A Case Study

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Abstract: Reducing the manufacturing costs of the products is considered of the main factors for lead-acid battery (LAB) manufacturers 'sustainability and survival in the automotive industry. Then in order to meaningfully decrease the due costs and enhance the competitive potential of the manufacturers in this field, it's important to choose the suitable sites for recycling centers in this industry's supply chain. In the present study, data envelopment analysis (DEA) has been utilized for evaluating and choosing the recycling centers as befitting for the supply chain of LABs in the automotive industry. Pursuant to DEA and a set of criteria, as being critical for decision makers in this filed, various locations are evaluated. As this method prescribes, the locations are ranked using the maximum scores of efficiencies and after that, more appropriate centers are picked and the inappropriate ones get removed. A LAB supply chain related case study in the automotive industry has been employed for evaluating the influencing power and efficiency of proposed method and following that, a number of beneficial management results have been extracted.

Keywords: Sustainability, Supply chain, Lead-Acid Battery, Efficiency, DEA.

1. Introduction

As a kind of rechargeable battery, lead-acid battery (LAB) was primarily developed by Gaston Planté, the French physicist in 1859 [1]. Although LAB is low in terms of its energy density as compared to its weight and size, it is utilized in motor vehicles because of its cheapness and high power supply. Concerning its structure, LAB is made up of a combination of chemicals, retainers, mechanical formers and electrical components. As a rule, 1) Anode, 2) Cathode, 3) Electrolyte, and 4) Separator can be viewed as 4 main parts of LAB. Electrons are absorbed to electrodes or positive plates, also called anodes, when discharge happens. The main chemical raw material which forms the positive plates in LABs is lead oxide (PbO_2). Through discharge process, electrons are released from electrodes or negative plates, or termed cathodes. Lead (Pb) is the main chemical component of the negative electrodes. Something deserving to be stated is that on mechanical terms, Pb and its oxide are not suitable for forming and adding different alloys and retaining networks often results in their formation. The adjacent of electrodes is filled with electrolyte and this way, a bed is supplied so that the charge passes through the positive and negative electrodes. In such batteries, both poles are immersed in a sulfuric acid (H_2SO_4) solution with a concentration of around 25%-40% and water (H_2O) at a concentration of around 60%-75%. Due to water and sulfuric acid combination, sulfuric acid is converted into ionized as H^+ and HSO_4^- ions. The other part of the above batteries is made up of the separators, the main function of which is to electrically isolate the positive and negative poles from each other. The design of these electromechanical isolators is part of the technology behind manufacturing lead-acid batteries. Since some types have no limit regarding the battery size, this isolation occurs through a physical distance created between the electrodes making the battery cheaper while its volume increases. The advantage of such batteries is their relative low cost in comparison to other identical types and also their high instantaneous current potential, which leads to considering the lead-acid batteries as the best option for various uses including cars and ships. Yet, as compared to nickel-cadmium batteries when fully discharged, a disadvantage of

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LAB is that its weight and volume are high and sensitivity and instability are high, too[2].

This study proposed a Data Envelopment Analysis (DEA) model in order to locate the proper recycling centers in a sustainable closed-loop supply chain (SCLSC) for LABs. We can point out these two cases:1) Contributing to the environmental aspects of the network and utilizing the recycled raw materials, and 2) Saving the costs using the recycled materials in the SC network, as two significant merits for the suitable location for the recycling centers in the SCLSC of LABs. DEA ,initially designed by Charnes et al. [3], was employed for the constant return to scale conditions, which is known as the CCR model in the literature. Then, a model known as BCC model in the literature, was developed by Banker et al. [4] considering variable returns to scale.

Lots of efforts have been made by the relevant researchers to propose diverse methods so that to boost and raise the discrimination power in DEA. The above methods are classified into four categories: 1) Employing the mutual efficiency method and evaluating each decision-making unit (DMU) through itself and its counterparts, 2) Simultaneously comparing good and bad DMUs, 3) Using the super-efficiency method in which the evaluated DMU itself is eliminated from the set and its efficiency and effectiveness are approximated via a linear function by other DMUs, and 4) Benefitting from the decision-makers' preferential information. The current research uses the method developed by Shen et al. [5]related to the second group, in order to evaluate the potential SCLSC associated recycling centers . Unlike other methods, the second category methods have this advantage: not being limited to a certain group and equipped with the potential to be applied in various problems. Shen et al. [5] used an indicator simultaneously taking the distance from the efficient and inefficient frontiers into account in order to promote the DEA's discrimination power. In the presented method, the standard and the inverted DEAs are concurrently applied to come up with more information about the frontiers. This problem boosts the discrimination power of DEA, which brings about a better ranking.

Some related articles on the literature will be reviewed in the following. A three-echelon mathematical model was developed by Ghadami et al. [6] to design municipal solid waste-to-biofuel supply chain network. A challenge regarding municipal solid waste-to-biofuel supply chain models is to locate the appropriate potential centers to site facilities. Consequently, in order to achieve this goal, Ghadami et al. applied a sustainable cross efficiency DEA model as an effective ranking method, the results of which displayed that in case of substituting biofuel for ordinary petrol, the 1-megajoule energy that is generated will reduce around 88 gr of CO_2 emission. Three interdependent challenges of the blood supply chain network including : 1) The motivation of donors; 2) The optimization of location and capacity decisions; and 3) Controlling the network's reliability and robustness under combinatorial risk, were studied by Hosseini-Motlagh et al. [7] .As the research suggested, the motivational initiatives are involved in three directions: 1) Advertisement, 2) Education, and 3) Medical credits to boost blood donation. An augmented version of DEA was employed for detecting the efficiency as the most critical factor when evaluating the pool of location alternatives for building the facilities. Therefore, an innovative mixed possibilistic-stochastic flexible robust programming (MPSFRP) was designed for this issue. Thus, in order to concurrently deal with the blood demand, budget, and costs uncertainties and also the disruptions in the facilities, a mixed possibilistic-stochastic flexible robust formulation was developed, which guarantees the supply chain network under the combinatorial risk performing in a robust and reliable manner. A biodiesel supply chain was designed by Mohtashami et al. [8] through proposing a multi-objective, multi-product, multi-period mathematical model, which focused on three pillars of sustainability ,especially concentrating on social indicators. Additionally, a two-stage approach was presented by the above researchers, which first off was to analyze the potential locations for biomass cultivation using CWDEA method and after that, to select the optimum locations for JCL cultivation and facility construction through the mathematical model. The multi-objective model deals with cost minimization plus social benefits and environmental-induced effects. Pursuant to the results, the managers are informed about this matter that producing and selling biodiesel to the domestic consumers or exporting it is more reasonable than selling JCL oil. A productivity evaluation model was developed by Alidrisi [9] for nine DCs belonging to an international automotive vehicles and spare parts company according to two multi-criteria decision-making (MCDM) approaches termed as : The Preference Ranking Organization Method for the Enrichment of Evaluations II (PROMETHEE II) and DEA, where the former tests the effectiveness, while the latter evaluates the studied DCs' efficiency. The resulting hybrid model collectively establishes what termed a DEA-based PROMETHEE II model which has been explained conceptually and practically in the current article as a productivity evaluation model. Besides, based on the results, RBC performed meaningfully despite being located relatively far away from the main warehouse. Rahimi et al. [10]pursued the goal to achieve an optimal DEA efficiency score simultaneously with facility location pattern for two-stage supply chain, and proposed a Bender's decomposition algorithm (BDA)based solution approach in order to address the large-scale size and compare the result of the solution gained by BDA with that of the original problem by CPLEX. The efficiency score was calculated by the DEA, while the total cost objective was overlooked. In supply chain, it is required to locate the minimum facilities (i.e., plant and warehouse) so that to efficiently transship and assign the products to the retailers. Besides, as the solution approach (BDA) showed, this algorithm outperformed compared to the CPLEX in the large scale. A classification of the previous studies and the present study are listed in Table 1 with the model, the type of network, and the type of data.

Table 1. *A classification of the previous studies and the present study*

Reference	Model	Type of network	Type of data
Ghadami et al. [6]	Cross-efficiency DEA model	municipal solid waste-to-biofuel supply chain network	Desirable
Hosseini-Motlagh et al. [7]	The augmented version of DEA	blood supply chain network	Desirable
Mohtashami et al. [8]	cw DEA	biodiesel supply chain	Desirable
Alidrisi [9]	PROMETHEE II & DEA	international automotive vehicles and spare parts company	Desirable
Rahimi et al. [10]	DEA	facility location pattern for two-stage supply chain	Desirable
Cattani [11]	DEA and random forest	solar pv plants	Desirable
Tavassoli&Farzipoor Saen [12]	fuzzy network DEA	combined cycle power plants	Desirable
The present study	The integrated model based on standard DEA and inverted DEA	lead-acid battery supply chain	Desirable& Undesirable

In the current research, in order to select the suitable potential locations of the recycling centers in SCLSC, a DEA model based on efficient- inefficient frontiers is proposed, for which a set of very important criteria are assessed for selecting the centers in this field. Concerning the pros of this method, we can mention that it can result in selecting more desirable locations and removing the undesirable ones from the decision-making. At the end, a case study related to the lead-acid battery supply chain in the automotive industry was applied to evaluate the effectiveness and efficiency of the proposed method, and the achieved results and findings were analyzed.

Finally, the current study innovations were summarized as the following:

- Unlike the conventional DEA models, the proposed method here can determine the distinction and difference between the alternatives using the information about the efficient and inefficient frontiers.
- Contrary to the conventional DEA models, the presented model here can find out and select the efficient units in a better manner.
- A non-parametric test based on Spearman's rank correlation method is used to validate the resulted ranking.
- A case study on lead-acid battery supply chain in the automotive industry is employed to measure the effectiveness and efficiency of the introduced method, and some practical management insights are provided.

The article has been organized this manner. The DEA model is employed in the following section. Section 3 presents the performance ofa case study. At last, section 4 illustrates the study results and the directions for future research.

2. Proposed Method

The process behind selecting the optimal location for LAB supply chain is planned in two phases, through the first phase of which the appropriate criteria are picked upso that to evaluate the desired locations for building the recycling centers. And then, the second phase is particularly for evaluating and raking the locations using DEA. Fig. 1 depicts the framework of the above-mentioned process.

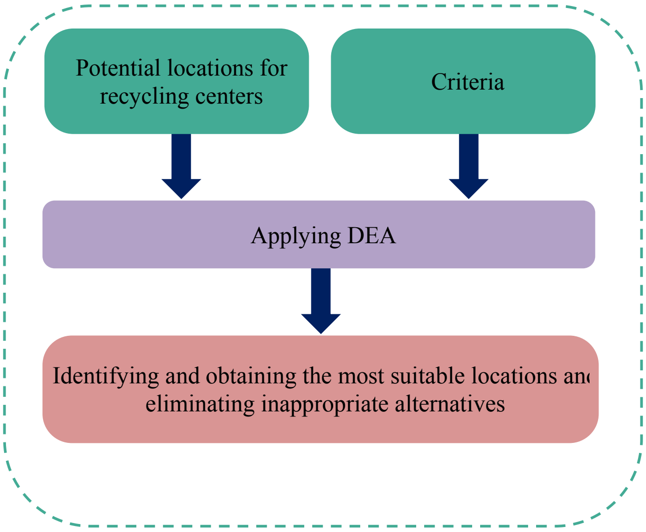

Fig. 1. Framework of the current research process

2.1 DEA Model

DEA refers to the method based on linear programming which is employed to evaluate the relative efficiency of DMUs performing the same tasks. The above technique is particularly for comparing and evaluating the efficiency of a number of identical DMUs with various numbers of consumption inputs and production outputs, i.e., the units which can be the branches of schools, refineries, a bank, hospitals, power stations, the offices covered by a ministry or similar factories. The reason for this comparison and evaluation of the efficiency is to what extent a DMU has benefitted from its resources in terms of production compared to other DMUs. The DEA method is based on comparing the inputs and outputs of a set of DMUs by evaluating their pertinent efficiency. Through this method, when no other DMU can produce more output by the same or less input or when no DMU can produce the same or more output using less input, a DMU is considered as efficient, so that in case these conditions are not held, that unit is regarded as inefficient. DEA as a performance evaluation has this merit that it's not only capable to compare multiple inputs and multiple outputs, but also it has the potential to separate the efficient units from the inefficient ones. The DMUs in this study are the potential locations of recycling centers. In addition, the present study DEA model is equipped with the potential to boost the discrimination power between the alternatives using the information extracted from the efficient and inefficient frontiers. The most important concept of the classic DEA model is to detect the production frontier, i.e., where DMUs are efficient. After that, the score of the units not being located on the frontier is calculated via being compared with those of the efficient DMUs. It's worth mentioning that the units on the frontier have the same score and the maximum score, too.

Not requiring predetermined weights is one of most significant characteristics of DEA. Since, the weights are typically regarded as the decision variables and their value is defined in this way that the highest efficiency is achieved for the question DMU. Anyway, because of lots of DMUs often lying on the efficiency frontier, this relatively high flexibility might cut down the potential to make a difference in DEA and impair the DEA's ranking performance. Suppose n number of DMUs in such a way that their index is indicated as C (c=1,..., n). Additionally, the inputs and outputs of DMU$_c$ are x_{dc} (d=1,..., g) and y_{ec} (e=1,..., q), respectively. The standard DEA model is shown by Eqs. (1) -(4):

$$Min\, h_{bl}^{*} = \theta_l \tag{1}$$

$$\sum_{c=1}^{n} x_{dc}\lambda_c \le \theta_l x_{dl} \quad , \quad d = 1,\dots,g \tag{2}$$

$$\sum_{c=1}^{n} y_{ec}\lambda_c \ge y_{el} \quad , \quad e = 1,\dots,q \tag{3}$$

$$\lambda_c \ge 0 \;\; , \;\; c = 1,\dots,n \;\; , \;\; \theta_l \text{ unconstrained.} \tag{4}$$

And the inverted DEA model is displayed by Eqs. (5) -(8):

$$Max\, h_{wl}^{*} = \theta_l \tag{5}$$

$$\sum_{c=1}^{n} x_{dc}\lambda_c \ge \theta_l x_{dl}, \; d = 1,\dots,g \tag{6}$$

$$\sum_{c=1}^{n} y_{ec}\lambda_c \le y_{el}, \; e = 1,\dots,q \tag{7}$$

$$\lambda_c \ge 0 \;\; , \;\; c = 1,\dots,n \;\; , \;\; \theta_l \text{ unconstrained.} \tag{8}$$

Where θ_l displays the return value of DMU$_l$, and x_{dl} and y_{el} stand for the inputs and outputs of DMU$_l$, respectively. Andλ_c shows the dual weight attributed to the total inputs and outputs of DMU$_c$. In order to find out the efficiency scores of h_{wl}^{*} and h_{bl}^{*},both of the above models are solved for DMU$_l$. Simply stated, the two models are solved n times to come up with the frontiers. The standard and inverted DEA models particularly produce the efficient and inefficient frontiers, respectively. In Fig. 2, you get to see the geometric representation of efficient and inefficient frontiers.

Fig. 2 depicts that the best DMUs, i.e., D, E, F, and A are selected in the standard DEA model, so that to construct the efficient frontier, and moreover, the worst DMUs, i.e., A, B, C, and D are selected in the inverted DEA model to get tobuild the inefficient frontier. In order to take both frontiers and the efficiency scores of standard and inverted DEA models into account, the index given in Eq. (9) is utilized for decision-making.

$$h_{il}^{*} = \frac{\left[h_{bl}^{*} + (1 - \frac{1}{h_{wl}^{*}}) \right]}{2} \tag{9}$$

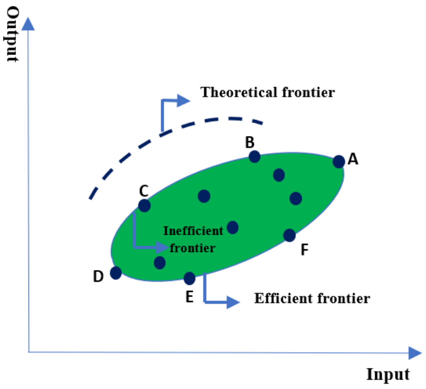

Fig. 2. Graphical representation of efficient and inefficient frontiers

Something required to be noticed is that if the DMU$_l$ lies on the inefficient frontier (e.g., the DMUs of B and C),then, $h^*_{wl} = 1$ and $hi^*_l = \frac{h^*_{bl}}{2} \leq \frac{1}{2}$ and if it lies on both frontiers (e.g., DMUs A and D), that means, $h^*_{bl} = 1$, $h^*_{wl} = 1$.Plus, if the DMU is located only on the efficient frontier (DMUs F and E),then, hi^*_l is higher than 0.5, so that this DMU performs more efficiently than other DMUs lying on both frontiers.

3. Case Study and Computational Results

The present study data are extracted from a case study about the supply chain of LABs in the automotive industry applied to indicate the efficiency and potential of the presented approach. Thus, the criteria which exert effects on selecting the optimal recycling centers are initially introduced in SCLSC, and in the second step, the optimal recycling centers are located via the standard DEA and inverted DEA models. In order to validate the integrated method-induced ranking, a non-parametric test, i.e., Spearman's rank correlation method is used.

2.1 Criteria

And it should be pointed out that a disturbing factor in the city system is to discover the location of the waste recycling centers in urban areas because of its major effects on ecology, health, urban landscape, traffic, property value, etc. As a result, to locate the recycling centers of the urban recyclable waste has to be carried out by meticulous and comprehensive studies so that to environmentally speaking restrain the expansion of the due threats and disorganizations. So if such recycling centers are built in a location without doing any studies because of the potential social consequences and also the environmental pollution and noise induced by such centers, some negative outcomes will be created, too, and if being transferred to the inappropriate locations, some huge costs will be imposed on their owners. Therefore, it’s necessary to consider some very hair-splitting measures before doing any activity using an efficient approach and also to take the befitting criteria into account for planning in this regard and as a result, to develop and implement the best strategy for the process. This research aims to accurately locate the best and the most appropriate sites in order to come across with fewer ongoing problems and dilemmas. In Table 2, you can spot the suitable criteria used for selecting the candidate sites for building the recycling centers in SCLSC.

Table 2. Criteria for selecting candidate sites for locating recycling centers

Criterion	Output Type
Distance from commercial & residential areas	Undesirable
Distance from the urban thoroughfares	Desirable
Distance from river	Undesirable
Distance from hospitals and educational centers	Undesirable
Distance from hotels, banks and offices	Undesirable

Regarding the nature of the criteria in Table 2, it is perceived that all of them are of output type. Additionally, some of the criteria are considered desirable and some undesirable. Overall, in DEA, the logic behind this work is the fewer the inputs, the better, and instead, the more the outputs, the better. If the very logic is violated for a criterion, then that criterion is taken as undesirable.

2.1 Computational Results

Twenty-three potential sites have been considered for locating the recycling centers. The two DEA models mentioned above have been employed tor evaluating and ranking such centers. For this purpose, the mathematical models have been coded in GAMS software and the CPLEX solver has been applied to solve the models. Moreover, a laptop with Intel Core i5 CPU, 2.5 GHz and 4GB RAM specifications was used to run all experimental tests. Table 3 illustrates the summarized results. Plus, the efficiency scores gained by integrating the standard and inverted DEA models from Eq. (9) are given in Table 3.

To filter the suitable sites for locating the recycling centers, the resulted scores have been employed. As the managerial perspective indicates, the min score permitted for the desired index, i.e.,)hi^*_l(has been equal to 0.8. To put it simply, the DMUs with the score higher than 0.8 are chosen as the potential sites where the recycling centers are established. Thus, as seen in Table 4, 10 selected sites as the candidate locations are 3, 4, 5, 7, 9, 10, 11, 15 and 17 where the recycling centers are built and the other options having lower scores are regarded as the undesirable sites considering management. In case of finding out the appropriate and reliable sites for the supply chain’s recycling centers, the performance efficiency of this chain gets promoted.

Table 3. Evaluating and ranking the results from standard DEA and inverted DEA models

DMU	h^*_{bl}	**Rank**	**DMU**	h^*_{wl}	**Rank**
DMU1	0.910	12	DMU1	1.100	11
DMU 2	1.000	1	DMU 2	1.304	4
DMU3	1.000	1	DMU3	1.00	18
DMU4	0.776	17	DMU4	1.015	16
DMU5	0.709	19	DMU5	1.145	9
DMU6	1.000	1	DMU6	1.111	10
DMU7	1.000	1	DMU7	1.185	7
DMU8	1.000	1	DMU8	1.000	18
DMU9	0.918	10	DMU9	1.089	12
DMU10	0.745	18	DMU10	1.005	17
DMU11	0.891	13	DMU11	1.000	18
DMU12	0.791	15	DMU12	1.165	8
DMU13	0.875	14	DMU13	1.000	18
DMU14	1.000	1	DMU14	1.076	13
DMU15	0.551	20	DMU15	1.000	18
DMU16	0.787	16	DMU16	1.030	15
DMU17	0.916	11	DMU17	1.284	5
DMU18	1.000	1	DMU18	1.070	14
DMU19	1.000	1	DMU19	1.000	18
DMU20	1.000	1	DMU20	1.222	6
DMU21	0.910	12	DMU21	1.55	2
DMU22	1.000	1	DMU22	1.36	3
DMU23	1.000	1	DMU23	1.78	1

In the second column of Table 3 for the standard DEA model, DMUs 2, 3, 6, 7, 8, 14, 18, 19, 20, 22, and 23 have come up with similar efficiency value as "1". Besides, in the fifth column of Table 3 for the inverted DEA model, DMUs 3, 8, 11, 13, 15, and 19 have shown the same efficiency value as "1". As perceived, the integrated method resulted in higher discrimination power between these alternatives and removed a series of the suppliers not considered befitting from the model. A non-parametric test known as Spearman's rank correlation method is employed to verify the ranking achieved by the integrated method which calculates the degree of positive correlation between the ranks from the standard DEA model and the integrated DEA model given by the criterion below:

$$\rho = \frac{6\sum \mathrm{id_i}}{\mathrm{n(n^2-1)}} \tag{10}$$

What needs remembering here is that *di* indicates the difference between the ranks achieved for DMU$_i$ by the two stated methods above. Regarding this point, assuming the null hypothesis, H_0, versus the alternative hypothesis, H_1, is illustrated as it follows:

H_0: No positive correlation exists between the ranks coming through the standard DEA model and the integrated DEA model.

H_1:A positive correlation exists between the ranks yielding from the standard DEA model and the integrated DEA model.

Table 4. Efficiency scores and final ranking results of recycling centers

DMU	Potential locations of recycling centers	h^*_{il}	Rank
DMU1	1	0.75	14
DMU 2	2	0.78	12
DMU3	3	0.83	8
DMU4	4	0.92	6
DMU5	5	0.82	9
DMU6	6	0.68	18
DMU7	7	0.88	7
DMU8	8	0.67	19
DMU9	9	0.96	4
DMU10	10	0.99	3
DMU11	11	0.81	10
DMU12	12	0.65	20
DMU13	13	0.62	22
DMU14	14	0.78	12
DMU15	15	1	1
DMU16	16	0.79	11
DMU17	17	1	1
DMU18	18	0.65	20
DMU19	19	0.73	15
DMU20	20	0.72	16
DMU21	21	0.95	5
DMU22	22	0.62	22
DMU23	23	0.71	17

The confidence level (i.e., 1- α) has been considered 0.94 for this testing. The hypothesis testing statistics and the P-value as 0.925 have been considered. Due to the p-value being lower than the α-value, the null hypothesis H_0 is rejected and it can be possible to assume an effective relationship between the ranking of the standard DEA and the integrated DEA. Consequently, the results' validity is verified.

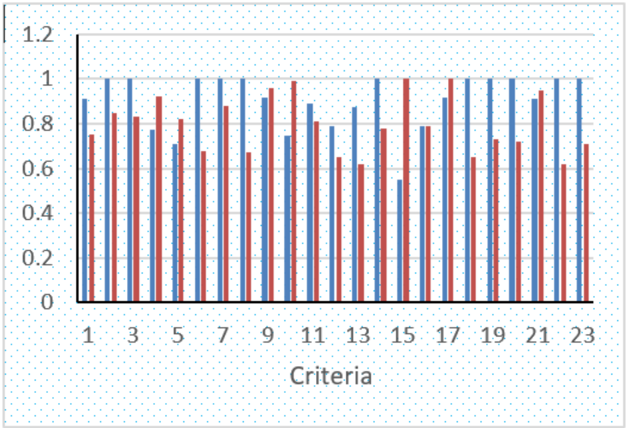

Fig. 3. Comparison of ranking between standard DEA and integrated DEA (blue column for standard DEA and red column for integrated DEA)

As observed in Fig. 3, the ranking results of the standard DEA and the integrated DEA have been given as being simultaneously utilized. And this Figure displays that the DMUs 2, 3, 6, 7, 8, 14, 18, 19, 20, 22, and 23 in the standard DEA have come up with similar value as "1"; however, their ranking is regarded problematic. Nevertheless, the applied DEA has increased such distinctions and as a result, the ranking process has been facilitated. According to this result, the potential of the proposed integrated DEA model has been demonstrated.

4. Conclusion

The current study has employed an integrated DEA model in order to evaluate and select the potential locations considered proper for building the recycling centers for the supply chain of lead-acid battery. Several locations have been evaluated in this method with a series of technical and geographical criteria and more clearly, the elimination of the unsuitable sites from decision-making takes place in this stage and the sites whose scores are the highest in terms of management are nominated as the appropriate sites. A case study pertinent to lead-acid battery supply chain has been utilized in this research for evaluating the effectiveness and efficacy of the suggested method, through which some critical results have been achieved. Considering this goal, the discrimination and distinction between the DMUs has increased via the integrated DEA method. As explained by the following statements, by Spearman's non-parametric hypothesis test measuring the degree of positive correlation between the rankings resulting from the standard DEA model and the proposed DEA model, an effective relationship has been proved to exist between the ranking of the standard DEA and the integrated DEA. Accordingly, we can mention that the proposed model's solutions are verified and the yielded results are valid.

In short, we can get the chance to point out the most significant advantage of the proposed method that in contrast to other approaches, this method is equipped with the capability to simultaneously apply both the efficiency frontier resulting from the standard DEA model and the efficiency frontier from the inverse DEA model. And it's worth stating that the current research is of the studies which has been proposed for locating the optimal recycling centers in LAB supply chain. From many aspects, this research can be broadened so that to enrich the literature. And it's recommended to usea decent mathematical planning model so that to be able to select the optimal locations through multi-criteria decision-making techniques, etc. for the studies designed to optimally select the desired locations. Moreover, the DEA model has the potential to be developed through considering the data uncertainty.

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