Inventory-related costs in green supplier selection problems with Data Envelopment Analysis (DEA)

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1. Introduction

Purchasing decisions have increasing significance: suppliers have a substantial effect on the financial and supply chain performance of firms, and as a result of outsourcing decisions, their added value has increased. In this context, finding the best suppliers is a key task of purchasers. As suppliers' role in company competitiveness became increasingly recognized, it increased the complexity of selecting the best partners. The literature indicates that the focus of evaluation has shifted from assessing bids based on operative supply criteria to considering more complex attributes of the supply situation. In a longer term strategic context, reducing uncertainty and risk (Govindan et al., 2015, Ravindran et al., 2010) become important, and process cost optimization (Ghodsypour, O'Brien, 2001, Aissaoui et al. 2007) and green aspects (Handfield et al., 2002, Jabbour, Jabbour, 2009) come into view.

Firms that choose to strategically manage their suppliers may develop differentiated processes and new tools. Two-stage purchasing process models differentiate the roles of prequalification and selection (Jin et al., 2014). Other papers highlight the role of evaluation after the selection. In the operative phase of the purchasing process (Weele, 2005), evaluation can support feedback and development. Supplier segmentation and management can also be related to post-evaluation data (Rezaei, Ortt, 2012).

Supplier evaluation means a comparison of relevant criteria for decision-making. However, criteria are not equally important, and criteria or criteria groups play different roles in the evaluation; this poses challenges to researchers and managers aiming to develop better methods. This paper will focus on the supplier selection (supplier choice) phase of the purchasing process. The aim of this paper is to evaluate the challenges of managing different groups of criteria and suggest a method of supplier evaluation that integrates existing solutions in a manner that meets the identified complex expectations.

Our paper contributes to the literature on managing differences of criteria, as it comprises several novel perspectives. First, it will show that the evaluation criteria most frequently cited in the literature set special requirements for supplier selection methods. Second, the paper will address a special methodological problem of handling nonlinear data in multiple-criteria decision-making (MCDM) methods. Data envelopment analysis (DEA) is one of the most frequently used MCDM methods in supplier selection problems, and we apply it in this paper as well. The DEA method is based on a quotient type efficiency measure that divides the criteria into two sets: inputs and outputs. The input criteria are in the denominator of the efficiency measure, while the output criteria are in the numerator. In the paper of Dobos and Vörösmarty (2014), traditional management criteria were chosen as the input criteria, and the output criteria were the green, or sustainable, criteria. This partitioning of the set of criteria is used throughout the paper. The traditional management criteria, i.e., the input criteria, can be extended with process costs, including inventory-related costs and the nonlinear, but convex, costs of the lot sizes. In the literature, the cost effect of the economic order quantity (EOQ) has never been investigated in a DEA-type supplier selection problem as a criterion. The introduction of EOQ-related process costs into DEA necessitates the nonlinear parametrization of technological coefficients in a linear programming environment, a method that has not yet been applied to DEA-type supplier selection problems.

The paper is organized as follows. In the next section, the literature results will be presented for works on supplier evaluation. The groups of evaluation criteria will be discussed, considering their demands on the evaluation methods. Then, reviews of supplier evaluation methods will be presented. In the second section, a new method will be suggested that connects the efficiency measures of DEA to the trade-offs of logistical costs. The suggested method uses a concept of parametric linear programming, i.e., the parametrization of technological coefficients, but in a nonlinear way. The paper ends with a conclusion regarding the results, potential further research and implications for researchers and practitioners.

2. Theoretical background

Supplier evaluation criteria and methods are the cornerstones of the literature on supplier evaluation. The criteria capture those aspects that are important to the purchasing organization, while the methods help the purchaser to collate different judgements of the evaluators and to compare the criteria against each other.

2.1. Criteria of supplier evaluation

An important stream of literature addresses the criteria of supplier evaluation. Since Dickson's (1966) study, there have been many publications aimed at identifying criteria in practice and theory (e.g., Choi, Hartley, 1996, Gunasekaran et al., 2001, Wu and Weng, 2010). Quality, price, delivery, and services are often highlighted as important elements of supplier evaluation (e.g., Wilson, 1994, Verna and Pullman, 1998, Bharadwaj, 2004, Ho et al., 2010). Publications also reveal that the growing importance of suppliers makes certain supplier skills and capabilities valuable. Supplier management focuses on these data (Sarkis, Talluri, 2002, Simpson et al., 2002). The total costs of ownership (TCO) approach to supplier evaluation highlights the importance of costs and cost drivers, as the aim is to reveal the true cost of buying a particular good or service from a particular supplier. Internal and external processes and related costs to the buyer are considered. (Ellram, 1995) TCO is, ultimately, the measurement of quality, delivery, etc. performance offered by a supplier on a financial basis.

Recent publications distinguish traditional management and green criteria (Rezaei et al. 2016, Govindan et al. 2015, Nielsen et al. 2014, Hashemi at al. 2015), as is presented in Figure 1. Traditional management criteria reflect those priorities that are important to reach business goals, such as a low price to achieve low costs. Since the 1990s, along with these management criteria, the literature has highlighted green criteria. (e.g., Handfield et al., 2002, Jabbour, Jabbour, 2008, Rezaei et al., 2016) While the former evaluation criteria clearly reflect business aspects, green criteria go beyond the direct economic interests and consider expectations that represent broader social and environmental values.

Figure 1. Structure of supplier evaluation criteria based on the literature results

There are special requirements imposed by the above criteria that should be met.

- The unit of evaluation is different depending on the criteria (e.g., price is measured in Euros, delivery can be measured in days). The evaluation method is expected to ensure that the criteria can be compared to each other and to allow consideration of trade-offs (Wilson, 1994, Tahriri et al., 2008, Nielsen et al., 2014)

- There are a number of qualitative criteria among those measuring supplier capabilities (e.g., reliability of the supplier, adequate capacity, willingness to cooperate) (Sarkis, Talluri, 2002). The evaluation method should allow the comparison of qualitative and quantitative criteria. (Nielsen et al., 2014)
- Green criteria impose further requirements, as they should be aligned with business criteria, and fundamental competitiveness measures cannot be compromised. (Zhu et., 2012, Govindan et al., 2015)
- Cost-based approaches predict that the supplier's selection decision can not only rely on static performance elements but can also consider the effects of decision-making (e.g., delivery date or lot sizing) on process costs. (Ellram, 1995, Woodward, 1997, Visani, et al., 2016)

The identified requirements are summarized in Figure 2.

Figure 2. Summary of the literature results for the requirements a methodology should meet to compare criteria in supplier evaluation

2.2. Methods of supplier evaluation

Supplier evaluation methods are the central theme of the literature. Many publications are available that address evaluation methods developed to support or to be applied to supplier evaluation. To evaluate these methods, the results of review articles will be considered.

To match different criteria and expert opinions, many techniques have been formulated, so the literature reviews often aim to classify them. Agarwal et al. (2011), based on a review of 68 articles, identified nine groups of techniques (DEA, mathematical programming, the analytic hierarchy process, case-based reasoning, the analytic network process, fuzzy set theory, simple multi-attribute rating technique, genetic algorithm, and criteria-based decision-making methods). They found that there were various approaches focusing on the evaluation of both qualitative and quantitative factors. Ho et al. (2010) had similar results based on a review of 78 articles. In addition to the above presented independent techniques, they also identified integrated approaches (which combine techniques). Chai et al. (2013) identified 26 techniques and developed three categories to structure these methods (multi-attribute decision-making techniques, mathematical programming techniques, and artificial intelligence techniques). Essentially the same classification was suggested by Araz and Ozkarahan (2007), except that they offered an additional category. In their review, TCO is also mentioned. These reviews confirm that many techniques exist to assist purchasing, to compare criteria with different measures, to help scale qualitative criteria and to compare experts' opinions.

In addition to methodological categorizations, application features were recognized in reviews. The literature highlights that different phases of the supplier selection process (problem definition, formulation of the criteria, qualification, and selection) require different methods (de Boer et al., 2001, Aissaoui et al., 2007) Differences in the purchasing situation also influence the choice of methods. De Boer et al. (2001) categorize the methods based on the work of Faris et al. (1967). Masi et al. (2013) emphasize the link between the buying situation and the selection technique; they assigned the selection techniques to the metamodel with the axis being degree of difficulty in managing the purchase and the impact of the purchase on the project. These reviews consider a much broader array of techniques than those considered among the decision-making methods. The implication of these studies is that there is a need for diversity. Risky and difficult situations justify the use of complex methods requiring thorough (and time consuming) evaluation, while routine situations require simpler and less demanding techniques.

Only a few results investigating the practical utility of these evaluation methods are available in the literature. Degraeve et al. (2000) found that from a TCO perspective, mathematical programming methods outperform rating methods, and multiple item methods generate better results than single methods in an investigated case study. Selos and Laine (2012) evaluated five methods with the result that the analytic hierarchy process (AHP) (and perhaps other decision-making methods) is too complex for practitioners to understand, and TCO was too complex and required too much input data. Bhutta and Huq (2002) compared the salient features of AHP and TCO; their results show that both methods are suitable for the evaluation of complex situations with both qualitative and quantitative measures, but AHP requires intense management involvement, and TCO requires the extensive tracking and maintenance of cost data.

The methods reviewed in the literature answered the identified challenges in that they address the problems of comparability in terms of trade-offs among measures, a comparison of qualitative and quantitative criteria, and aligning green criteria with business criteria. However, the review of the criteria and methods literature found that existing methods rarely integrate the process cost aspects of supplier selection. There are only a few models that can help us to understand the impact of management decisions regarding processes on the supplier evaluation decision. Therefore, cost-based evaluations should be combined with MCDM methods. Thus, there is a gap in the literature: current methods not handle or are unable to handle traditional management criteria, process cost criteria with trade-offs and green criteria in a unified model.

As the supply chain management approach gains recognition in practice, companies are realizing that the key to better profitability is not only selecting the best offer but also developing better and cheaper processes. Supplier evaluation methods should support this new approach, and the previously mentioned requirements should be met. Process costs can be managed by the application of functions describing the main processes and cost drivers. These functions will focus on handling the main and stable processes of supply chains. One of the methods for capturing important cost functions and their trade-offs is the EOQ model, which integrates ordering and inventory holding costs. These are important measures of the process costs of supply chains.

As cost-focused methods require data that are difficult to obtain, there are some limitations in usage. Considering the diversity of the purchasing situation, these methods are useful in cases of large value and stable processes (e.g., direct material supply). The main cost drivers and the trade-offs between them should be identified to avoid costly data collection. Such situations are adequate when not only one decision but a series of decisions needs to be made. In the supply chain process, major costs are assigned to inventory holding and ordering, and methods to handle these costs have been frequently published. However, only limited results are available on how to connect these results to traditional management and new green efficiency measures for suppliers.

This paper will address a supplier selection problem and aims to handle the requirements posed by the theoretical literature and practical applications. The suggested method will consider the following explicit expectations:

- It provides a rank and a best supplier.
- It is suitable for comparing diverse criteria.

It will also consider the implicit expectations identified in the literature:

- It can be tailored to all purchasing categories, as it can be expanded to fit complex purchasing situations, but it is suitable for making quick decisions.
- It connects complex sets of criteria capturing traditional management, green, and supply process cost aspects.

The next section of the paper will present a concept of an integrated method of supplier evaluation in which traditional management criteria are extended to include green criteria and logistics process costs. In the previous sections, the expectations were identified based on a literature review. The proposed method is an attempt to involve the considerations raised in the literature.

3. A DEA framework for green supplier selection under lot sizing

Because it is easy to use, the DEA method is of practical importance in purchasing management, and thus it is relevant to investigate its applicability. One of the most important limitations of this method is that the weights are arbitrarily set for the various supplier performance attributes used in the weighted, additive scoring methods (Narasimhan et al. 2001). Thus, the final ranking of the supplier is heavily dependent on the assignment of these weights, which are often difficult to specify in an objective manner. In this section, with the help of DEA, a framework was developed to assist in the selection of suppliers in a way that allows us to control the result of the selection process. Our goal is to choose lot sizes that affect the results of the selection process. In the linear programming literature, this is referred to as sensitivity analysis.

The supplier selection method is formulated as a decision-making problem. Let us assume that suppliers are evaluated according to management and green criteria. The management criteria are the usual supplier evaluation criteria, such as trustworthiness, purchasing price, lead time, and product quality. The green criteria are listed in the last section of this paper. It is assumed that the green criteria are the outputs of the examined method.

3.1. The application of the green DEA method in supplier selection

Let us assume that the purchaser evaluates $p+1$ suppliers. The number of traditional management criteria is n, and the number of green criteria is m. The evaluation of supplier i is defined with vectors $(\mathbf{x}_i,\mathbf{y}_i)$, where vector $\mathbf{x}_i$ is the value of the management criteria and vector $\mathbf{y}_i$ is the green criteria. This partitioning of the selection criteria was initiated by Dobos and Vörösmarty (2014), and this paper follows their method.

The DEA method is a general framework to evaluate suppliers in materials and supply management in the absence of weights for the criteria. The application of the DEA method is based on the categories “inputs”, “outputs”, and efficiencies. The basic method was developed by Charnes et al. (1978) to determine the efficiency of decision-making units (DMUs). Their model is a hyperbolic programming model under linear conditions. A general solution method for this type of model was first investigated by Martos (1964), who examined the problem as a special case of linear programming models. The aim of the DEA model is to construct the weights for the management (input) and green (output) criteria. The weights are the vectors **v** and **u** for the management and green criteria, respectively.

Let us formulate the DEA model, assuming that the efficiency of the 0^{th} DMU is examined:

$$\mathbf{u} \cdot \mathbf{y}_0 / \mathbf{v} \cdot \mathbf{x}_0 \rightarrow \max \qquad (1)$$

s.t.

$$\mathbf{u} \cdot \mathbf{y}_j / \mathbf{v} \cdot \mathbf{x}_j \leq 1; j = 0,1,2,...,p. \qquad (2)$$

$$\mathbf{u} \geq \mathbf{0}, \mathbf{v} \geq \mathbf{0}. \qquad (3)$$

(1)-(3) is the basic DEA method, which can be reformulated in a linear programming model in the following form:

$$\mathbf{u} \cdot \mathbf{y}_0 \rightarrow \max \qquad (4)$$

s.t.

$$\mathbf{v} \cdot \mathbf{x}_0 = 1, \qquad (5)$$

$\mathbf{u} \cdot \mathbf{y}_j - \mathbf{v} \cdot \mathbf{x}_j \leq 0; j = 0,1,2,...,p.$ (6)

$\mathbf{u} \geq \mathbf{0}, \mathbf{v} \geq \mathbf{0}.$ (7)

(4)-(7) can be solved with commercial software, e.g., with Microsoft Excel Solver. Throughout the paper, this software is applied to construct numerical examples.

3.2 The extension of the green DEA method to include inventory costs in supplier selection

The models (4)-(7) can be extended to include process or EOQ-type inventory costs. The newly introduced inventory-related costs are regarded as an input criterion, as mentioned above. To the best of our knowledge, inventory-related costs were not involved in DEA-type supplier selection problems. In this case, the suppliers' ability to supply an ordered quantity is examined in an inventory cost-saving way. Let us assume that the firm knows the setup and inventory holding costs of its suppliers; i.e., $(S_j; h_j)$, $j = 0,1,2,\ldots p$ are known. The inventory costs for a known lot size can be calculated as

$$\mathrm{x}_j(q)=S_j \cdot D / q + h_j \cdot q / 2,$$

where parameter D is the yearly demand of the firm, and q is a given lot size.

The management indicators are now $(\mathbf{x}_{i;}\ \mathrm{x}_j(q))$. As can be seen, the management indicators are parametrized with lot size q.

Let us introduce a new weight for the inventory costs v_{n+1}. The new weight vector is extended with the weight of the inventory costs ($\mathbf{v}$; v_{n+1}) for all suppliers. The new model has the next form

$$\mathbf{u} \cdot \mathbf{y}_0 \rightarrow \max \qquad (4')$$

s.t.

$$\mathbf{v} \cdot \mathbf{x}_0 + v_{n+1} \cdot x_0(q) = 1, \qquad (5')$$

$$\mathbf{u} \cdot \mathbf{y}_j - (\mathbf{v} \cdot \mathbf{x}_i + v_{n+1} \cdot x_j(q)) \leq 0; j = 0,1,2,...,p. \qquad (6')$$

$$\mathbf{u} \geq \mathbf{0}, (\mathbf{v}; v_{n+1}) \geq \mathbf{0}. \qquad (7')$$

The problem (4')-(7') is a parametric linear programming problem. In parametric linear programming, there are three types of parametrization:

- parametrization of the right-hand-side (RHS),
- parametrization of the cost function, and
- parametrization of the technological coefficients.

For the first two parametric problems, there are very good results in the literature (See Dantzig and Thapa, 2003). The third problem is hard to solve and depends on the changes in the technological parameters; so, in this case, there are no good, standard results to characterize the optimal solution. Some results in the field are summarized in a book by Gal (1979).

Because there are no standard results in parametric linear programming, some numerical examples were chosen to construct optimal weights of the DEA methods.

3.3. Numerical example for the green supplier selection method extended with lot sizing

The numerical analysis provides an example. Let us assume that the firm has information about the management criteria of its suppliers, such as lead time, product quality, offered price, and the EOQ-related costs, depending on the lot sizes. The relevant green criteria in our analysis are the reusability level of the supplied products and the CO2 emissions during the production process.

The basic data for the example are represented in Table 1 in the case of a lot size $q = 50$, interest rate $k = 0.1$, and demand $D = 100$ in a year. The example fulfils the general rule for the number of DMUs (suppliers) to obtain proper results. The number of suppliers is equal to 18, i.e., $p = \max\{m \cdot n; 3 \cdot (m+n)\}$, where p is the number of suppliers and m and n are the number of outputs and inputs (Cooper et al., 2001).

Table 1. Data for the numerical example (q = 50)

Table 1 presents a parametrization of suppliers in the lot size. This means that a number of data tables can be constructed, depending on the lot sizes. The EOQ-related cost parameters are shown in Table 2.

Table 2. EOQ cost parameters

The EOQ costs for suppliers 1, 2, 3, etc. were calculated in the following way:

$x_1(50)=20 \cdot 100 / 50 + 2 \cdot 50 / 2 = 90,$

$x_2(50)=40 \cdot 100 / 50 + 3 \cdot 50 / 2 = 155,$

$x_3(50)=60 \cdot 100 / 50 + 5 \cdot 50 / 2 = 245,$

etc.

The optimal lot sizes of these suppliers are 89.44, 154.92, and 244.95 units, respectively.

Let us transform the data of Table 1 in a form in which a better evaluation of a criterion is higher than a worse evaluation. If a better criterion has a higher value, than the evaluation of that criterion is not changed. (This is the case for, e.g., reusability, lead time and price). If the better criterion receives a lower value, then two methods are available to use in the table: either a negative sign is used before the given data, or the inverse of the data is used. In the analysis, the second solution is chosen to handle this problem. The new, transformed table is now as follows:

Table 3. The transformed data for q = 50

The optimal efficiency measures for the suppliers are represented in Table 4, depending on the lot sizes.

Table 4. Parametrized solution of the DEA model for the first supplier

(DEA efficiency measures)

In the numerical example, two sets of criteria were formulated: management (traditional purchasing criteria extended with EOQ-related costs) and green criteria. The results show that the 17th and 6th suppliers are efficient for a wide range of lot sizes if the chosen lot size of the buyer is greater than 100. If the lot size is not greater than 100, then the best supplier is the 17th

supplier. If the basic information is studied, it is clear that the 17^{th} supplier has the best lead time, quality, and price; thus, this supplier is Pareto optimal in a decision theory context.

The weights vector suggests that the weights of the lead time and price aspects should be neglected in the evaluation of the suppliers. The reusability aspect received a higher weight than other criteria. In this evaluation situation, the reverse logistic subsystem of the vendor should receive a high weight to influence the selection decision.

4. Conclusions

The theoretical background presented that the literature of supplier selection identifies two sets of criteria: management and green criteria. Management criteria can be extended with process cost criteria. This criteria system extended with process costs poses new requirements that selection methods must meet. Supplier selection methods reviewed in literature addressed certain aspects of the identified challenges, while some gaps were identified: the reviewed MCDM methods were insufficient to connect the management criteria, the process cost and the green criteria.

Thus the basic supplier selection method presented in this paper investigates two groups of criteria: managerial and green. The proposed selection method adds process costs to the managerial criteria in the form of EOQ-type inventory ordering and holding costs. The solution method is based on a parametrized data envelopment method (DEA), where the parametrization is in the technological coefficients. The sum of EOQ-type ordering and holding costs is a nonlinear convex function of lot size. The parametrization of technological coefficients in the literature is based on linear approximation; the literature has not yet investigated the nonlinear characteristics of a parameter of DEA. The functions describing cost evolution are nonlinear, presenting a major barrier to methodology development, especially because the process cost approach is increasingly gaining importance. Thus, it is worth paying attention to how nonlinear cost functions can be linked to the most commonly used methods.

In the presented method, the nonlinearity of the EOQ-type cost function caused a serious problem for solving the parametrized linear programming DEA model. Due to this difficulty, the functioning of the DEA model was shown by presenting a numerical example. This is a new approach in the literature, as there is no theoretically established method for handling that type of DEA problem.

The proposed method is an extension of a green supplier selection method published in the literature. The literature is rich in methods that incorporate traditional management criteria with green criteria, as the importance of environmental issues has become more recognized. The suggested method was developed to provide a solution for connecting traditional management criteria and green criteria with process costs. The evaluation of the traditional management criteria implies a static analysis of information, but incorporating process costs assures a dynamic approach. The numerical example showed that the change in lot sizes affected the efficiency measure of the suppliers. This result underpins the findings of the literature review that traditional management criteria should be extended not only with green criteria but also with process cost factors.

In further research, the nonlinearity of parametrized technological coefficients could be tested in a detailed manner. A subsequent problem is the use of such model, in which the information data are not fully known. In this case, the supplier can be informed about the required improvements to meet the expectations of the decision makers. This last model can be used in supplier prequalification and evaluation systems to extend potential applications to support strategic supplier management activities.

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Figure 1. Structure of supplier evaluation criteria based on literature results

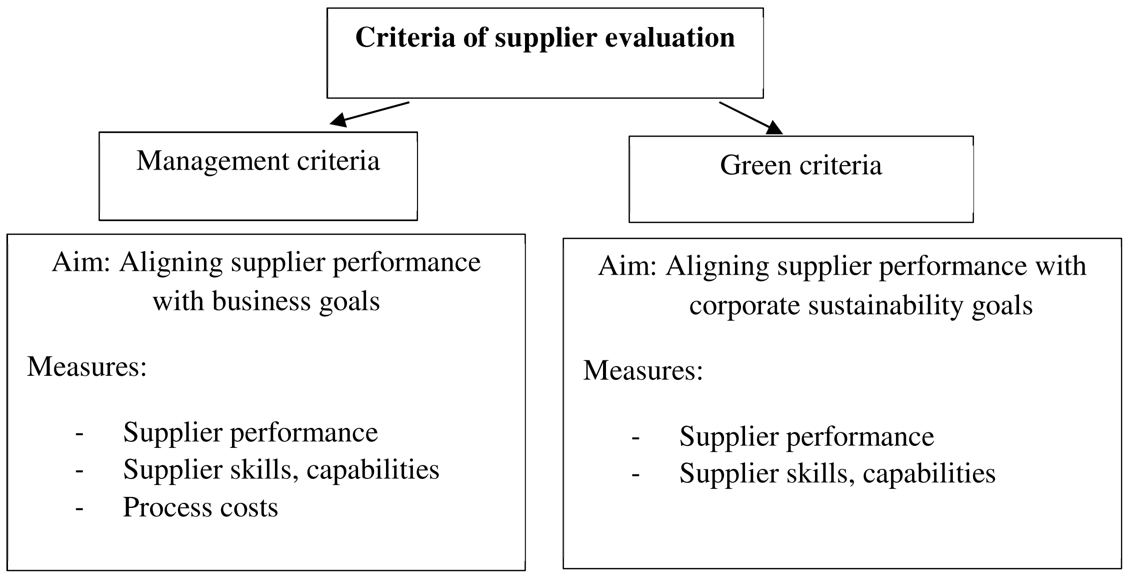

Figure 2. Summary of the literature results for the requirements a methodology should meet to compare criteria in supplier evaluation