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Innovative Applications of O.R.

Using a DEA-cross efficiency approach in public procurement tenders

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ABSTRACT

The paper addresses the topic of supplier selection in public procurement. According to European directives, when tenders are awarded through the ''Most Economically Advantageous Tender'' (MEAT) criterion, the awarding committee has to decide the tender evaluation criteria of the presented bids in advance. The authors propose a decision making tool that is aimed at helping the awarding committee in this difficult task and, at the same time, maintaining a transparent procedure in accordance with governmental procurement regulations and requirements as well as guaranteeing fair and equal evaluation of all bids. In this regard, the decision problem of supplier selection is addressed by applying an extension of the DEA (data envelopment analysis) methodology. The cross-efficiency evaluation is used for selecting the best supplier among the eligible candidates. The proposed technique allows the evaluation of quantitative data related to vendor selection and keeps the transparency features requested by public procurement. In addition, all bids are equally assessed according to the same objectively defined weights without any subjective setting by the public officers. The effectiveness and efficiency of the approach is supported by a case study that pertains to the tender of an Italian public agency.

1. Introduction

Vendor selection and its related evaluation process are a critical management issue for any organization. The identification of top suppliers, i.e., the candidates that are best equipped in meeting a customer's expected level of performance, and their periodic control pose a complex challenge (Baily et al., 2005). Consequently, the supplier selection process has received considerable attention in the business management literature (Bruno et al., 2009; de Boer et al., 2001; Huang and Keshar, 2007), with a particular attention to the quality of supply (Chen et al., 2004). Indeed, incorrect decisions may lead to disruptions in the supply of product/services and, therefore, to serious problems in the operations of an organization (Piramuthu, 2005). The problem is a significant one in both public and private organizations.

As far as public procurement is concerned, research attention is mainly driven by the large amount of sums that are spent each year in this area. In 2003 the potential value of public procurement in Europe was more than 1500 billion €, equal to about 16% of the EU Gross Domestic Product (Lewis, 2007). Thus, government policies aim at encouraging competitiveness among candidate suppliers, in terms of price and other environmental and qualitative factors (Malmberg, 2003), and, at the same time, forbidding any award based on discretional criteria.

Differently from the private sector, the awarding committee (usually a commission of experts, selected by the public authority) must follow prescribed procedures and maintain transparency in public procurement (Panayiotou et al., 2004). In other words, the committee must adopt strict and clear decisional procedures that optimize the specific service objectives, and at the same time consider the impact on the procurement protocols of the considered governmental organization and avoid any subjective evaluation of vendors. In this context all potential suppliers are treated equally and their selection must be based on a rigorous ranking that is obtained by applying the above mentioned transparent decisional procedures.

In most cases of public procurement the selection of the winning proposal may turn out to be a highly complex process when both prices and technical aspects are to be considered. Because the number of bidders is very large in relation to what is needed, usually one product/service for every tender, the award deliberation may become a time-consuming and expensive process. This happens when imprecise and qualitative information, such as enhancement plans, quality and performance, must be considered. In addition, rating the potential suppliers on the basis of their capability to meet technical requirements according to a merely qualitative evaluation is in potential contrast with the need for transparency. A corrupt evaluator could favor a bidder unfairly to the detriment of other competitors, while objective assessment

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makes such event more difficult to occur. In public procurement decisions must be based on a strict and unambiguous ranking of the available offers. Consequently, the awarding method should have the largest possible degree of objectivity.

In the last few years, in many countries public governments have started using innovative supplier selection methodologies that are drawn from the established practices of private sector (de Boer et al., 2001; Panayiotou et al., 2004; Erridge and Callender, 2005; Love et al., 2011). Thus, the procurement methods of these two sectors share some common features. In a review of 74 articles, Weber et al. (1991) conclude that supplier selection is a multi-objective problem because the selection process includes conflicting objectives, such as quality, quantity, delivery, performance, capacity, communication, service, geographical location, in addition to lowest price (Degraeve et al., 2000; Morlacchi, 1999).

The proposed approach consists of a novel use of a well-known methodology, i.e., the cross efficiency evaluation based on the Data Envelopment Analysis (DEA), for evaluating different offers in a public tender awarded through the MEAT criterion. This multi-criteria evaluation procedure, to be explained in the following notes, is objective and it allows the assessment of bidders without the setting of weights or scoring functions by public officers.

In the private sector, the use of DEA for solving the supplier selection problem is not new. One of the first applications (Weber and Desai, 1996) uses slacks variables and parallel coordinates representation to find what inputs the inefficient suppliers can reduce in order to reach efficiency. This is a useful indication for the decision maker in the negotiation phase. In this regard, Braglia and Petroni (2000), Liu et al. (2000), and Talluri and Narasimhan (2004) have given other important contributions. Many versions of DEA instruments for vendor selection have been proposed. Talluri and Narasimhan (2005) adapted the technique for comparing existing and potential suppliers, while Saen considered ordinal and imprecise data, through the Imprecise DEA (Saen, 2007), also with the use of assurance regions (AR-IDEA; Saen, 2008). More detailed reviews of the DEA's applications to the issue of supplier selection can be found in the studies of de Boer et al. (2001) and Ho et al. (2010).

The paper is structured as follows. In Section 2 the supplier selection problem in public procurement is defined and some approaches to its solution, as peer literature review, are outlined. Section 3 introduces the DEA approach and the cross-efficiency methodology. In Section 4 the case study is presented and the application of the chosen approach is illustrated. In the concluding Section 5 the paper objectives and results are summarized and some directions for future research are proposed.

2. The multi-criteria selection in public procurement

In all countries, public procurement must comply with specific legislative requirements. For instance, in the European Union, this matter is regulated by the 2004/18/EC Directive, also called the Public Procurement Directive (European Parliament and Council Directive, 2004). The law sets the application of one of the two following award criteria: the Lowest Price (LP) and the Most Economically Advantageous Tender (MEAT). Typically, the LP criterion is used when technical and qualitative features of the supplied product, service or work, are standardized and price is the only criterion that differentiates offers (Piga and Zanza, 2005). Differently, when the contract is awarded on the basis of the MEAT criterion, various (quantitative and qualitative) factors are simultaneously considered. In this last case, different factors are incorporated into the overall score by using a linear weighting method (European Parliament and Directive 2004/18). In this regard, the committee has to assign a weight to each criterion in advance. These weights, to be disclosed upon the request for proposal (Lorentziadis, 2010), generally are set on the basis of subjective judgments that, of course, are affected from internal consistency and validity problems (Borcherding et al., 1991). Consequently, there is no absolutely optimal choice of weights (Dulmin and Mininno, 2003). In addition, when this awarding arrangement is used, public officers can grant an unfair advantage to a given bidder by assigning a high weight to a criterion that only this competitor can meet fully (Søreide, 2002). In order to overcome these limitations, several studies have proposed the adoption of vendor rating methods that are used in the private sector and that offer an alternative to the simple linear weighting of performance values and weights allocated by public officers.

Lorentziadis (2010), for instance, proposes linear programming for evaluating criteria weights by suggesting the choice of the average of the least or most favorable set of weights for all candidate suppliers. The weights range according to the limits established by the public client. Differing degrees of importance for suppliers can be chosen in the evaluation, but only if these are selected according to criteria that are known in advance by competitors. This evaluation mechanism must be known by all participants when the request for proposal is announced.

Other approaches use performance indices as inputs to the Analytic Hierarchy Process (AHP) for defining the best offer among alternative bids (Sipahi and Esen, 2010). Costantino et al. (2011), for example, determined the best offer in a public tender through a Fuzzy Analytic Hierarchy Process (FAHP) that was based on pair-wise comparison of alternatives according to different factors and on fuzzyfication according to specific membership functions.

Other authors have focused on evaluating the utility of the overall bids. Holt et al. (1993, 1995), for instance, define a three-stage evaluation procedure for construction related tenders. After a pre-qualification phase on the basis of non-subjective criteria, all bids are assigned a score according to the utility resulting from pre-defined project criteria and, successively, a second score is assigned to each offered price. A weighted sum of these two indicators determines the final ranking. Differently, Hatush and Skitmore (1998) use six evaluation criteria (bid value and other attributes of the bidding company, such as its financial strength, technical ability, management capability, health and safety records, and reputation). For each of these attributes, a score is determined. The corresponding utility is given by a curve that is developed after bid opening and reflects all offers. The bidder with the highest overall utility is awarded the contract. A similar method is proposed by Lambropoulos (2007), with two fundamental differences: the considered criteria are cost and delivery time discounts and the utility curves are defined before the request for proposals and known *a priori* by all bidders.

Many authors have argued about the need for differentiating cost and benefit criteria in the evaluation of tenders. For instance, Topcu (2004) proposes a model in which, after the pre-qualification of contractors with weights determined by AHP, each bidder receives a score resulting from the weighted sum of the normalized overall pre-qualification score (estimated benefits) and bid price. A similar, but more complex, approach is proposed by Bana e Costa et al. (2007). Cost and benefits are evaluated in different ways. Cost is considered with the use of an adequate coefficient, while benefits are determined by a set of qualitative sub-factors. The shift to a quantitative scale and the definition of a set of weights for the sub-factors is obtained through a pairwise comparison that is based on the MACBETH method (Bana e Costa and Vansnick, 1994). In this case the trade-off between cost and benefit scores is obtained by a weighted sum (where the weights are selected by decision makers).

In the last twenty years, the MEAT criterion has been used also in the United States, particularly in the construction sector. Ellis and Herbsman (1991) propose bid price and completion time as the basis for awarding highway projects. For each proposal a factor, known as the Road User Cost per day, is estimated. This includes the client's contract administrative costs and the cost to road users for the unavailability of the road (or lane) during construction. The Road User Cost per day is then multiplied by the completion time (in days) proposed by the bidder and the result is added to the bid price. The contractor with the lowest total bid is awarded the project. The same authors (Herbsman and Ellis, 1992) extend their model by considering also the quality of the work (e.g., in terms of roughness index of provided road asphalt). The analysis of 101 highway projects (that had been awarded with the MEAT method) shows substantial benefits in terms of time savings in comparison with similar projects awarded with the LP method (Herbsman, 1995). Table 1 lists all the above outlined MEAT approaches.

These methods have some limitations, notwithstanding the benefits of their application, particularly to infrastructure projects (which are addressed by most of the cited studies). Most of them are based on some subjective selection criteria, such as the interval between weights or membership functions (to be selected by public officers). Differently, other methods require the subjective estimation of the bid (i.e., in the pairwise comparison). The qualitative scores, as defined by an evaluation committee, can easily favor a corrupt bidder (Lengwiler and Wolfstetter, 2006). Consequently, this type of arrangement can corrupt the transparency of the process.

The distinction between the cost and benefit of each bid, furthermore, does not take into account that any given project requires other resources (e.g., time and maintenance services), in addition to money.

Finally, some of these methods do not respect the EU legislation, because of confusing selection and awarding criteria or lack of transparency (for example, when awarding conditions are not known before bid opening) (Lambropoulos, 2007).

In order to overcome the above illustrated limits, this paper proposes a tender evaluation method that is based on the data envelopment analysis (DEA) and related concept of cross-efficiency. In this way, there is no need for using subjective scoring systems. No scoring functions are required and objective features of the different bids can be used for assessment. In addition, the qualitative evaluation of bids is avoided and weights or utility functions are not required. Moreover, different indicators for the bids can be compared, even if their scales are not homogeneous. As a consequence, both monetary and non monetary inputs and outputs can be assessed at the same time. Finally, the described procedure meets the transparency requirements of the EU Directive, with one limitation: weights or priority ranking are not predefined (as required). This approach results from the need for reducing room to subjective decisions by public officers who may favor a corrupt bidder unfairly. In any case, it is possible to extend the presented model to define a priority ranking among weights (and consequently among factors).

The following section describes this approach which allows determining the ranking of tenders from whom the best one can be selected.

3. The data envelopment analysis (DEA) and the cross-efficiency DEA

The data envelopment analysis (DEA), proposed in the seminal study of Charnes et al. (1978), is a linear programming-based technique that is used for determining the efficiency of a set of Decision Making Units (DMUs). Efficiency is a function of given input values (corresponding to the resources used by the DMUs) and output values (i.e., the outcomes of the DMUs activities).

Since its introduction, the DEA method has been adopted for the efficiency assessment in several fields: banking, education, health care, hospitals (Emrouznejad et al., 2008). In addition, DEA is also one of the most used techniques for supplier selection (Ho et al., 2010). Consequently, this study extends the use of such a method to the particular case of public procurement.

When the DEA is applied to supplier selection, this technique allows the differentiation between input and output performance measures. Input performance is given by the amount of resources used by the vendor to carry out the supply activity (e.g., the purchasing price). Output parameters express the fairness of the service provided to the buyer (i.e., the quality of purchased product and timeliness of deliveries).

In the traditional DEA approach, the efficiency of supplier i is typically defined as follows:

$$E_i = \frac{\sum_{k=1}^{K} u_k \cdot y_{ki}}{\sum_{h=1}^{H} v_h \cdot x_{hi}}, \tag{1}$$

where y_{ki} is the k output performance value ($k = 1,2,\ldots,K$) for the actor i ($i = 1,2,\ldots,F$), x_{hi} is the h input performance value ($h = 1,2,\ldots,H$) for the actor i, u_k is the weighting coefficient for the k output performance value, and v_h is the weight coefficient for the h input performance value. The supplier i is efficient if $E_i = 1$; otherwise, the vendor is considered as non-efficient.

In the classical DEA method, the efficiency of each actor is obtained by determining the set of coefficients u_k and v_h which maximizes this value and, at the same time, by taking into account that, for each actor i, $E_i \leqslant 1$ holds by definition. Hence, the measure of supplier efficiency can be obtained by solving the following optimization problem for each considered vendor i:

$$\max \quad E_i \tag{2}$$

$$\text{s.t.} \quad \frac{\sum_{k=1}^{K} u_k \cdot y_{ki}}{\sum_{h=1}^{H} v_h \cdot x_{hi}} \leqslant 1 \text{ with } i = 1,2,\ldots,F, \tag{3}$$

$$u_k, v_h \geqslant 0 \quad \text{for } k = 1,2,\ldots,K;\ h = 1,2,\ldots,H. \tag{4}$$

Table 1
Methods for the MEAT evaluations.

Authors	Techniques
Bana e Costa et al. (2007)	Weighted sum of cost and benefit scores determined with the MACBETH method
Costantino et al. (2011)	Fuzzy Analytic Hierarchy Process
Ellis and Herbsman (1991)	Sum of bid price and Road User Cost during the construction
Herbsman and Ellis (1992)	Sum of bid and Road User Cost during the construction with quality cost
Hatush and Skitmore (1998)	Utility functions for a set of six criteria
Holt et al. (1993, 1995)	Bidder pre-qualification and weighted sum of utility and cost scores
Lambropoulos (2007)	Cost-utility and time-utility curves
Lorentziadis (2010)	Linear Programming that defines the weights used for Linear Weighting evaluation
Sipahi and Esen (2010)	Analytic Hierarchy Process
Topcu (2004)	AHP-based pre-qualification and weighted normalized sum of pre-qualification score and price

The problem (2)–(4) can be easily solved through linearization that can be performed in two ways: minimizing the inputs and keeping fixed the output values (*input-oriented method*) or maximizing the outputs and keeping fixed the input values (*output-oriented method*).

According to second method, the problem becomes as follows:

$$\max \quad E_i = \sum_{k=1}^{K} u_k \cdot y_{ki} \tag{5}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} u_k \cdot y_{ki} - \sum_{h=1}^{H} v_h \cdot x_{hi} \leqslant 0 \text{ with } i = 1, 2, \ldots, F, \tag{6}$$

$$\sum_{h=1}^{H} v_h \cdot x_{hi} = 1. \tag{7}$$

and (4).

The efficiency of analyzed suppliers can be found by solving the problem (5)–(7) and (4) for each ith supplier with $i = 1, 2, \ldots, F$. Therefore, suppliers can be ranked on the basis of E_i.

The DEA method differentiates inefficient and efficient suppliers only (de Boer et al., 2001) and it does not allow the ranking of the efficient ones. In fact, this instrument is often used only for the pre-evaluation phase of supplier selection (Araz and Ozkarahan, 2007). Consequently, in order to increase the discriminatory power of DEA, cross-efficiency evaluation was proposed (Sexton et al., 1986). According to this method, the coefficients, resulting from maximizing the efficiency of each supplier, are used to estimate the efficiency of all vendors: each of them is assigned F efficiency estimates. Consequently, the cross efficiency of the ith supplier is the mean value of its efficiency measures, as shown in Table 2.

While in the traditional DEA approach each DMU can maximize its efficiency by increasing the weight of its most favorable criteria, the cross-efficiency approach takes into account the most favorable weight set of all other DMUs for each DMU. Thus, the DEA cross efficiency approach consists of the peer-evaluation of each alternative solution (Wang and Chin, 2010), in addition to self-evaluation. This method, at the same time, does not require the decision maker to rank evaluation criteria and allows each DMU to highlight its strength as much as possible in self-evaluation.

For each target DMU i, there are many sets of coefficients that give the same value of efficiency for i. As these sets vary, so do the cross-efficiency values of the other DMUs. Consequently, there is a need for defining a univocal criterion for selecting one of these sets. The choice is generally made by a secondary goal optimizing input and output weight, while keeping unchanged the CCR-efficiency of the target DMU. The two most used formulations are those proposed by Doyle and Green (1994).

$$\min \sum_{k=1}^{K} u_k \left(\sum_{j=1, j \neq i}^{F} y_{kj} \right) \tag{8}$$

or

$$\max \quad \sum_{k=1}^{K} u_k \left(\sum_{j=1, j \neq i}^{F} y_{kj} \right) \tag{9}$$

$$\text{s.t.} \quad \sum_{h=1}^{H} v_h \left(\sum_{j=1, j \neq i}^{F} x_{hj} \right) = 1, \tag{10}$$

$$\sum_{k=1}^{K} u_k y_{ki} - E_i \sum_{h=1}^{H} v_h x_{hi} = 0, \tag{11}$$

$$\sum_{k=1}^{K} u_k \cdot y_{kj} - \sum_{h=1}^{H} v_h \cdot x_{hj} \leqslant 0 \text{ with } j = 1, 2, \ldots, F \text{ and } j \neq i \tag{12}$$

and (4).

The secondary objective function (8) is defined as *aggressive formulation*, because it minimizes the sum of weighted output of other suppliers. Differently, Eq. (9) is used for the *benevolent formulation*, which aims at maximizing the sum of the weighted outputs of other vendors. Both formulations provide a set of optimal weights for the ith DMU$(u_1^i, u_2^i, \ldots, u_H^i, v_1^i, v_2^i, \ldots, v_K^i)$. Target DMU i can be considered as a pivot whose weights are used for determining its own efficiency and also the efficiency values that of all other bids are calculated according to i. These values can be observed in the ith row of the matrix in Table 2, whose generic element E_{ij} represents the efficiency value of the jth DMU with respect to the optimal weights for the ith target DMU. This also implies that the diagonal element E_{ii} is equal to the maximum efficiency value E_i determined by (5)–(7) and (4).

The DMUs (i.e., the suppliers' bids in the case of public procurement) can be ranked according to their cross-efficiency: the higher the cross-efficiency, the better is the bid.

It can be easily demonstrated that, by applying the cross-efficiency approach, all bids are evaluated according to the same set of weight. In fact, the jth DMU cross-efficiency value is equal to:

$$CE_j = \frac{1}{F} \sum_{i=1}^{F} E_{ij} = \frac{1}{F} \sum_{i=1}^{F} \left(\frac{v_1^i y_{1j} + v_2^i y_{2j} + \cdots + v_K^i y_{Kj}}{u_1^i x_{1j} + u_2^i x_{2j} + \cdots + u_H^i x_{Hj}} \right). \tag{13}$$

By using the properties of the sum operators, the cross-efficiency can be written in the following way:

$$CE_j = \frac{\left(\frac{1}{F}\sum_{i=1}^{F} v_1^i\right) y_{1j} + \left(\frac{1}{F}\sum_{i=1}^{F} v_2^i\right) y_{2j} + \cdots + \left(\frac{1}{F}\sum_{i=1}^{F} v_K^i\right) y_{Kj}}{\left(\frac{1}{F}\sum_{i=1}^{F} u_1^i\right) x_{1j} + \left(\frac{1}{F}\sum_{i=1}^{F} u_2^i\right) x_{2j} + \cdots + \left(\frac{1}{F}\sum_{i=1}^{F} u_H^i\right) x_{Hj}}. \tag{14}$$

The resulting final weights are not dependent on the evaluated DMU. Each jth bid, with $j = 1, 2, \ldots, F$ is therefore evaluated fairly with the same weights as the other bids.

Cross-efficiency evaluation is not the only instrument that is used for discriminating among efficient DMUs. Another tool is the super-efficiency evaluation (Andersen and Petersen, 1993). The efficiency of each DMU is estimated as in (5), (6), (7), (4), but without being limited to 1. However, this approach has some limitations which make unfit its application to the public procurement case. Each DMU is evaluated according to a different set of weights and specialized DMUs are favored in the ranking (Adler et al., 2002).

This mechanism has some features that make it particularly suitable for choosing the best offer in a public tender. In fact, a public client does not need to define weights for all criteria or fuzzy membership functions or other kinds of scoring functions on the basis of subjective judgment. Such a limitation could be overcome also by defining weights randomly, but the proposed method is fairer. It gives each bidder the right to be evaluated according to the set of weights that favor her against the other competitors. This happens by following a pre-defined algorithm: the choice of weights is not directly made by bidders, because in this case there could be an incentive for collusive behavior. In fact, each set of weights used for a bidder is then used for evaluating the remaining ones.

Table 2
Cross-efficiency matrix for K DMUs.

Target DMU	DMU			
	1	2	...	F
1	E_{11}	E_{12}	...	E_{1F}
2	E_{21}	E_{22}	...	E_{2F}
...	...	...	...	...
F	E_{F1}	E_{F2}	...	E_{FF}
Cross-efficiency	$\frac{1}{F}\sum_{i=1}^{F} E_{i1}$	$\frac{1}{F}\sum_{i=1}^{F} E_{i2}$	...	$\frac{1}{F}\sum_{i=1}^{F} E_{iF}$

Consequently, the approach is objective and, even if weights are determined after bid opening, the specific algorithm is well defined in advance, so that a bidder can execute it and verify whether public officers have complied with it. Therefore, the hazard of discretionary evaluation by public officers is reduced significantly. The former cannot select parameters that give advantage to a bidder to the detriment of other competitors. This mechanism, in addition, allows the consideration of all bids according to the same set of weights (related to the target DMU, that is, to the target bid) at each step of the cross-efficiency evaluation. Consequently, as demonstrated previously, the approach guarantees the equal treatment of all proposals (Lorentziadis, 2010). At the same time, a full relative evaluation, which takes into account both the advantages of each bid and those of the other bids, is allowed.

In addition, the distinction between the resources required for carrying out the project and the performance of the final product/service is maintained. As the above review shows, few MEAT determination methods in the literature consider such distinction. Moreover, these generally consider only monetary costs and neglect other types of required resources.

Due to the linearity of the optimization procedures, the method requires small computational efforts even in presence of many bidders or criteria. Lastly, this mechanism can be made known to all tender participants in the Call for Proposals. In this way transparency is maintained.

A limitation of the proposed DEA application is that the comparison of weights cannot provide an immediate comparison of the relative importance of weights. This is due to the use of inputs and outputs with different scales. A possible remedy could be the use of normalized input and output data. Lastly, the proposed method does not provide the priority ranking of factors (to be defined before the tender), as the EU public procurement directive requires (if weights are not given in advance, as in this case). The approach of the authors is driven by the need for avoiding subjective choices by the public agents. In any case, the application of the so-called "assurance regions" (Thompson et al., 1990) would allow the determination of importance ranking among factors.

4. The case study

In order to validate the proposed methodology for awarding MEAT tenders, the above outlined decision making approach is applied to a case study, concerning the refurbishment work of a facility at the Polytechnic of Bari (Italy), that was undertaken by some of the authors in the past (Costantino et al., 2011). The reserve price is € 148,500.00 plus VAT and the maximum acceptable work duration is 35 weeks. The expected time for a new refurbishment intervention is 15 years (180 months).

The number of bidding suppliers was $F = 45$. This large participation is common in Italy when public projects of small dimensions are tendered. In the following, let us define the ith bid with s_i. Each offer was (see Table 2) evaluated according to four criteria that had been defined in the call for proposals. Following one of the options established by the European legislation pertaining to the MEAT award procedure, the four criteria were:

(1) offered price (defined with $h = 1$), with the corresponding performance value x_{1j} measured in € for the jth supplier and $j = 1,\ldots,45$;
(2) the execution time of planned work (defined with $h = 2$), with the corresponding performance value x_{2j} measured in weeks and $j = 1,\ldots,45$);
(3) duration of the post-delivery free maintenance (defined with $k = 1$), with the corresponding performance value y_{1j} measured in months and $j = 1,\ldots,45$;
(4) quality of enhancement plans (defined with $k = 2$), with the corresponding performance value y_{2j} and $j = 1,\ldots,45$ ranked by the tender committee on a 0–10 scale that pertains to the quality of the proposed changes of the design plans.

Table 3 shows the performance values proposed by each bidder.

It should be noted that the fifth column of Table 3 shows the performance scores of enhancement plans, on a scale ranging from 0 to 10. The scores are assigned to each offered enhancement plan according to a pre-defined scale. Up to 5 out of 10 points are assigned to the materials to be used (tiles, floor, fixtures, etc.), 2 points to the proposed installation methodology (plaster, cement, concrete, etc.), and the remaining 3 points to the logistics of the proposal. Obviously, all the evaluation rules are stated in the request for proposal.

According to Table 3, the offered prices range from 107,967.74 (see s_{42}) to 131,714.23 (see s_9); the execution time ranges from 10 (see s_{19}) to 35 weeks (see s_{24}); and the duration of the post delivery maintenance ranges from 0 (see s_{30}) and 120 days (see s_{24}). The enhancement plans by s_9, s_{10}, s_{12}, s_{13}, s_{20}, and s_{39} are the best, while those by s_{22}, s_{32}, s_{34}, and s_{40} are the worst.

The tender was actually awarded on the basis of a Linear Weighting mechanism. The following weights iw_h and ow_k had been used: $iw_1 = 0.55$ for the price, $iw_2 = 0.15$ for delivery time, $ow_1 = 0.15$ for post-delivery free-maintenance and $ow_2 = 0.15$ for the quality of enhancement plans. The scoring functions were obtained by dividing the performance values by their maximum value and, only in the cases of input factors, subtracting these ratios from 1. Consequently, the overall score of the ith bid can be determined as follows:

$$LW_j = iw_1\left(1 - \frac{x_{1j}}{148500}\right) + iw_2\left(1 - \frac{x_{2j}}{35}\right) + ow_1\left(\frac{y_{1j}}{180}\right) + ow_2\left(\frac{y_{1j}}{10}\right). \quad (15)$$

In applying the cross-efficiency DEA evaluation, price and execution time are considered as input factors: these are the resources used to carry out the work. Differently, post-delivery maintenance and enhancement plans are considered output factors, given their relationship to the quality of the final delivery. Consequently, the $H = 2$ criteria are considered as input criteria, while the $K = 2$ criteria are output criteria.

The DEA approach, according to Eqs. (5)–(7) and (4), is applied to defining the efficiency of each candidate supplier. These values are used for estimating the cross-efficiency values, as shown in Table 2. In this case, the aggressive formulation is used as a secondary optimization [Eqs. (8), (10)–(12)], because it allows obtaining better conditions for each considered target bid. The results of the cross-efficiency DEA are shown in Table 3.

If the findings of the presented approach are compared with the results of the case study solved by Fuzzy Analytic Hierarchy Process (FAHP) (Costantino et al., 2011) and with those obtained in the actual tender, some important differences emerge (see the different rankings in Table 4). Only four out of ten FAHP best bids and six out of ten LW best bids are present in the cross-efficiency top-10 bids. In our case, the best offer is s_{10} (which is ranked second by FAHP), while the FAHP-best bid is s_{39} (ranked third by cross-efficiency method). In addition, the cross-efficiency second best offer $s_{23}$is not ranked in the FAHP top-10 bids. These discrepancies result from the use of a triangular FAHP membership function for time completion which penalizes very low durations. Due to the same reason, s_{39} (with a completion time closer to the maximum of the triangular function) gets a better evaluation than s_{10}.

The cross-efficiency method is not based by an *a-priori* defined set of weights; consequently, each offer is better analyzed as a whole and the evaluation is not affected by a subjective definition

Table 3
Case study: bids, related decision matrix elements, cross efficiency values and ranking.

Vendor j	Price x_{1j} [€]	Execution time x_{2j} [weeks]	Post-delivery free maintenance y_{1j} [months]	Enhancement plans y_{2j}	Cross-efficiency	Ranking
1	110,238.11	27.00	48.00	8.00	0.6160	18
2	110,963.63	31.00	9.00	9.00	0.5328	24
3	109,514.93	15.00	29.00	1.00	0.1606	39
4	110,484.45	27.00	15.00	9.00	0.5673	19
5	110,681.87	22.00	22.00	6.00	0.4300	29
6	111,092.92	31.00	29.00	1.00	0.1471	40
7	112,930.37	20.00	50.00	3.00	0.3385	32
8	112,783.38	28.00	6.00	5.00	0.3006	37
9	131,714.23	19.00	108.00	10.00	0.8290	5
10	109,920.87	18.00	113.00	10.00	0.9940	1
11	110,821.52	16.00	59.00	2.00	0.3192	34
12	109,775.89	24.00	59.00	10.00	0.7837	6
13	108,511.70	33.00	41.00	10.00	0.6953	9
14	111,457.61	29.00	108.00	5.00	0.6227	16
15	111,127.97	12.00	44.00	8.00	0.6738	12
16	108,990.13	31.00	13.00	1.00	0.0985	42
17	115,299.67	14.00	94.00	4.00	0.5473	21
18	111,242.01	22.00	47.00	9.00	0.6872	10
19	112,036.06	10.00	29.00	8.00	0.6348	14
20	111,461.96	33.00	48.00	10.00	0.7017	8
21	111,009.58	24.00	12.00	7.00	0.4497	27
22	110,504.87	32.00	16.00	0.00	0.0504	45
23	110,247.06	11.00	113.00	8.00	0.9153	2
24	110,438.76	35.00	120.00	9.00	0.8707	4
25	112,457.83	16.00	69.00	7.00	0.6596	13
26	108,469.71	15.00	7.00	8.00	0.5441	22
27	110,667.84	13.00	28.00	7.00	0.5510	20
28	111,660.57	33.00	42.00	4.00	0.3512	31
29	110,500.76	25.00	99.00	7.00	0.7269	7
30	110,918.29	29.00	0.00	2.00	0.1136	41
31	115,520.49	15.00	5.00	7.00	0.4481	28
32	119,535.68	24.00	20.00	0.00	0.0596	44
33	110,183.27	12.00	78.00	3.00	0.4586	26
34	109,839.68	30.00	88.00	0.00	0.2801	38
35	110,583.74	28.00	78.00	1.00	0.3052	36
36	110,186.17	31.00	54.00	8.00	0.6220	17
37	125,075.21	32.00	66.00	7.00	0.5392	23
38	111,151.44	13.00	36.00	3.00	0.3140	35
39	109,224.97	21.00	89.00	10.00	0.9013	3
40	110,556.28	21.00	23.00	0.00	0.0744	43
41	110,575.67	31.00	82.00	4.00	0.4836	25
42	107,967.74	14.00	22.00	4.00	0.3385	33
43	111,367.66	19.00	44.00	8.00	0.6311	15
44	116,276.03	26.00	75.00	8.00	0.6745	11
45	118,868.15	22.00	94.00	2.00	0.3959	30

Table 4
Top-ranked bidders for the case study according to the cross-efficiency DEA, the LW and the FAHP.

Position	Cross-DEA	LW	FAHP
1	s_{10}	s_{10}	s_{39}
2	s_{23}	s_{23}	s_{10}
3	s_{39}	s_{39}	s_{29}
4	s_{24}	s_{15}	s_{12}
5	s_{9}	s_{12}	s_{25}
6	s_{12}	s_{19}	s_{14}
7	s_{29}	s_{25}	s_{33}
8	s_{20}	s_{24}	s_{7}
9	s_{13}	s_{29}	s_{36}
10	s_{18}	s_{9}	s_{41}

of priorities among criteria. As shown in Table 4, the winning bid according to the LW approach (addressed by the contracting authority) is the same as the best bid selected according to the proposed DEA cross-efficiency model. In addition, the top-3 cross-efficiency DEA bids are the same as the top-3 ranked by the Linear Weighting. This coincidence is not common since it results from a particular weight setting chosen by the contracting authority. A different weight choice could have determined a dissimilar ranking of bids. In this case, even if the weights for the actual tenders were arbitrarily chosen, the evaluation determined results which can be considered objectively valid.

5. Conclusions

A new approach to public procurement has been introduced in this paper. Because the European legislation prescribes transparent and objective procedures for all types of public procurement, the cross-efficiency DEA approach is proposed for ranking different bids, when the MEAT procedure is considered. Differently from previous proposals, the presented approach can rank bidders without the need for subjective judgments, with an important gain in terms of transparency. In addition, the approach takes into account the distinction between required resources and generated benefits (by considering their ratio) as bidding criterion. With these features, the proposed procedure positively addresses some of the limitations that are typical of the other methods for supplier selection in public procurement.

The effectiveness of the approach was tested with a case study of Italian public procurement. The aggressive formulation in second level optimization was adopted since it was considered the best suited approach for the purpose.

Future work should address the use of normalized input and output data and weights in order to compare the relative importance of the factors and to obtain a set of weights that is comparable with those used in other procedures. In addition, the more complex case of multi-items exchange could be analyzed. Lastly, a further evaluation step of the efficiency of the method could encompass its comparison with the traditional linear weighting methodology by means of bidding games among practitioners, agent-based model or simulations.

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