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Rethinking Government Supplier Decisions: The Economic Evaluation of Alternatives (EEoA)

November 20, 2019

Dr. Francois Melese, Professor

Dr. James Fan, Assistant Professor

Graduate School of Defense Management

Naval Postgraduate School

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Executive Summary

Public procurement is big business. In 2018, the U.S. Department of Defense (DoD) spent more than $300 billion on procurement and research, development, test, and evaluation, most of it sourced to the private sector. This exceeds the gross domestic products (GDPs) of Egypt, Chile, or Finland. The Organisation for Economic Co-operation and Development reports its members spent more than $6 trillion on procurement in 2015. One of the biggest challenges for public procurement officials is to conduct “source selections” when benefits cannot be monetized. The problem of ranking vendors when benefits cannot be monetized has spawned an extensive literature that underpins widely applied decision tools. This technical research report analyzes and extends a popular multi-criteria decision-making (MCDM) tool commonly used to guide public procurement decisions. Our research extends the standard technique and offers an economic approach to assist public procurement officials in ranking competing vendors when benefits cannot be monetized. An important defense application is “source selection”—choosing the most cost-effective vendor to supply military equipment, facilities, services, and supplies.

Our *Economic Evaluation of Alternatives* (EEoA) methodology addresses two assumptions in the conventional decision science (DS) model as they are frequently applied in practice. DS “value” (utility) functions often a) normalize attributes, which we demonstrate risks losing valuable information; and b) combine costs and nonpecuniary attributes, which requires assigning a relative importance weight to cost. We explain how overall budget/funding estimates for a public procurement (product, service, project, etc.) need to be included as part of the analysis in order to properly incorporate affordability.

A unique feature of EEoA is to model vendor decisions in response to government funding projections. In contrast to traditional approaches, EEoA structures the procurement official’s decision as a two-stage problem. In the first stage, the official provides budget/funding guidance to competing vendors along with desired characteristics or “attributes” of the product or service. Vendors engage in constrained optimizations based on their respective production technologies to generate proposals that satisfy projected budgets. Vendor proposals (bids) consist of bundles of nonmonetary attributes. In the second stage, the procurement official ranks vendors according to the government’s utility function over the attributes.

The bulk of the MCDM literature, and most government-mandated decision tools, focus on the demand side of a public procurement. The EEoA extends the analysis to the supply side. Given a parsimonious set of continuously differentiable evaluation criteria, EEoA provides a new tool to rank vendors. In other cases, it offers a valuable consistency check to guide government supplier decisions. The value of this tool for procurement officials is to facilitate explicit evaluation of the multiple factors that enter into bid proposals, and for vendors, increased transparency of funding realities in responding to solicitations.

Author Bios

Francois Melese – Dr. Melese is a professor of economics at the Naval Postgraduate School and former executive director of the Defense Resources Management Institute (DRMI). He earned his BA at the University of California, Berkeley, and his doctorate at the Catholic University of Louvain, Belgium. A widely published economist, he has over 30 years of experience conducting executive management courses and workshops for domestic and international military and civilian officials at NPS and in partner countries around the world. In 2005, Melese participated in the Defense department's Quadrennial Defense Review (QDR), and in 2008, contributed to the department's first strategic management plan. More recently, he has advised the joint chiefs of staff, the Defense Business Board, and Canada's Defence Forces. Melese has represented the United States as a speaker and moderator at NATO meetings throughout Europe and is currently on the board of NATO's Building Integrity Program. He has been an active participant, speaker, and moderator in the Acquisition Research Program's yearly symposia and is co-editor of a new book entitled *Military Cost–Benefit Analysis: Theory & Practice*.

James Fan – Dr. Fan is an assistant professor of operations management at the Defense Resources Management Institute (DRMI). He received a BA in economics (2009) from Vanderbilt University, an MA in mathematics from Pennsylvania State University (2016), and a PhD in business administration with a focus in supply chain and information systems from Pennsylvania State University (2017). Prior to joining DRMI in 2018, Fan was a postdoctoral research fellow at the Carey Business School at Johns Hopkins University. His research interests include behavioral economics and behavioral operations, laboratory and field experiments with decision-makers and organizations, and decision analysis for procurement and defense acquisitions.

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Introduction

"If we do not have a good economic model for supplier decisions, we are not on a level playing field. And we already spend [too] much … time on that uneven playing field."

Colonel John T. Dillard, U.S. Army (Ret.),
Senior Lecturer, Naval Postgraduate School,
Past Program Manager for Advanced Acquisition Programs

One of the biggest challenges for public procurement officials is to rank vendors when benefits cannot be monetized. Indeed, public benefits are often depicted as bundles of desirable characteristics, or attributes, that cannot easily be combined with costs into a single overall measure such as profitability. The problem of ranking government investment alternatives when benefits cannot be monetized has spawned an extensive literature generally referred to as *multi-criteria decision-making* (MCDM).

Today, widespread application of MCDM tools and techniques is mandated through various laws, rules, and regulations that govern public procurement, though the specific approach is not prescribed. For example, the main guide for federal procurement officials in the United States is the Federal Acquisition Regulation (FAR).[1] FAR 15.304, Evaluation Factors and Significant Subfactors, details how the "award decision is based on evaluation factors and significant subfactors that are tailored to the acquisition." A general overview follows:

> Evaluation criteria are the factors an agency uses to determine which of several competing proposals submitted in response to an RFP [Request for Proposal] would best meet the agency's needs. In establishing effective evaluation criteria, an agency must clearly identify the factors relevant to its selection of a vendor and then prioritize or weight the factors according to their importance in

[1] Note the exclusive focus on the demand side in the FAR—ranking exogenously-determined bids received from vendors (see https://www.acquisition.gov/browse/index/far). Also note that the standard practice for U.S. military (and other procurement officials) is to i) announce factors ("evaluation criteria") relevant to the selection, but only after receiving vendor proposals, and ii) assign specific relative importance/weights to those factors to rank vendors. This practice is modeled in the Economic Evaluation of Alternatives (EEoA).

satisfying the agency's need in the procurement. … This allows the agency to rank the proposals received. (AcqNotes, 2020, p. xx)

Similar source selection techniques are frequently applied in the United States at state and local levels and in the private sector.

EEoA encourages public procurement officials to carefully consider the impact on vendor proposals of announced priorities—that is, desired criteria, characteristics, or attributes for solicited quantities of products, services, or projects (e.g., computer systems, vehicles, weapon systems, logistics packages, and buildings)—including the impact of anticipated future budgets. In response to government priorities—evaluation criteria, quantities, and funding—competing vendors, with different input costs and production functions, maximize their production offers (i.e., bid proposals) that consist of bundles of non-price characteristics or attributes.

EEoA models public procurement official decisions in two stages. In the first stage, along with the requirement (quantity demanded) and funding guidance, the procurement official reveals desired evaluation criteria (characteristics or attributes) of the product or service (but not the relative importance/weights). Given this information, competing vendors engage in constrained optimizations based on their respective production technologies and input costs to generate proposals that match anticipated future funding. Since input costs and production functions vary among vendors, they play a critical role in their bid proposals. Bids consist of bundles of non-price characteristics or attributes embedded in each identical unit offered by a particular vendor. In the second stage, the procurement official ranks competing vendors according to the government's utility function over the evaluation criteria (see Figure 1).[2]

[2] Note this is analogous to steps mandated in the FAR, except that, since funding is fixed in EEoA (i.e., the price is the same for each vendor), the second step involves the submission by vendors of sealed nonprice bids for the announced level of funding, interpreted and evaluated by procurement officials as bundles of characteristics, attributes, and so on, that respond to previously announced evaluation criteria (for example, see FAR Subpart 14.5).

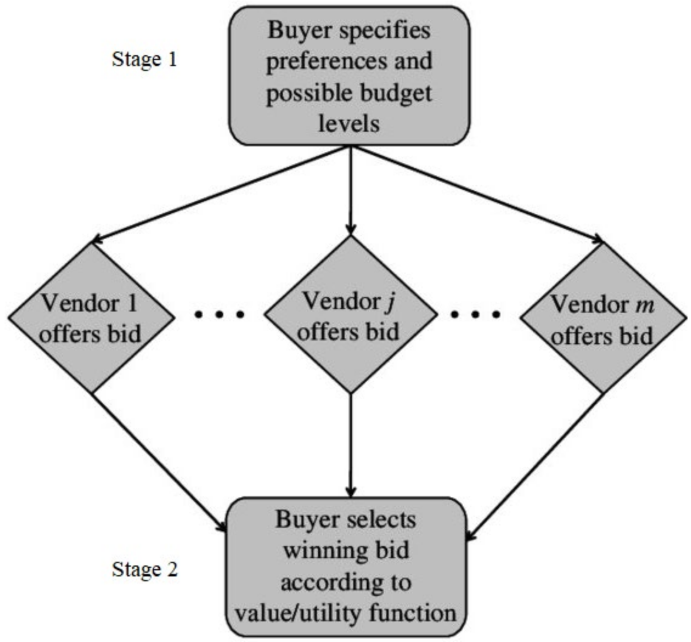

FIGURE 1. The Two-Stage Procurement Process

The dual objective of EEoA is to encourage governments i) to consider the supply side (i.e., to recognize the importance of modeling vendor responses to information provided or inferred in public procurements) and ii) to offer an alternative to the standard MCDM approach when benefits cannot be monetized. An attractive feature of EEoA is that it offers a novel technique to measure benefits that serves as a valuable consistency check for standard MCDM preference trade-offs elicited from decision-makers among key attributes.[3] We explore assumptions under which the two decision models (MCDM and EEoA) are isomorphic from a procurement official's perspective. In practice, however, we demonstrate how careful application of EEoA can yield significantly different solutions (rank orderings) than the standard MCDM approach.

[3] Both the Australian and Canadian Ministries of Defence are considering implementing this consistency check for the MCDM component of their portfolio decision models (Personal correspondence with fellow NATO SAS-134 Defence Official Panel Members studying Defence Portfolio Management for NATO; emails received November 2018).

Related Literature

MCDM as a methodology has been well-studied in theory and in practice. A proliferation of applications of decision tools derived from this literature has appeared in management science, operations research, and decision sciences (prominent examples include Beil and Wein [2003], Che [1993], Dyer and Sarin [1979], Keeney and Raiffa [1976], Kirkwood [1997], and Parkes and Kalagnanam [2005]). Consequently, international and U.S. public acquisition regulations implicitly promote this popular deterministic approach, which serves as the primary guide and mandate for public procurement officials[4] (OECD, WTO, EU, FAR 5000, DFAR, etc.). Similar source selection techniques are frequently recommended/applied in the United States at state and local levels and occasionally in the private sector to evaluate/rank vendors/investments.

Recently, demand-side developments of MCDM models have been extensively studied in the academic literature for government decision-making (Ewing, Tarantino, & Parnell, 2006) and industry supplier choice (Jamil, Besar, & Sim, 2013); however, the literature is mostly silent about the supply-side (vendor) problem. Vendor decisions (bid proposals) are generally treated as exogenous. In contrast, the EEoA captures both the demand side of procurement official decisions and the supply side of vendor optimization decisions.

Our model formulation is in the spirit of Lancaster's (1966, 1971) "Characteristics Approach to Demand Theory" as modified by Ratchford (1979) and closely corresponds to the third of six approaches to structure an EEoA introduced in Chapter 4 of *Military Cost–Benefit Analysis: Theory & Practice* (Melese,. 2015, p. 96). We first develop a two-stage EEoA model for vendor selection. Two special cases are explored: a) where competing vendors have identical attribute costs but different

[4] "Evaluation criteria are the factors an agency uses to determine which of several competing proposals submitted in response to an RFP [Request for Proposal] would best meet the agency's needs. In establishing effective evaluation criteria, *an agency must clearly identify the factors relevant to its selection of a vendor and then prioritize or weight the factors according to their importance* in satisfying the agency's need in the procurement. … This allows the agency to rank the proposals received while simultaneously providing offeror's with a fair basis for comparison." (FAR, Proposal Development, Section M-Evaluation Factors for Award, downloaded from DAU website May 20, 2018, emphasis added)

production technologies, and b) where vendors have different attribute costs but identical production technologies. The EEoA model is subsequently extended to account for uncertainty where future states of nature (e.g., changes in the political or defense environment) could impact the government's utility function. This fills a gap in the literature, which focuses on the demand-side of an acquisition but mostly ignores supply-side decisions.

The paper proceeds as follows: The next section develops the two-stage EEoA model. On the supply side, two cases are presented to illustrate the model: i) where competing vendors have identical attribute costs but different production technologies, and ii) where vendors have different attribute costs but identical production technologies. A simple example serves to integrate procurement official (demand) considerations, with vendor (supply) decisions, under varying (probabilistic) scenarios. The third section contrasts EEoA with a standard textbook application of MCDM. The final section concludes with recommendations for future research.

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The Economic Evaluation of Alternatives Model

The challenge for a public procurement official is to select a competing vendor that delivers the best combination of desired non-price attributes for each identical unit of a requirement (for example, 50 identical computers, or 20 identical drones, or two identical hospital ships, etc.), at affordable funding levels. The Economic Evaluation of Alternatives (EEoA) framework can be thought of as a multi-attribute sealed bid procurement auction that extends traditional price-only auctions to one in which competition among $j \in [1, m]$ vendors (bidders) takes place exclusively over bundles of $i \in [1, n]$ non-price characteristics or attributes (a_{ij}).

The EEoA model structures the problem as a two-stage optimization (see Figure 1). In the first stage, the public procurement official provides j competing vendors with the evaluation criteria, available funding, and the requirement (quantity demanded).[5] Given the anticipated budget, **B**, and their respective production technologies and input costs, competing vendors offer their best possible non-price attribute packages bundled into each identical unit required.[6] Note that the greater the funding available, the greater the available funding per unit, which allows vendors to bundle more of the desired attributes into each identical unit (e.g., better computers, drones, or ships).[7]

The First Stage EEoA vendor (supply side) problem is formulated later in this section. Competition takes place exclusively over non-price bid proposals from each

[5] Since there is a fixed requirement (quantity demanded), the budget, **B**, can be interpreted as the unit funding/budget available to vendors to produce a unit of the required product or service. For example, if we anticipate that $25,000 of funding is available for 50 computers, the budget (**B**) used by competing vendors to build their proposals would be $500 per unit.

[6] For example, suppose we have $25,000 of funding for 50 notebook computers, or a budget, **B**=$500/unit. Then, for example, each of 50 identical Apple computers offered at $500/unit would satisfy the basic evaluation criteria (screen size, memory, battery life, software, and so on), but consist of a somewhat different bundle of those characteristics/attributes than each of 50 identical Microsoft (or Dell, or HP, for example) computers.

[7] The greater the funding available, the greater the funding per unit, allowing vendors to offer more of the desired attributes for each identical unit demanded by the buyer. For example, suppose for our 50 computers, instead of $25,000 (**B**=$500) of funding, it turns out $50,000 (**B**=$1,000) will be available. Then, each of the 50 identical laptop computers offered by Apple will have more and/or better characteristics/attributes, and so will each of the 50 identical laptop computers offered by Microsoft (bigger screen size, more memory, longer battery life, and so on).

vendor, evaluated by procurement officials as bundles of attributes offered by each vendor for a standard unit of the requirement. Whereas attributes for each unit of the requirement are identical for each vendor, the proposed bundles differ among vendors. Competing vendors' bid proposals (bundles of attributes) depend on a vendor's specific costs to generate each attribute, the vendor's particular production technology to combine those attributes, and anticipated future funding.

In the second stage, the procurement official's objective is to select the vendor j that maximizes the government's utility function, $U_j = U_j(a_{1j}, a_{2j}, \dots, a_{nj})$, subject to projected funding (i.e., the per unit affordability or budget constraint), **B**. For analytic tractability, we assume the utility function is quasi-concave and that attributes are continuous, non-negative, monotonic increasing variables—that is, the domain of the buyer's utility function, and sellers' production functions and attribute cost functions, are the non-negative real numbers. Non-satiation in the relevant range of attributes is also assumed, such that, $\partial U_j / \partial a_{ij} > 0$, or the greater the score of the $i \in [1, n]$ desired attributes, a_{ij}, the more value (utility/benefit) for the buyer, but the more costly it is for sellers to produce.

Following the literature, we allow the buyer's utility function (scoring/ranking rule) to be linear, additive, and separable across attributes (Keeney & Raiffa, 1976; Kirkwood, 1997). The public procurement official's problem is to select a vendor $j \in [1, m]$ that maximizes the government's utility function:

$$(1)\ \boldsymbol{U_j} = \mathrm{U_j}(\boldsymbol{A}_j^T) = \boldsymbol{W}\boldsymbol{A}_j^{\mathrm{T}},$$

where desired attributes are known to sellers and the bundle of attributes in vector $\boldsymbol{A_j}$ = $[a_{1j}\ a_{2j} \dots a_{nj}]$ represents each vendor's offer (bid proposal) for each unit required. The relative weights for each attribute are the procurement official's private information, given by the vector:

$$\boldsymbol{W} = (w_1, w_2, w_3, \dots, w_n \mid w_i \in \mathbb{R}^+, i \in [1, n]).$$

The procurement official maximizes Equation 1 subject to a funding/affordability constraint:

$$(2)\ TC_j \ \leq \ \mathbf{B},$$

such that the total unit cost (price) of any vendor's bid proposal, TC_j, must fit within forecasted future funding (i.e., the per unit budget, $\mathbf{B}$.) Note that whereas the set of non-price attributes in the buyer's utility function is revealed to the $j \in [1, m]$ competing vendors, the ***relative*** (preference or "trade-off") ***weights***, w_i, are not.[8] This reflects practical application of FAR instructions:

> In government acquisition, procuring commands have their own best practices and priorities … but they all follow the [Federal Acquisition Regulation]. And in their selection of suppliers, they assign weights to their parameter criteria in accord with their priorities. … These weights for scoring of proposals do not have to be specifically revealed as an algorithm, but are typically communicated to offerors in terms of [rank ordering of] importance. (Dillard, 20XX, p. xx)

In this formulation of the procurement problem, both buyer and seller suffer from imperfect and asymmetric information. While the seller does not know the specific relative importance/weights assigned to desired attributes (or "evaluation criteria"), the buyer (procurement official) does not know the competing vendors' costs of producing a particular attribute, nor the technology (production functions) that combines those attributes into vendor proposals.[9] The supply-side vendor problem is examined in detail in the next section, followed by the demand-side procurement problem.

[8] For example, consider the following summary of FAR Sections 15.1 and 15.3, "Evaluating proposals under the RFP [Request for Proposal] best value trade-off analysis criteria:" In a negotiated bid, there are factors [evaluation criteria] with varying weights assigned. The solicitation tells you the weight of each factor; however, government contracting agencies are not required to publicize the actual source selection plan [it is an internal document]. The agency has broad discretion on what it believes to be the best value. Note, however, that the agency must be consistent in following its source selection plan in evaluating every vendor or risk bid protests (see Melese, 2018).

[9] "Seller costs can be expected to depend on [the] local manufacturing base, and sellers can be expected to be well informed about the cost of (upstream) raw materials" (Parkes & Kalagnanam, 2005, p. 437).

First Stage EEoA: The Vendor's Problem (Supply Side)

The first stage of the two-stage EEoA optimization framework focuses on the vendor's problem. The economic approach assumes vendors are strategic players, so that the anticipated/forecasted (per unit) funding/budget, **B**, for the procurement, impacts vendors' formulation of their competing bid proposals (attribute bundles, $\boldsymbol{A_j}$).[10]

Given n desired attributes (a_{ij}) and anticipated future funding (the per unit budget, **B**), the m vendors each offer competing bid proposals (bundles of attributes), $\boldsymbol{A_j}$, based on their production technology and their unit costs of producing each attribute, $c_{ij}(\boldsymbol{B})$.[11] For any fixed requirement (quantity demanded) and funding level (per unit budget, **B**), a representative vendor's problem is to maximize the attribute output function for each (identical) unit required, subject to the vendor's costs of producing each attribute. Competing vendors offer their best possible non-price attribute bundle for the projected per unit funding/budget, **B,** given their idiosyncratic technology. As Wise and Morrison (2000) observed, a multi-attribute auction allows competing vendors to differentiate themselves in the auction process and bid on their competitive advantages.

The vendor's problem can be expressed as selecting an attribute vector (bid proposal), $\boldsymbol{A_j}$ = $[a_{1j}, a_{2j}, \ldots, a_{nj}]$ that maximizes output:

$$(3)\ \ \boldsymbol{Q_j} = Q_j(\boldsymbol{A}_j^T),$$

subject to unit costs (TC) not exceeding anticipated per-unit funding (**B**) for the project,

$$(4)\ \ \boldsymbol{TC_j} = \sum_{i=1}^{n} c_{ij}\,(B)\,a_{ij} \leq\ \mathbf{B}.$$

For ease of exposition, the remainder of the study focuses on two competing vendors and two (non-price) attributes.

[10] Further implications are explored later in the section Demand and Supply: A Two Scenarios, Two Vendor, Two Attribute Example. Note the supply-side development in this section generalizes a special case of the multi-attribute auction found in Simon and Melese (2011).
[11] Each vendor's bundle is a technologically-determined combination of attributes For instance, a computer is a combination of screen size, memory, battery life, and other components, with unit costs associated with each attribute.

Suppose each vendor has a different technology to combine the two attributes and different attribute costs. Then the Lagrangian function for the vendor's problem is given by:

$$(5)\ \mathcal{L}_j = Q_j(a_{1j}\ , a_{2j}, \boldsymbol{B}) + \lambda_j[\boldsymbol{B} - \sum_{i=1}^{2} c_{ij}\ (\boldsymbol{B})\ a_{ij}], \text{ for j=1,2.}$$

If vendors compete on "quality," they are likely to use the maximum expected per unit funding, **B**, to develop their bid proposals, so Equation 4 is treated as an equality. First-order necessary conditions for an optimum are given by:

$$(5a)\ \partial\mathcal{L}_j/\partial a_{1j} = \partial Q_j/\partial a_{1j} - \lambda_j c_{1j}(\boldsymbol{B}) = 0,$$

$$(5b)\ \partial\mathcal{L}_j/\partial a_{2j} = \partial Q_j/\partial a_{2j} - \lambda_j c_{2j}(\boldsymbol{B}) = 0,$$

$$(5c)\ \partial\mathcal{L}_j/\partial \lambda_j = \boldsymbol{B} - \sum_{i=1}^{2} c_{ij}\ (\boldsymbol{B})\ a_{ij} = 0.$$

Solving equations 5a–5c yields optimal attribute bid proposals (outputs) for each vendor $j = 1{,}2$, for each identical unit required, for any given per unit budget, ***B***:

$$(6a)\ \ a_{1j}^{*} = a_{1j}^{*}(\alpha_{1j}(\boldsymbol{B}), \alpha_{2j}(\boldsymbol{B}), c_{1j}(\boldsymbol{B}), \boldsymbol{B}),$$

$$(6b)\ \ a_{2j}^{*} = a_{2j}^{*}(\alpha_{1j}(\boldsymbol{B}), \alpha_{2j}(\boldsymbol{B}), c_{2j}(\boldsymbol{B}), \boldsymbol{B}).$$

For tractability, we assume a standard Cobb–Douglas production function, with attributes $(a_{1j}\ , a_{2j})$ as inputs:

$$(6)\ Q_j\left(a_{1j}\ , a_{2j}\right) = \ a_{1j}^{\alpha_{1j}} a_{2j}^{\alpha_{2j}}.$$

Two special cases help illustrate the model: i) where competing vendors share common attribute costs, but have different production technologies, and ii) where vendors share the same production technology but have different attribute costs.

Vendors with Different Production Technologies

In the first case (illustrated in Figure 2), vendors $j = 1{,}2$ have different, constant (i.e., independent of funding) technologies (i.e., in equation 6: $\alpha_{1j}(\boldsymbol{B}) = \alpha_{1j}$ and $\alpha_{2j}(\boldsymbol{B}) = \alpha_{2j}$) but identical (constant) attribute costs (i.e., $c_{1j}(\boldsymbol{B}) = c_1$ and $c_{2j}(\boldsymbol{B}) = c_2$). From the first order, necessary conditions for optimum equations 5a – 5c and equation 6, competing vendors' optimal attribute bundle bid proposals, for the expected per unit funding/budget level **B**, are given by:

$$(6a')\ a_{1j}^{*} = [\alpha_{1j}/(\alpha_{1j} + \alpha_{2j})\ c_1]\ \mathbf{B}, \text{ and}$$

$$(6b')\ a_{2j}^{*} = [\alpha_{2j}/(\alpha_{1j} + \alpha_{2j})\ c_2]\ \mathbf{B}.$$

Figure 2 illustrates optimal attribute bundle bid proposals for each vendor for a specific unit funding/budget level, **B**: $A_1 = (a_{11}^{*}, a_{21}^{*})$ and $A_2 = (a_{12}^{*}, a_{22}^{*})$. The optimum for each vendor is determined graphically by the tangency of each vendor's isoquant (derived from their separate production functions) with the common budget constraint.

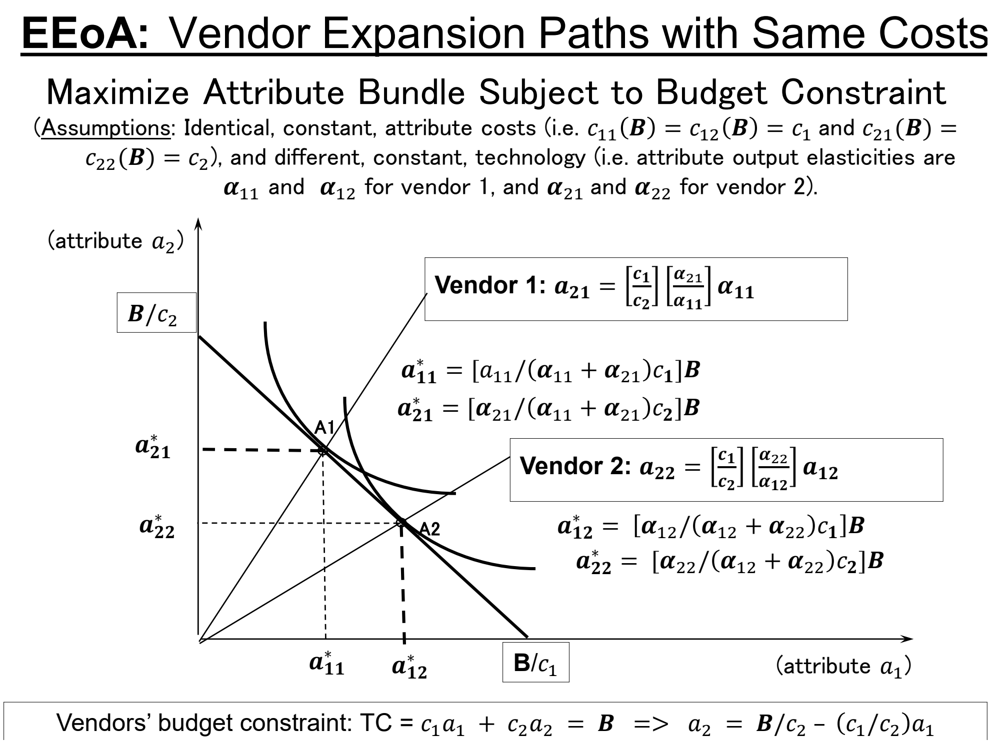

FIGURE 2. Common Attribute Costs but Different Technologies

Suppose instead of a single funding forecast, the buyer (procurement official) reveals a range of possible budget estimates for the procurement (say optimistic, pessimistic, and most likely).[12] Then equations 6a' and 6b' can be combined to yield each vendor's expansion path, given by:

$$(7)\ \ a_{2j} = [(c_{1j}(B)/c_{2j}(B))\,(\alpha_{2j}(B)/\alpha_{1j}(B))]\, a_{1j}\ \text{, for } j = 1{,}2.$$

The two expansion paths defined by Equation 7 reveal optimal attribute bundles offered by each vendor at different possible funding levels, *B*. Each point on the expansion paths derived for each vendor reveals optimal attribute bundle offers (bid proposals) for each identical unit required over different possible budgets.

Given this formulation, if attribute costs and technology parameters are constant (i.e., independent of funding levels), then the expansion paths are linear. Expansion paths for the first case, where vendors share common costs but different technologies, are given by:

$$(7a)\ \ a_{21} = [c_1/c_2\,][\alpha_{21}/\alpha_{11}]\, a_{11}, \text{ for vendor 1, and}$$

$$(7b)\ \ a_{22} = [c_1/c_2\,][\alpha_{22}/\alpha_{12}]\, a_{12}, \text{ for vendor 2,}$$

illustrated as two straight lines from the origin in Figure 2. For the specific per-unit budget level, **B**, the two competing attribute bundle bid proposals offered by each vendor (from 6a' and 6b') appear as points $A_1 = (a_{11}^*, a_{21}^*)$ and $A_2 = (a_{12}^*, a_{22}^*)$ on the competing vendors' expansion paths.

Vendors With Different Attribute Costs

Turning to the second example (illustrated in Figure 3), suppose vendors have different (constant) attribute costs, but identical (constant) production technologies (i.e., in Equation 6: $\alpha_{1j}(\mathbf{B}) = \alpha_1$ and $\alpha_{2j}(\boldsymbol{B}) = \alpha_2$ for j=1,2), together with constant returns to scale (such that: $\alpha_1 + \alpha_2 = 1;\ i.e. if\ \alpha_1 = \alpha\ then\ \alpha_2 = 1 - \alpha$). In this case, the two vendors' optimal bid proposals for unit funding/budget level, **B**, are given by:

$$(6a'')\ \ a_{1j}^* = [\alpha/c_{1j}]\,\mathbf{B}, \text{ and}$$

$$(6b'')\ \ a_{2j}^* = [(1-\alpha)/c_{2j}]\,\mathbf{B}, \ (j=1,2).$$

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[12] For example, see Simon and Melese (2011).

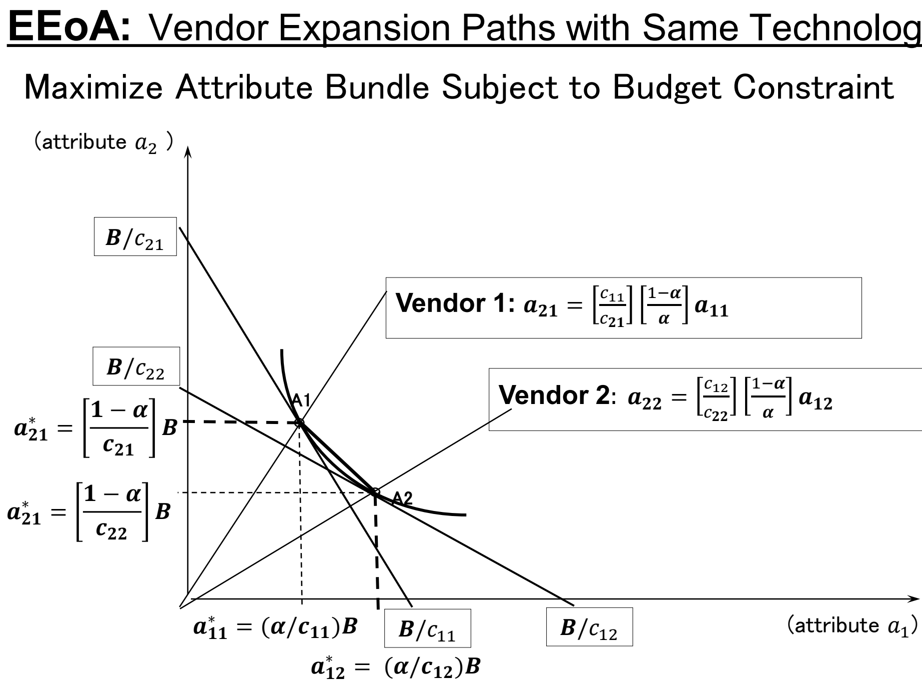

FIGURE 3. Common Technology but Different Attribute Costs

Similar to the first case, Figure 3 illustrates competing optimal attribute bundle bid proposals for each vendor, for the unit funding/budget level, **B**: $A_1 = (a_{11}^*, a_{21}^*)$ and $A_2 = (a_{12}^*, a_{22}^*)$. Now the optimum for each vendor occurs at the point where their respective budget constraints are tangent to their common isoquant. If vendors' technology and attribute cost parameters are constant (i.e., independent of funding levels), both expansion paths are again linear. Expansion paths for this second case (where vendors share a common technology but have different attribute costs) are illustrated as two straight lines from the origin in Figure 3, given by:

(7a') $a_{21} = [c_{11}/c_{21}][(1-\alpha)/\alpha]\, a_{11}$, for vendor 1, and

(7b') $a_{22} = [c_{12}/c_{22}][(1-\alpha)/\alpha]\, a_{12}$, for vendor 2.

Focusing on this second case (where vendors share a common technology but have different attribute costs), for any unit funding/budget level, **B**, connecting the two optimal vendor attribute production points (A_1 and A_2) creates an attribute "production possibility frontier" (PPF), illustrated in Figure 3. The slope of this PPF reflects attribute trade-offs possible in the marketplace by switching from one vendor to another. This technical (or engineering) trade-off is given by the slope $\Delta a_2/\Delta a_1$ = $(a_{21}^* - a_{22}^*)/(a_{11}^* - a_{12}^*)$.

The first-stage vendor optimization problem in the two-stage EEoA framework highlights the importance of modeling the supply side—considering competing vendor decisions in response to anticipated future funding. The second stage focuses on the demand side—the procurement official's source selection problem.[13]

Second Stage EEoA: Procurement Official's Problem (Demand Side)

For any given requirement (quantity demanded), and forecasted per-unit funding/budget, **B**, the procurement official (decision-maker) must rank vendors' optimum bid proposals. For example, in Figure 3: Vendor 1=>(a_{11}^*, a_{21}^*) and Vendor 2=>(a_{12}^*, a_{22}^*). Recall that the lens through which the government evaluates competing vendors is the utility function given by Equation 1.[14] In EEoA, the government supplier decision ("source selection") depends on the public procurement official's (decision-maker's) preferences revealed through explicit trade-offs for any pair of attributes that leave decision-makers indifferent in any given scenario. These explicit pair-wise comparisons elicited from a public procurement official (or expert decision-makers) generate relative weights assigned to the desired attributes.

The public procurement official's problem is to select the vendor $j \in [1, m]$ with bid proposal (per unit attribute bundle) $\boldsymbol{A}_j$ = $[a_{1j}, a_{2j}, \dots, a_{nj}]$) that maximizes the government's utility function given by Equation 1. Following the standard assumption in the literature (see Keeney and Raiffa [1976] and Kirkwood [1997]), the utility/benefit provided by any vendor j is given by the linear, separable utility function:

$$(1') \; \boldsymbol{U_j} = \mathrm{U_j}\left(\boldsymbol{A}_j^T\right) = \boldsymbol{W}\boldsymbol{A}_j^{\mathrm{T}} = \sum_{i=1}^{n} w_i \, a_{ij},$$

[13] Note this second-stage demand-side problem is the exclusive focus of most textbooks, the majority of the literature, and standard support tools and algorithms.

[14] An interesting extension of Equation 1 is developed later to address uncertainty when different possible scenarios (states of nature) impact the government's utility function (for example, due to possible future changes in the political, economic, or threat environment).

where the vector $\boldsymbol{A_j}$ = $[a_{1j}\, a_{2j} \dots a_{nj}]$ represents the bundle of attributes for each unit, offered by each of the $j \in [1, m]$ competing vendors. As discussed earlier, specific relative trade-off weights for every attribute are the procurement official's private information, given by the vector:

$$\boldsymbol{W} = (w_1, w_2, w_3, \dots, w_n \mid w_i \in \mathbb{R}^+, i \in [1, n]).$$

The procurement official is also fiscally informed, with a forecasted funding/budget (affordability) constraint for the procurement given by Equation 2. So, the per-unit price (total unit costs) of any vendor proposal, TC_j, must fit within forecasted future funding (the anticipated per unit budget, $\mathbf{B}$), or $TC_j \leq \mathbf{B}$. The next step is to combine demand and supply (i.e., the procurement official's source selection problem) with vendors' (optimization-generated) bid proposals. The following simple source selection example demonstrates how EEoA integrates demand and supply.

Demand and Supply: A Two-Scenario, Two-Vendor, Two-Attribute Example

For purposes of illustration, suppose a public procurement official responsible for UN peacekeeping missions is asked to select a vendor for a new fleet of Autonomous Electric Off-Road Light Armored Transport Vehicles (AEOLATVs). Assume the anticipated (per unit) budget, **B**, for the program allows two competing vendors to offer the required set of vehicles and that there are only two evaluation criteria in the government's utility function: ***Top Speed*** of each vehicle measured in miles per hour (a_1) and ***Range*** measured in miles (a_2).[15] In Figure 3, this involves a choice between Vendor 1 that offers less speed but more range (a_{11}^*, a_{21}^*) and Vendor 2 that offers more speed but less range (a_{12}^*, a_{22}^*).

In EEoA, the source selection decision (vendor ranking) depends on the procurement official's (decision-maker's) preferences revealed through pair-wise comparisons (i.e., explicit acceptable trade-offs between pairs of attributes within a particular scenario). This generates relative weights assigned to the desired attributes within a particular scenario.

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[15] For example, we could assume all other characteristics (or attributes) of the vehicles offered by the vendors are the same, so top speed and range are the only differentiating factors.

A straightforward modification of Equation 1' allows us to extend the analysis to address different possible scenarios (states of nature) that could impact the procurement official's pair-wise comparisons.[16] Equation 8 accounts for k possible scenarios (or "states of nature"), Ns, $\forall s \in$ [1,k], with corresponding probabilities, $P(Ns)$. This linear, separable, ***expected*** utility function captures the differing relative weights, derived from explicit preference trade-offs among pairs of attributes that depend on specific scenarios (states of nature). Now the procurement official's problem is to select the vendor (e.g., bidder or investment alternative), $j \in$ [1,m], that maximizes the government's ***expected*** utility, given by:

$$(8)\ \mathbf{E}(\boldsymbol{U_j}) = \sum_{s=1}^{k} P(Ns) \sum_{i=1}^{n} w_{is}\, a_{ij}.$$

Consider a simple case with two possible states of nature, N1 and N2, (e.g., Scenario s=1, a High-Tech Threat environment, versus Scenario s=2, a Low-Tech Threat Environment), with corresponding probabilities P(N1) and P(N2).[17] From Equation 8, the government's expected utility function (scoring rule) for the two-scenario, two-attribute case is:

$$(8')\ \mathbf{E}(\boldsymbol{U_j}) = P(N1)[w_{11}a_{1j}+w_{12}a_{2j}] + P(N2)[w_{21}a_{1j}+w_{22}a_{2j}].$$

Totally differentiating the procurement official's (government's) utility function 8' and setting the result equal to zero in each scenario (N1 and N2) generates two sets of relative weights (or indifference curves). In general, relative weights for any two pairs of attributes (a_1, a_2) in each of the k scenarios in Equation 8 are given by:

$$(9)\ \partial a_2 / \partial a_1 = -(w_{1s}/w_{2s}) = -X_s,\ \forall s \in [1,k].$$

The last term in Equation 9, $X_s > 0$, represents the acceptable trade-off determined by a decision-maker (procurement official) between any pair of attributes (a_1, a_2) for a specific scenario: $w_{1s} = (w_{2s})\text{x}(X_s)$. It reflects acceptable pair-wise trade-offs for the government over the relevant range of attributes in each scenario. These preference trade-offs define linear indifference curves between any two pairs of

[16] For example, different possible threat environments in which the UN might operate.
[17] In the AEOLATV example, scenario N1 could represent the possibility of facing a fast adversary with limited range with probability P(N1), and scenario N2, a slower adversary with greater range with probability P(N2), where P(N1)+P(N2)=1.

attributes in each scenario (or piecewise linear approximations over specific ranges of attributes). The slopes of these indifference curves are the relative weights for each pair of attributes, in each state of nature, over relevant ranges of each attribute.

Optimal vendor rankings in EEoA can be determined by comparing the slope of the government's (buyer's) revealed preferences (indifference curves) with the competing vendor-proposed bundles of attributes (production possibility frontiers). For example, Figure 4 illustrates two different sets of indifference curves (dashed lines) that reflect two different scenarios. In turn, these yield two different vendor rankings.

For a given per unit budget, **B**, if the slope of the indifference curve is steeper than the slope of the production possibility frontier (where the PPF reflects technical trade-offs available between competing vendors), or if from Equation 9, -X = $-(w_1/w_2) < -(a^*_{21} - a^*_{22})/(a^*_{11} - a^*_{12})$, then vendor 2 is selected, since U^*_2**>**U_1. If the reverse is true, then vendor 1 wins, since U^*_1**>**U_2 (see Figure 4).

Suppose a government decision-maker (public procurement official) is willing to trade off relatively more range (a_2) for the same incremental increase in top speed (a_1) in scenario N1 than in scenario N2 (for example, 20 miles of range for an extra 10 mph top speed in N_1, versus only 10 miles for an extra 10 mph in N_2). In this case, $-X_1 = -2 < -X_2 = -1$ implies the slope of the indifference curve is steeper (more negative) in Scenario N_1 than in N_2.[18] From Figure 4, vendor 2 is ranked higher (offers greater utility) in scenario N1, and vendor 1 in scenario N2. This is consistent since the decision-maker revealed a stronger relative preference for top speed in scenario N1 (i.e., was willing to trade off more range), and vendor 2 offers relatively higher top speed (a^*_{12}), than vendor 1 (a^*_{11}).

[18] In this case, under scenario N1, vendor 2 ranks higher (offers greater utility) than vendor 1, and there is a rank reversal under scenario N2.

EEoA: Procurement Agency Choice

Maximize Utility Subject to Budget Authority Constraint

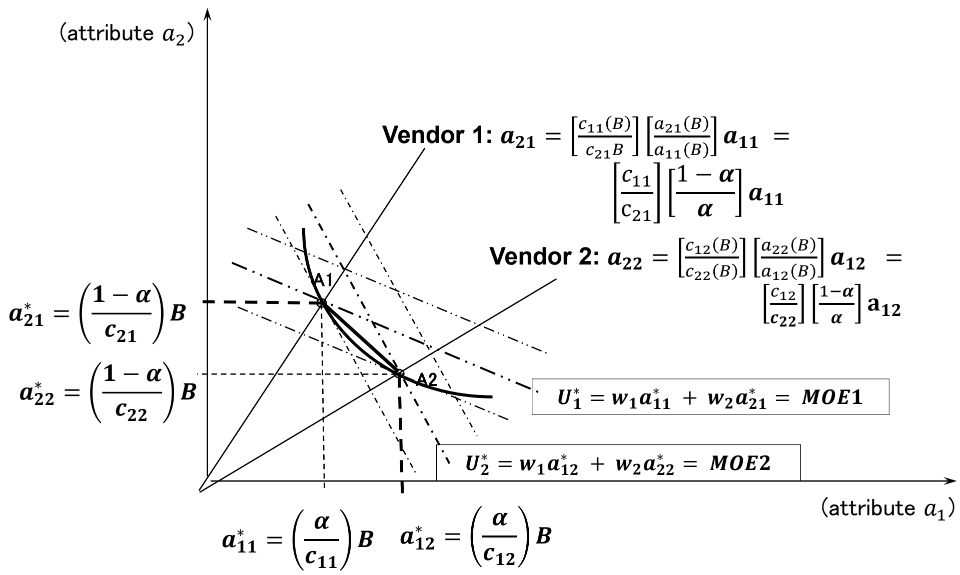

FIGURE 4. Procurement Agency Vendor Selection

In general, probabilities assigned to each scenario in Equations 8 or 8' generate an ***Expected Utility*** vendor ranking metric that consists of a probability-weighted average of pair-wise attribute trade-offs (-Xs) that define expected utility functions in each of the $s \in [1,k]$ scenarios. For example, in the two scenarios, two vendors, two attributes case, the solution determines the slope of a new indifference curve that is a combination of the two indifference mappings illustrated in Figure 4. For any specified budget, the tangency (or corner point) of this new indifference curve with the PPF reveals the optimal expected utility ranking of the two vendors. The next section contrasts this EEoA solution with the standard textbook MCDM model commonly applied by analysts and public procurement officials to guide government supplier decisions.

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Comparison of EEoA and MCDM Models

The topic of multi-criteria decision-making (MCDM) has spawned a rich literature with many variations to account for decision-making in complex scenarios. This section uses a standard textbook MCDM model frequently applied to guide government supplier decisions as a baseline (see Keeney and Raiffa [1976] and Kirkwood [1997]). We contrast this MCDM model with the EEoA approach within a single scenario. The MCDM additive value function typically used to rank vendors is given by:

$$(10)\ \boldsymbol{V_j} = \mathrm{V_j}\left(\boldsymbol{A}_j^T\right) = \boldsymbol{\lambda} v_i(a_{ij}) = \sum_{i=1}^{n} \lambda_i\, v_i(a_{ij}).$$

This value function is the sum of individual value functions, $v_i(a_{ij})$, defined over relevant ranges of each attribute $i \in [1, n]$, for any vendor j. The vector of preference weights is given by:

$$\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3 \dots, \lambda_n \mid \lambda_i \in \mathbb{R}^+, i \in [1, n]).$$

The individual value functions $v_i(a_{ij})$ are typically monotonic and scaled (normalized), while the preference weights (λ_i) reflect the importance of each attribute. While these weights $(\boldsymbol{\lambda})$ are analogous to the relative weights $(\boldsymbol{W})$ in EEoA, they are only equivalent if raw attribute measures are used in MCDM instead of normalized values to determine pair-wise trade-offs (i.e., if $v_i\left(a_{ij}\right) = a_{ij}$). For purposes of comparison with EEoA, it is convenient to assume procurement officials (decision-makers) are subject to the same funding/affordability constraint given by Equation 2: $TC_j \leq \mathbf{B}$. Implications of this MCDM model are explored later under the usual assumption that attribute measures are normalized using individual value functions with preferential independence.

Implicit Trade-Offs in MCDM vs. Explicit Trade-Offs in EEoA

From Equation 10, the only theoretical difference between the procurement official's objective function 1 or 1' in EEoA and MCDM is an additional step in Equation 10 that involves normalizing attribute measures through individual value functions. In fact, the demand side of EEoA can be thought of as a special case of MCDM, where $v_i(a_{ij}) = a_{ij}$.

In theory, any value function, v_i, in conjunction with the appropriate attribute weights λ_i, can recover the EEoA utility function for any given vector of attributes $\boldsymbol{A_j}$.This is clear when we consider a procurement official's value function with two attributes as before:

$$(10') \; \boldsymbol{V_j} = \sum_{i=1}^{n} \lambda_i v_i(\, a_{ij}) \Rightarrow [\lambda_1 v_1(a_{1j}) + \lambda_2 v_2(a_{2j})].$$

Totally differentiating Equation 10 or Equation 10' and setting the result equal to zero yields ***implicit*** trade-offs in the MCDM approach between any two pairs of attributes (a_1,a_2; i.e., the first two terms in Equation 11). For the sake of consistency given a particular decision-maker's preferences, this should precisely correspond to the explicit trade-offs (revealed preferences) obtained from that decision-maker in EEoA (i.e., represented by the last two terms in Equation 9).

$$(11) \; \partial a_2/\partial a_1 = -[\lambda_1 v_1{}'(a_1)]/[\lambda_2 v_2{}'(a_2)] = -\frac{w_1}{w_2} = -X_s.$$

While the MCDM approach adds a degree of freedom for procurement officials and expands the decision space, it risks obscuring explicit trade-offs between attributes revealed in the EEoA approach. From Equation 11, we see that:

$$\lambda_1 / \lambda_2 = X_s[v_2{}'(a_2)/v_1{}'(a_1)], \text{ or}$$

$$Z = [v_2{}'(a_2)/v_1{}'(a_1)],$$

where the constant Z= $\lambda_1 / (\lambda_2 X_s)$. So in general, for any pair of attributes and alternatives (i.e., vendors j ∈ [1,m]),

$$(12) \; Z v_1'(a_{1j}) = v_2{}'(a_{2j}).$$

Integrating both sides of Equation 12 yields:

$$(13) \; v_2(a_{2j})/v_1(a_{ij}) = Z = \lambda_1/(\lambda_2 X_s).$$

That is to say, if the goal is to ensure that EEoA and MCDM approaches generate the same rank ordering, procurement officials must set individual attribute value functions v_i's and attribute weights λ_i's in the precise ratio specified in Equation 13.

In practice, there is no reason to assume this happens, and reconciling the two approaches to generate the same rank ordering is nontrivial. While a procurement official may have a certain trade-off in mind between pairs of measurable attributes when developing the MCDM value function, normalizing each attribute with individual value functions, and selecting appropriate weights to assign to those value functions, can easily yield *implicit* pairwise trade-offs among attributes that generate different rank orderings than the *explicit* pairwise trade-offs determined in EEoA.[19] Which decision support model best elicits public procurement officials' (decision-makers') preferences remains an important empirical question and warrants further research.

From a practical standpoint, a limitation of the EEoA approach is that as the number of attributes (n) under consideration expands, it is increasingly burdensome to generate required pairwise comparisons. For example, assuming each alternative (vendor proposal) includes a set of n attributes, applying EEoA requires $\frac{n(n-1)}{2}$ pairwise comparisons. Interestingly, however, EEoA could be applied in combination with MCDM as a consistency check for important attributes. That is to say, if $\partial a_2/\partial a_1$ = $-(w_{1s}/w_{2s}) = -X_s$ is the explicitly determined trade-off (indifference) that a public procurement official (decision-maker) is comfortable with in a particular scenario (for specific ranges of attribute measures) in EEoA, then weights developed in MCDM should reflect this relative preference (trade-off).[20] The test simply involves application of Equation 11. We now turn to another important contribution of EEoA: the

[19] Note: Linear normalization combined with careful swing weighting in MCDM could recover similar trade-offs to those explicitly revealed in EEoA (Sse Equation 9), resulting in an identical rank ordering of competing vendors. (An example is available upon request.)

[20] If the extra burden of normalization and swing weighting required in MCDM causes a decision-maker to "misevaluate" their trade-off preferences, then EEoA offers an alternative framework/perspective that can help to realign their weighting. Note that in theory, a rational decision-maker with perfect information and infinite computational capability would never need to do this. Since in practice it is difficult to define a "correct" weighting, contrasting the development of weights in MCDM and EEoA may be an empirical question worth investigating.

importance of modeling the supply side—specifically, accounting for vendor responses to anticipated future funding.

Accounting for Vendor Responses to Anticipated Future Funding

Traditionally, MCDM models focus on the demand side of a public procurement and treat supply-side vendor decisions as exogenous. This section demonstrates the importance of explicitly accounting for vendor responses to anticipated future funding (affordability or budget constraints).

Since each vendor's expansion path represents their optimal attribute bundle bid proposals for any given budget (see Figures 2, 3, and 4), these expansion paths can easily be converted, through the buyer's utility function 1', into cost-effectiveness (or Budget-Utility) ***functions*** for each vendor. For example, substituting each vendor's optimal attribute bundle 6a'' and 6b'' into Equation 1' for any specific scenario yields two points in cost-effectiveness space that represent the utility of each vendor's bid proposal for the per unit funding/budget, **B**: $(\mathrm{U}_1^*, \mathbf{B})$ and $(\mathrm{U}_2^*, \mathbf{B})$. Different budgets represented along the expansion paths generate different utility. For example, the cost-effectiveness/utility relationships illustrated in Figure 6 reflect the value to the government of each vendor's offers at different funding levels.

It is important to contrast the endogenously-derived EEoA cost-effectiveness *functions* for each vendor, with the exogenous cost-effectiveness *points* used to illustrate vendor offers in MCDM.[21] For an example of the latter, see the *Defense Acquisition Guidebook*, which states:

> Cost-effectiveness comparisons in theory would be best if the analysis structured the alternatives so that all the alternatives have equal effectiveness (the best alternative is the one with lowest cost) or equal cost (the best alternative is the one with the greatest effectiveness). Either case would be preferred; however, in actual practice, in many cases the ideal of equal effectiveness or equal cost alternatives is difficult or impossible to achieve due to the complexity of AoA [Analysis of Alternatives] issues. *A common method for dealing with such situations is to provide a scatter plot of [points representing competing vendor proposals'] effectiveness versus cost* [emphasis added]. (DAU, n.d., Ch. 2–2.3.2.7).

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The contrast between the two approaches becomes especially apparent when vendor costs in EEoA depend on anticipated future funding. For instance, with bigger budgets, a vendor's costs to provide more of a particular attribute (say computer memory) might enjoy increasing returns to scale because of quantity discounts, the ability to employ just-in-time inventory techniques, or the possibility of adopting other process improvements that reduce a vendor's costs of incorporating/producing a desired attribute.

Consider the case illustrated in Figure 5, where vendor 1's costs of producing attribute 1 are assumed to depend on the funding level or anticipated per unit budget, **B** (i.e., $c_{11}(\boldsymbol{B})$). For ease of exposition, suppose both vendors $j = 1{,}2$ have identical, constant production technologies (i.e., $\alpha_{1j}(\mathbf{B}) = \alpha_1$ and $\alpha_{2j}(\boldsymbol{B}) = \alpha_2$) and constant returns to scale $\alpha_1 + \alpha_2 = 1$. The difference between them is in their individual attribute costs. As before, let $c_{12}(\boldsymbol{B}) = c_{12}$; $c_{22}(\boldsymbol{B}) = c_{22}$; and $c_{21}(\boldsymbol{B}) = c_{21}$, but now suppose vendor 1's costs for attribute 1 depend on the budget. For example, assume the following relationship: $c_{11}(B) = c_{11} - k\boldsymbol{B} > 0$. Also let $\boldsymbol{B} < c_{11}/k$, $c_{11} > c_{12}$, and $k \in [0,1)$.[22] In this case (from Equations 6a'' and 6b''), each vendor's optimal attribute bundle proposals for a unit funding/budget level $\boldsymbol{B}$ is given by:

$$\text{(14a)} \quad a_{11}^{*} = [\alpha/c_{11}(\boldsymbol{B})]\,\boldsymbol{B} = [\alpha/(c_{11} - k\boldsymbol{B})]\boldsymbol{B},$$

$$\text{(14b)} \quad a_{21}^{*} = [(1-\alpha)/c_{21}]\boldsymbol{B}, \text{ and}$$

$$\text{(15a)} \quad a_{12}^{*} = [\alpha/c_{12}]\boldsymbol{B},$$

$$\text{(15b)} \quad a_{22}^{*} = [(1-\alpha)/c_{22}]\boldsymbol{B}.$$

Figure 5 illustrates each vendor's optimal attribute bundle bid proposals (given by Equations 14a and b and 15a and b) for a specific budget, **B** (i.e., points $A_1\colon (a_{11}^{*}, a_{21}^{*})$ and $A_2\colon (a_{12}^{*}, a_{22}^{*})$).

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[22] These simple assumptions help illustrate our point. A model with quadratic costs could add another dimension (a "knee of the curve"—that is, monotonic increasing with a single inflection point) to the cost-effectiveness function, which could offer an interesting extension of the model.

EEoA: Procurement Agency Choice

Maximize Utility Subject to Budget Authority Constraint

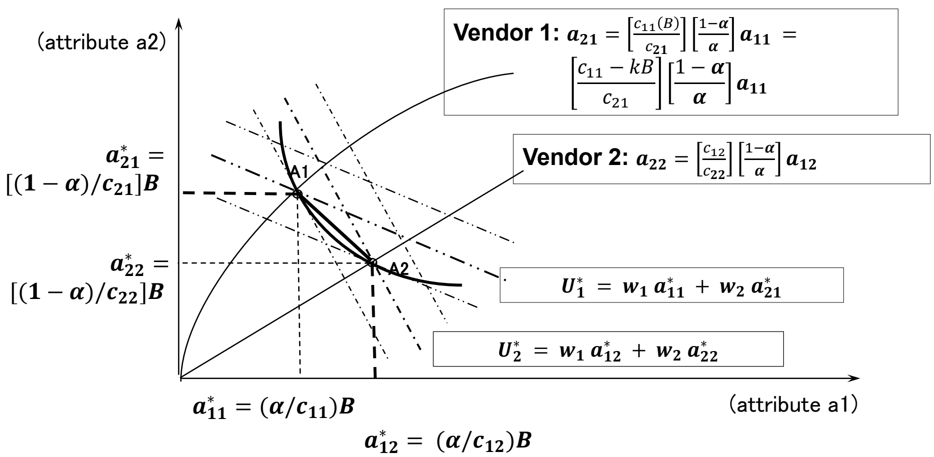

FIGURE 5. Vendor Selection when Vendor 1's Attribute Costs Depend on Budget

The expansion path for vendor 2 is again linear, with the same positive, constant slope for any budget (i.e., identical to equation 7b'); however, since vendor 1's attribute costs now depend on the anticipated per unit funding/budget, B, vendor 1's expansion path is nonlinear, increasing at a decreasing rate as illustrated in Figure 5 and given by:[23]

$$(16)\ \ a_{21} = [c_{11}(B)/c_{21}][(1-\alpha)/\alpha]\, a_{11} = [(c_{11} - kB)/c_{21}][(1-\alpha)/\alpha]\, a_{11},$$

where the slope (first derivative) is given by:

$$(16')\ \ \partial a_{21}/\partial a_{11} = [c_{11}(B)/c_{21}][(1-\alpha)/\alpha] = [(c_{11} - kB)/c_{21}][(1-\alpha)/\alpha] > 0,$$

and change in slope with a change in the budget (second derivative) given by:

$$(16'')\ \ \partial(\partial a_{21}/\partial a_{11})/\partial B = [c_{11}{}'(B)/c_{21}][(1-\alpha)/\alpha] < 0.$$

[23] The illustration of the two expansion paths assumes that throughout the relevant range of budgets (funding levels), $(c_{11}(B)/c_{21}) > (c_{12}/c_{22})$.

Substituting vendor 1's and vendor 2's optimal attribute bundle offers (Equations 14a and b and 15a and b) into the procurement official's (buyer's) utility function for any given scenario in Equation 8' yields:[24]

$$(17)\ U_1^* = w_1 a_{11}^* + w_1 a_{21}^* = w_1\, [\alpha / c_{11}(B)]\, B + w_2\, [(1-\alpha)/c_{21}]\, B$$

$$(18)\ U_2^* = w_1 a_{12}^* + w_1 a_{22}^* = w_1\, [\alpha / c_{12}]\, B + w_2\, [(1-\alpha)/c_{22}] B.$$

Equations 17 and 18 represent functions that can be plotted in cost-effectiveness (budget-utility) space over a relevant range of funding scenarios (see Figure 6). In this case, assuming identical, constant costs for attribute 2 (i.e., $c_{21} = c_{22} = c_2$), from Equations 17 and 18,

$$(19)\ U_1^* \gtreqless U_2^* \text{ as } c_{12} \gtreqless c_{11}(\boldsymbol{B}) = c_{11} - k\boldsymbol{B} \text{ or as } \boldsymbol{B} \gtreqless (c_{11} - c_{12})/k = B'.$$

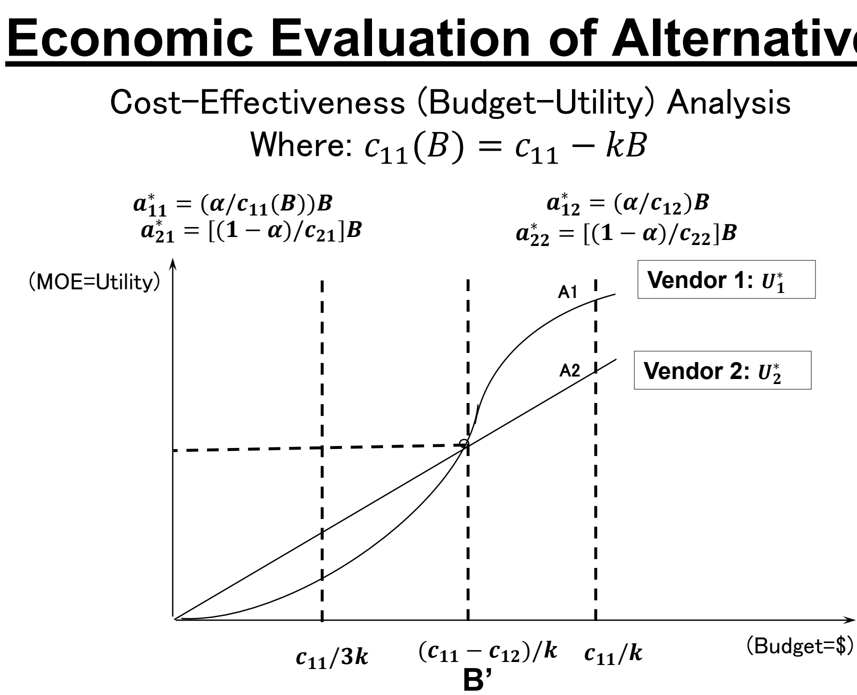

FIGURE 6. Vendor Selection in Cost-Effectiveness Space

[24] For a specific funding level **B**, this represents two optima that can be compared that represent the maximum utility a buyer can obtain from each vendor. This is illustrated in Figure 4 as the highest indifference curve attainable given the corresponding point on the attribute production possibility frontier.

An optimal rank reversal is revealed in Figure 6. In fact, Equation 19 indicates that it is optimal for the buyer to switch vendors at B'. For any unit funding/budgets **B**>B', vendor 1 is ranked higher than vendor 2. The two are ranked equally for the budget, **B**=B', and for budgets **B**<B', vendor 2 is ranked higher than vendor 1. As expected, evaluating the slopes of the two vendors' cost-effectiveness functions at the switch point, B'=$(c_{11} - c_{12})/k$, yields:

(20) $\partial \mathrm{U}_1^*/\partial \boldsymbol{B} > \partial \mathrm{U}_2^*/\partial \boldsymbol{B}$ or $(c_{11}(\boldsymbol{B}) - c_{11}'(\boldsymbol{B})\boldsymbol{B})/c_{11}(\boldsymbol{B})^2 > 1/c_{12}$ since $c_{11} > c_{12}$.

This highlights the importance of modeling the supply side. Specifically, this example emphasizes the importance for public procurement officials to obtain realistic budget forecasts for government programs and to offer those as guidance to vendors. As two pioneers in defense economics, Hitch and McKean (1967), wisely counseled:

> As a starter ... several budget sizes can be assumed. If the same [vendor] is preferred for all … budgets, that system is dominant. If the same [vendor] is not dominant, use of several … budgets is nevertheless an essential step, because it provides vital information to the decision maker. (p. 176)

In the textbook application of MCDM, competing vendor bid proposals are presented as single points in cost-effectiveness space. In sharp contrast, EEoA encourages procurement officials in fiscally constrained environments to solicit bids over a range of possible budget scenarios, such that each vendor is represented as a function, not a point, in cost-effectiveness (budget-value) space.[25]

[25] In this case, the standard technique of eliminating "dominated alternatives" could lead to suboptimal decisions. For example, see Melese (2015) or the specific example of the EEoA model developed in Simon and Melese (2011).

Conclusion and Avenues for Future Research

This technical report offers an economic model to assist public procurement officials facing the challenge of ranking competing vendors when benefits cannot be monetized. The problem of ranking public investment alternatives when benefits cannot be monetized has spawned an extensive literature generally referred to as MCDM that underpins widely applied decision tools.

The bulk of the MCDM literature, and most government-mandated decision tools, focus on the demand side of a public procurement. The EEoA extends the analysis to the supply side. Given a parsimonious set of continuously differentiable evaluation criteria, EEoA offers a new tool to help rank competing vendors. It also offers a valuable consistency check when MCDM is used to guide government supplier decisions. A unique feature of EEoA is that it can model vendor decisions in response to government funding projections.

Introducing the supply side offers multiple avenues for future research. Notably, it provides fertile ground to incorporate both auction and game theory literatures. An interesting extension would be to leverage auction theory and introduce strategic shading of bids by vendors. Other interesting extensions would be to consider the risk of collusion among vendors and/or to allow some vendors to enjoy economies of scale (i.e., to make production technology parameters a function of the budget). Also, whereas EEoA models competing vendors as maximizing their offers (proposed bundles of desired characteristics) to win funding (a “prize”), alternative optimization assumptions and strategic behaviors could be assumed.

Finally, a unique opportunity exists for both experimental and qualitative research to significantly improve public procurement. An important empirical question is whether analysts and procurement officials would have an easier time, and obtain better results, in applying EEoA or MCDM (or some combination). Consistency tests could be conducted in experimental settings to explore when the two techniques converge (offer identical vendor rankings), and when (and why) they diverge.

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Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net