A Stochastic AHP Method for Bid Evaluation Plans of Military Systems In-Service Support Contracts

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Abstract

Project management offices of defence acquisition projects are required to develop fair, transparent, and defensible bid evaluation plans for major procurement tenders. A key aspect of an evaluation plan is the development of an appropriate criteria weighting model. Given the uncertainties in criteria weights and performance scores, a sensitivity analysis is required to provide assurance to the overall bid evaluation plan, particularly the identification of potential extreme bids. This paper presents a stochastic Analytic Hierarchy Process method for performing high dimensional sensitivity analysis of bid evaluation plans for military systems in-service support contracts. The method integrates multi-criteria decision analysis, Monte Carlo simulation, and optimization techniques and determines a ranking probability matrix to assess the effectiveness of weighting models and to explore potential extreme bids. An example using a bid evaluation plan for a military ship in-service support contract is presented and discussed to illustrate the methodology. A set of hypothetical bid profiles, developed by military subject matter experts, is used in the analysis to wargame the bid evaluation plan. The study provides project managers with a decision support tool for refining and optimizing bid evaluation plans of military systems in-service support contracts.

Keywords
Bid Evaluation, In-Service Support Contract, Military, Stochastic, Sensitivity Analysis.

1. Introduction

The defence acquisition process is complex and generally involves three main strategy phases (planning, development and execution). The planning phase requires the establishment of an acquisition team to review the current strategy (e.g., identify future client requirements) and conduct a market search (e.g., identify potential suppliers). In the development phase, the acquisition team determines the project requirements, performance objectives and standards and develops an acquisition strategy. During the execution phase, the acquisition team develops a solicitation report that formally communicates the customer's requirements to industry, evaluates the bid proposals against criteria that will best determine the success of a potential contractor's approach, and conducts performance management after contract award (Defence Acquisition Guide, 2016).

One of the key documents that should be included in the solicitation report is the bid evaluation plan. A bid evaluation plan is a technical framework that details the evaluation process of bid proposals, including the evaluation criteria, their associated weight factors, and the selection method that will be used to differentiate between bids. The establishment of decision criteria is an important step in the bid evaluation process. When developed appropriately, criteria should determine whether or not a potential bidder is suitable, be directly related to the subject matter of the contract, and be clear enough to ensure that the potential bidder has an accurate understanding of what is most important to the contracting authority (Riabacke et al. 2012). Criteria and their assigned weights vary by the type of system that is being procured (e.g., aircraft, ship, ground vehicle, munitions). They could also be different for in-service support contracts (e.g., upgrade and maintenance of a current system) and on-paper (new acquisition) systems (Ghanmi, 2014). In-service support typically refers to the post-acquisition support of an established fleet; it represents the provision of support over the entire life of the fleet. In general, separate contracts are let for the acquisition and for the in-service support of military systems. These may both be let to a single contractor or may be tendered separately. The in-service support program is intended to provide a long-term support of the fleet, often for 20 years or more. It includes logistical support, engineering, spare parts, repair and maintenance services, program management, etc. It must be designed to sustain a high level of operational availability and reliability in harmony with the planned fleet mission profiles and expected usage.

To facilitate the bid evaluation process, decision makers sometimes use Multi-Criteria Decision Analysis (MCDA) methods in the development of bid evaluation plans (Kaluzny, 2009). The general form of a MCDA problem is the evaluation of a number of alternatives (bidders) against multiple non-commensurate, and frequently conflicting, decision criteria. One of the most frequently used MCDA methods for military bid evaluation of public tenders is the Analytic Hierarchy Process (AHP). The AHP is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Saaty (1980) and has extensively been applied a wide variety of decision situations in fields such as government, business, industry, healthcare, shipbuilding and education. There are several advantages of using AHP over other MCDA methods (Kendrick and Saaty, 2007). Using a hierarchical structure, AHP enables decision makers to define high level strategic objectives and specific metrics for a better assessment of alternatives. The method goes beyond financial analysis by integrating quantitative and qualitative considerations as well as competing stakeholder inputs into setting priorities. It also enables decision makers to measure the relative importance of alternatives (e.g., pairwise comparison), including their benefits, costs, risks and opportunities. It can be applied in any organization with any level of maturity because the inputs are normalized using either numerical data or subjective judgments when metrics are not available. Finally, the AHP process lends itself to sensitivity analysis, providing decision makers with greater analytical capabilities to identify potential extreme bids (for example). An extreme bid is a bid that neglects higher-ranking criteria in favour of scoring best at lower-ranking criteria.

This paper presents a case study on bid evaluation plan analysis for a military ship in-service support contract. Military ship in-service support is a complex problem and it involves multidisciplinary technical skills and specialized technologies to provide life cycle support to the equipment. The ship in-service support program should be customized to meet the military operational requirements (e.g., operational availability of the ship fleet) and would be unique and very expensive. As such, the bid evaluation plan for contracting these programs should be able to capture the key technical and management aspects of the contract. For the purpose of the study, the AHP method is used for the analysis of the bid evaluation plan of the ship in-service support contract. While the AHP method is mathematically simple and easy to implement, its practical applications to real decision problems, (e.g., bid evaluation of in-service support contract), could be complicated by uncertainty in such input parameters as the criteria weights and performance scores. Criteria weights and performance scores are always elicited from decision makers (through a pairwise comparison process) and are stochastic variables. To assess the impact of the uncertainties of weighting and scoring on bid performance, one could use a stochastic AHP method for evaluating bids. This would assist decision makers in wargaming the bid evaluation plan to assess the sensitivity of the criteria weights and performance scores and to identify potential extreme bids.

The paper is divided into five sections and structured as follows. Section 2 describes bid evaluation plans for military system in-service support contracts. Section 3 presents a proposed stochastic AHP method for conducting sensitivity analysis of bid evaluation plans. Section 4 provides an illustrative example of the methodology using a military ship in-service support contract. Concluding remarks and future work are indicated in the fifth section.

2. Bid Evaluation Plan

From a defence acquisition perspective, a bid evaluation plan is a framework that describes the evaluation approach for the procurement of a defence system, including details about the evaluation criteria, criteria weights, scoring methods, bid selection process, etc. Developing a bid evaluation plan for defence acquisition is an iterative process that involves multidisciplinary decision makers, including financial, operational, technical, legal, and strategic analysis teams (Bana e Costa et al., 2002). The establishment of decision criteria is an important step in the bid evaluation process. In military acquisition problems, evaluation criteria and their assigned weights vary by the type of system that is being procured and by the type of contract (in-service support or new acquisition).

The bid evaluation criteria for the military systems in-service support contracts can be grouped into three main categories (Ghanmi, 2014):

- *Technical Criteria*: Technical criteria are used to assess the system technical performance requirements and are usually divided into mandatory and rated criteria. Mandatory criteria identify the minimum requirements that are essential to the success of the procurement. These requirements are evaluated on a pass/fail basis. Bids that fail to meet the mandatory requirements are given no further consideration in the evaluation process. Examples of mandatory criteria for a military system might include its weight, dimensions, payload, range, speed, etc. For bids that meet the mandatory requirements, rated criteria are used to determine the relative technical merit of each bid and the best overall value to the Crown. They provide a means to assess and distinguish one bid from another. Examples of rated criteria for a military system might include its reliability and maintainability, engineering support, etc. Some criteria might have both mandatory and rated aspects.

- *Financial Criteria* The financial evaluation of a system includes the full cost of the system over its expected useful life (i.e., life cycle cost). This is to avoid buying systems that are cheaper up front but may actually cost more in the long term as maintenance costs may well be greater. Criteria for the financial evaluation would include: acquisition cost, in-service support cost, operations and maintenance costs, other additional work request cost (i.e., cost for additional work that is above the work included in the fixed price contract) and disposal costs.
- *Other Criteria*: Other evaluation criteria for the in-service support contracts would include the value proposition for the defence sector (e.g., impact of industrial development), suppliers development, skills development, research and development, as well as various relational contracting elements (e.g., joint governance, information sharing, collaboration).

In general, technical criteria for both in-service and on-paper systems are scored using the same evaluation method. However, the weights of the technical criteria for the in-service systems might be different from the weights of the technical criteria for the on-paper systems. Indeed, the bid evaluation plan for an in-service system would have more weights on the technical aspects as financial details of the system would relatively be known (e.g., less risk). For on-paper systems, both technical and financial data would be uncertain at the procurement time.

3. Method

The ship in-service support contract bid evaluation problem is complex and involves quantitative and qualitative decision criteria. One of the most commonly used decision analysis methods for military acquisition problems is the AHP method. The main advantage of the AHP is its ability to handle both quantitative and qualitative decisions and to rank alternatives in the order of their effectiveness in meeting conflicting objectives.

3.1 The AHP method

Introduced by Saaty (1980), the AHP is an effective and widely used technique for solving multi-criteria decision-making problems. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the inconsistency in the decision making process. The AHP can be used to determine the relative weights of criteria, bid scores or both relative weights and bid scores. To calculate the bid scores, pairwise comparisons are conducted between the submitted bids at the lowest pre-identified criteria level using the Saaty rating scale, for example (Table 1). These comparisons are converted into scores that allow the ranking of individual bids with respect to each other. The low level scores are then weighted and rolled up, in accordance with the pre-determined hierarchy and weighting factors, to determine an overall bid ranking.

For determining either bid scores or criteria weights, the AHP methodology is as follows (Saaty, 2008). Consider n bids ($B_1 \ldots B_n$) to be compared for a given evaluation criterion and denote the ratio of the importance intensity of B_i relative to B_j by a_{ij}. Form a square matrix $A = (a_{ij})$ of order n with the constraints that $a_{ij} = 1/a_{ji}$, for $i \neq j$, and $a_{ii} = 1$, all i. Such a matrix is said to be a reciprocal matrix. The elements of A are consistent if they are transitive, that is $a_{ik} = a_{ij} \times a_{jk}$ for all i, j, and k. Then find an eigenvector ω and an eigenvalue λ_{max} by solving the equation $A \times \omega = \lambda_{max} \times \omega$, where λ_{max} is the largest eigenvalue of the matrix. The eigenvector is used to determine the relative scores of bids and the eigenvalue is used to check the consistency of the matrix A. For a consistent matrix, $\lambda_{max} = n$. For matrices involving human judgement, the condition $a_{ik} = a_{ij} \times a_{jk}$ does not necessarily hold as human judgements are inconsistent to a greater or lesser degree. For that, a Consistency Index (CI) can be calculated from $(\lambda_{max} - n)/(n-1)$. However, numerical studies showed that the expected value of CI of a random matrix of size $n+1$ is, on average, greater than the expected value of CI of a random matrix of order n. Consequently, CI is not fair in comparing matrices of different orders and needs to be rescaled. The Consistency Ratio (CR) is the rescaled version of CI. Given a matrix of order n, CR can be obtained by dividing CI by a real number (Random Index) which is nothing else but an estimation of the average CI obtained from a large enough set of randomly generated matrices of size *n*. Saaty suggests that if that CR exceeds 0.1, the set of judgments may be too inconsistent to be reliable. A CR of zero means that the judgements are perfectly consistent.

Table 1: The Saaty Rating Scale.

Importance Intensity	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed

3.2 Stochastic AHP

The methodology discussed above assumes that the input parameters (a_{ij}) are known (deterministic AHP). This is not the case for most decision-making problems, where decision parameters are provided by subject matter experts and are subject to variations (Stochastic AHP). In this paper, we consider a stochastic AHP approach to conduct sensitivity analysis of the bid evaluation criteria for military systems in-service support contracts. In decision theory, sensitivity analysis is a fundamental concept for assessing the stability of an optimal alternative under changes in input parameters, the impact of the lack of controllability of certain input parameters, and the need for precise estimation of input parameter values (Evans, 1984). The bid evaluation problem is a potentially subjective exercise that contains uncertainties in the assessment of criteria weights and scores. Sensitivity analysis would be conducted to examine the solution space for the criteria weights and scores and to determine a robust bid evaluation method.

A simulation-based AHP algorithm was developed for performing high dimensional sensitivity analysis of bid evaluation plans. In the algorithm, the uncertainties in the importance intensity (a_{ij}) are represented by probability distributions. For example, a_{12} = 1 (20%), 3 (30%), 5 (40%), and 7 (10%). The algorithm can be thought of in three phases: Phase 1 uses Monte Carlo simulation to generate stochastic importance intensities. Phase 2 applies the AHP method to determine the overall scores of alternatives and to generate a ranking probability matrix (probability r_{ij} that alternative *i* ranks at position *j*). The values of r_{ij} are calculated by dividing the number of times alternative *i* ranked at a position *j* by the total number of simulation runs. Phase 3 uses the ranking probability matrix to determine the most likely ranks of alternatives. The condition that defines a particular rank as most probable is described in the context of an assignment problem. The assignment problem determines an assignment of alternatives to the set of rank positions without assigning a rank more than once and ensuring that all alternatives are ranked. It can be mathematically formulated as follows. Let x_{ij} be the assignment variable of alternative *i* to rank position *j* (x_{ij} = 1 if alternative *i* is ranked at position *j*, 0 otherwise). The objective function of the ranking assignment problem is to maximize the sum of the rank probabilities of alternatives (Ghanmi, 2015).

$$\max\ Z = \sum_{i=1}^{m}\sum_{j=1}^{m} x_{ij} r_{ij} \qquad (4)$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1 \quad ; \quad 1 \le i \le m \qquad \text{(a)}$$

$$\sum_{i=1}^{m} x_{ij} = 1 \quad ; \quad 1 \leq j \leq m \qquad \text{(b)}$$

$$x_{ij} \in \{0, 1\} \quad ; \quad 1 \leq i \leq m \quad ; \quad 1 \leq j \leq m \qquad \text{(c)}$$

The set of constraints given in (a) require that every alternative is assigned to exactly one rank position, while the set of constraints specified in (b) require that every rank position is assigned exactly one alternative. Constraints on the domain of the variables are specified in (c).

4. Illustrative Example

This section presents an illustrative example of bid evaluation for a military ship in-service support contract. A sensitivity analysis using the stochastic AHP method was performed to determine how the outcome of the bid evaluation depends on different subsets of hypothetical bidders, particularly in the presence of extreme bidders.

4.1 Evaluation criteria

A high level breakdown of the evaluation criteria and their associated hypothetical weights (in percentage) is illustrated in Figure 1. In summary, the ship in-service support contract bid evaluation plan involves four main rated criteria (for example): Technical, Value Proposition, Financial, and Relational. The technical criterion assesses the bidder's technical expertise in managing in-service support projects, including experience, management plans, and other technical expertise. The Value Proposition criterion assesses the bidder's commitments to industrial developments including defence sector, skills, suppliers and research & development. The financial criterion assesses the cost of the bid proposal. The relational criterion assesses the bidder's approach to key aspects of relational contracting (e.g., collaboration, innovation, information sharing).

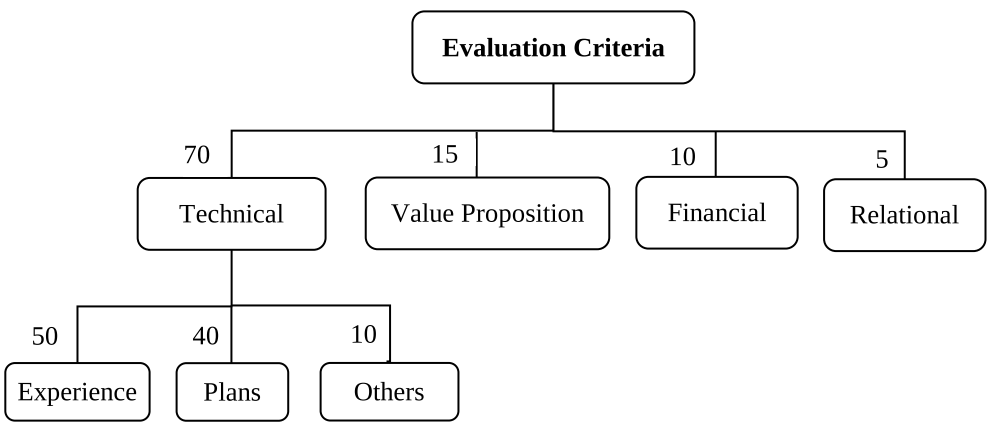

Figure 1: Evaluation criteria and relative weights (hypothetical).

4.2 Hypothetical bids

Four hypothetical bidders (denoted by letters A through D) and five potential extreme bids (denoted by letters E1 through E5) are considered in the analysis. The extreme bid profiles are developed by subject matter experts using various technical assumptions based on different historical acquisition projects. They are included in the analysis for wargaming the bid evaluation plan to determine the likelihood of an extreme bid to win the competition. Table 2 presents the bidder's input data (hypothetical) formatted for the AHP method. The AHP method requires a pairwise scale to determine a judgement matrix. For the purpose of this paper, a pairwise scale of (1, 3, 7) was used to express the relative importance of two bidders for a given criterion (1 = "as good as", 3 = "better than", 7 = "very much better than"). A probability distribution of the pairwise scale was also provided by subject matter experts for each criterion and bidder to conduct Monte Carlo simulation and perform sensitivity analysis (stochastic AHP). These probability distributions are based on past experience and historical submissions of bidders. Note that for the financial criterion, cost ranges were provided for each bidder to simulate stochastic variations of the bid scores for these criteria.

Table 2: Pairwise scale probabilities and financial ranges of the bids.

	Experience			Plans and Questions		
	1	3	7	1	3	7
Bidder A	15%	40%	45%	10%	40%	50%
Bidder B	10%	30%	60%	10%	40%	50%
Bidder C	20%	30%	50%	20%	40%	40%
Bidder D	10%	30%	60%	15%	35%	50%
Bidder E1	40%	40%	20%	5%	35%	60%
Bidder E2	5%	30%	65%	15%	25%	60%
Bidder E3	10%	35%	55%	10%	25%	65%
Bidder E4	15%	35%	50%	10%	30%	60%
Bidder E5	0%	40%	60%	10%	30%	60%

	Value Proposition			Financial	Relational		
	1	3	7	range	1	3	7
Bidder A	0%	40%	60%	300-400	10%	40%	50%
Bidder B	0%	25%	75%	400-500	10%	35%	55%
Bidder C	10%	60%	30%	405-525	5%	30%	65%
Bidder D	50%	30%	20%	515-620	15%	25%	60%
Bidder E1	0%	40%	60%	400-550	10%	30%	60%
Bidder E2	90%	10%	0%	800 -1000	80%	20%	0%
Bidder E3	90%	0%	10%	350-500	0%	40%	60%
Bidder E4	0%	40%	60%	900 -1000	10%	30%	60%
Bidder E5	10%	30%	60%	320-520	70%	20%	10%

4.3 Performance analysis

Five scenarios, involving the four hypothetical bids and one of the extreme bids, are examined to wargame the bid evaluation plan. For each scenario, a ranking probability matrix is calculated to determine how likely a given bid is ranked at a particular position (i.e., robustness of bid rankings). Table 3 depicts the ranking probability matrix for the bids in the first scenario (A, B, C, D, and E1) obtained after 100,000 replications of the simulation-based AHP algorithm. Figure 2 shows also the probability distributions of the total scores (calculated using the weighted sum method) for the different bids in the scenario. The analysis indicates that Bid E1 would be ranked last and would not be a critical extreme bid. The expected bid ranking and scores (%) would be: B (69), A(68), C(64), D(63), E1(60). The most probable bid rankings are highlighted in Table 3. As the rank probabilities are low (24% to 39%) it is anticipated, based on expected bidder profiles, that the bid competition will have multiple potential winners. In particular, bids B, C and D have comparable rank probabilities and would compete for the second position (the second position would be important if the bidder in the first position couldn't get the contract for other reasons). Results of the remaining scenarios are presented in Table 4 and Figure 3. The analysis indicates that E2, E3 and E4 would not be critical extreme bids (E2 ranked last and E3 and E4 ranked in the third position). Bid E5 would be a critical extreme bid as it has 37% probability of ranking first. However, the E5 profile (i.e., performs very poor for the relational criterion and very well for the remaining criteria) would make it an unlikely bid proposal (based on historical bid profiles).

Table 3: Ranking probability matrix (Scenario 1).

Bid	**Probability (%) for each Rank**				
	1	**2**	**3**	**4**	**5**
A	34	26	19	13	8
B	37	26	18	12	7
C	13	21	24	23	19
D	10	17	21	25	27
E1	6	10	18	27	39

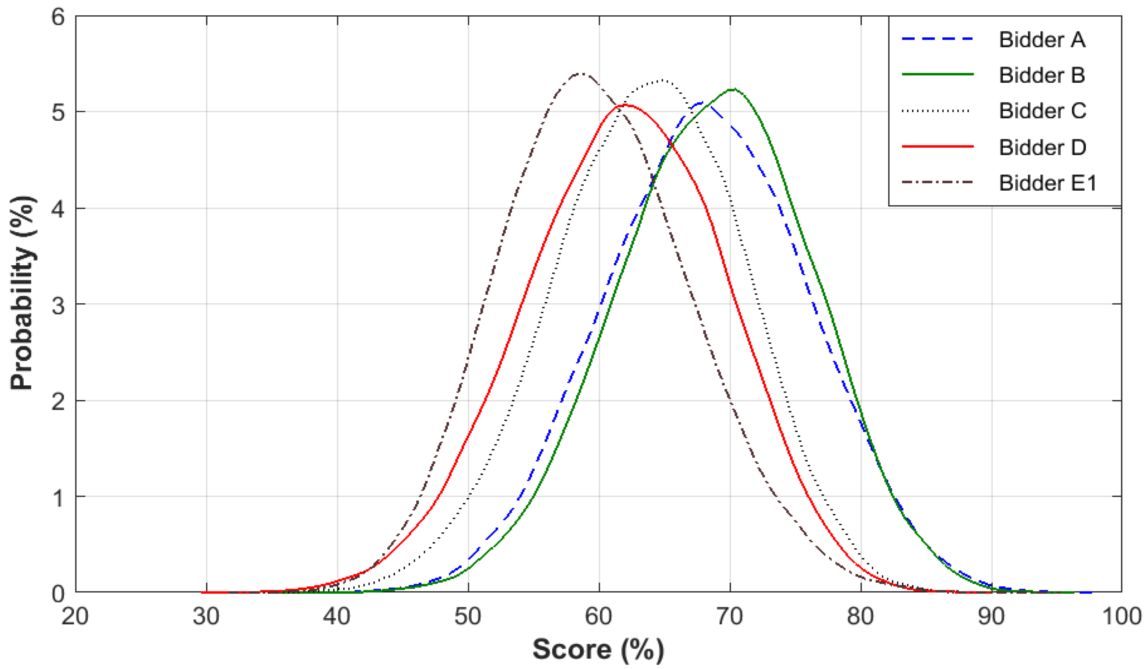

Figure 2: Bid score probability distributions (Scenario 1).

Table 4a: Ranking probability matrix (Scenario 2).

Bid	Probability (%) for each Rank				
	1	**2**	**3**	**4**	**5**
A	37	28	20	12	3
B	39	29	19	11	2
C	13	23	29	26	9
D	11	18	26	32	13
E2	0	2	6	19	73

Table 4b: Ranking probability matrix (Scenario 3).

Bid	Probability (%) for each Rank				
	1	**2**	**3**	**4**	**5**
A	33	24	19	14	10
B	35	25	18	13	9
C	11	18	22	25	24
D	9	15	19	24	33
E3	12	18	22	24	24

Table 4c: Ranking probability matrix (Scenario 4).

Bid	Probability (%) for each Rank				
	1	**2**	**3**	**4**	**5**
A	30	24	19	16	11
B	34	25	19	13	9
C	12	17	22	25	24
D	9	15	19	24	33
E4	15	19	21	22	23

Table 4d: Ranking probability matrix (Scenario 5).

Bid	Probability (%) for each Rank				
	1	**2**	**3**	**4**	**5**
A	23	23	22	19	13
B	25	25	22	17	11
C	8	15	21	27	29
D	7	12	17	25	39
E5	37	25	18	12	8

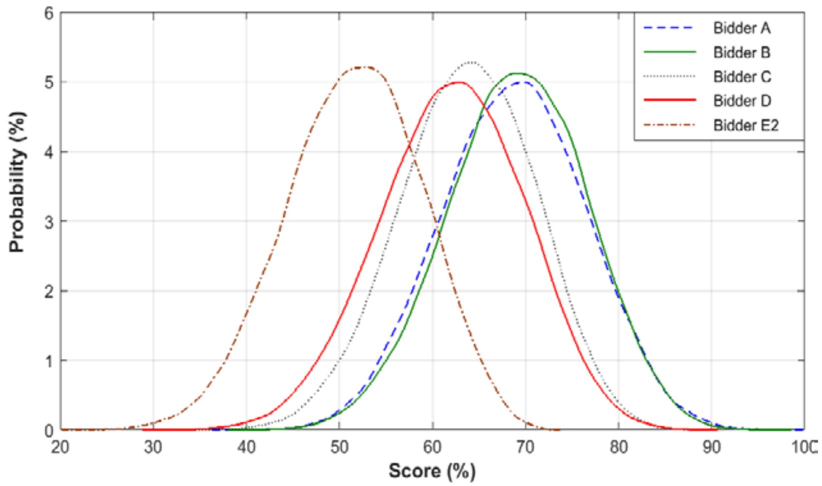

Figure 3a: Bid score probability distributions (Scenario 2).

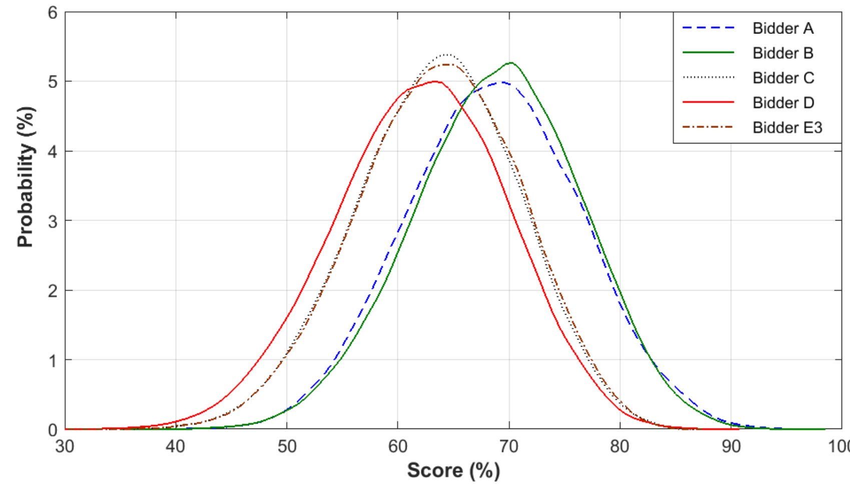

Figure 3b: Bid score probability distributions (Scenario 3).

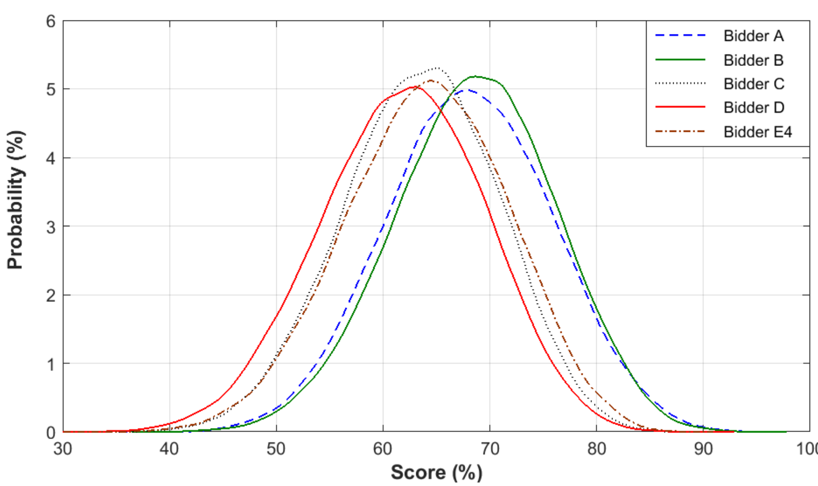

Figure 3c: Bid score probability distributions (Scenario 4).

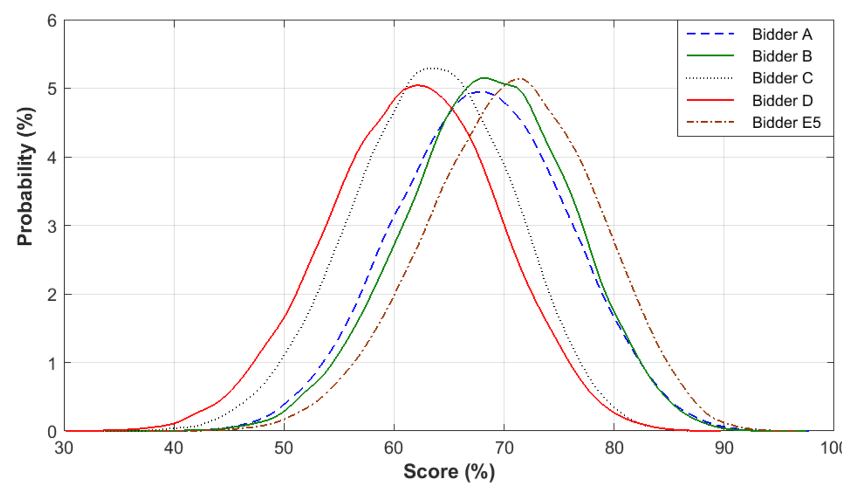

Figure 3d: Bid score probability distributions (Scenario 5).

4.4 Criteria ratio analysis

Technical and value proposition criteria are the most important criteria for the ship in-service support contract bid evaluation problem. A sensitivity analysis was conducted to assess the impact of varying the weights of these criteria on the probability that bidder B (for example) is ranked first. Figure 4 presents the ranking probability contour for different combinations of technical and value proposition criterion weights for scenario 2 (for example). The red dot represents the ranking probability using the current weight combination (70% for technical and 15% for value proposition). The analysis indicates that reducing the technical and/or the value proposition weights would reduce the ranking probability for bidder B. For this example, the minimum ranking probability is 27% and the maximum ranking probability is 40%.

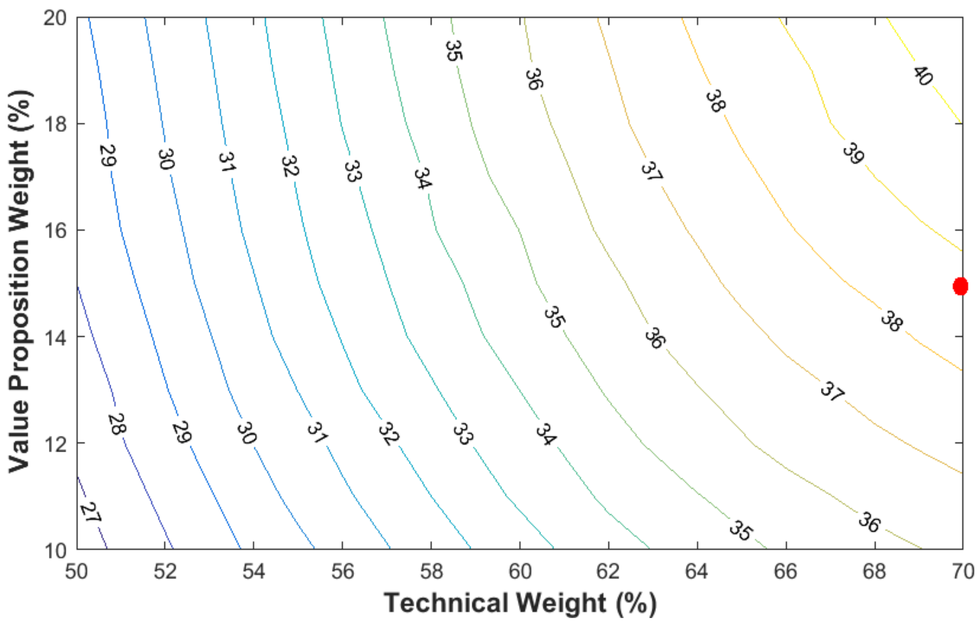

Figure 4: Probability (%) contour for bidder B ranking first.

5. Conlcusion

The paper presents a stochastic AHP method for analyzing the bid evaluation plan of military in-service support contracts. The method integrates multi-criteria decision analysis, Monte Carlo simulation, and optimization techniques and determines a ranking probability matrix to assess the robustness of the bid evaluation plan and to explore potential extreme bids. An example using a bid evaluation plan for a military ship in-service support contract is presented and discussed to illustrate the methodology. A set of hypothetical bids, involving different bidder profiles, is used in the analysis to wargame the bid evaluation plan and to identify potential extreme bids. For these bids, the overall ranking probabilities vary from 24% to 42%, indicating that the bid competition will have multiple potential winners. The analysis indicates that some bids (e.g., E1, E2, E3 and E4) would not be critical extreme bids, but other bids (e.g., E5) would be critical extreme bids. Options to prevent undesirable extreme bids would include using a lower bound on the technical experience score (minimum score requirement) or a higher weight of the value proposition criterion. The study provides project managers with a decision support tool for refining and optimizing bid evaluation plans of military systems in-service support contracts to avoid extreme bids. Future work would include exploring extreme bids using a constrained weighted-sum scoring method to count the number of the score-extremities (vertices of the convex polytope) allowed within a weighting model as well as applying the methodology to the acquisition of other military systems (e.g., aircraft).

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Biography

Ahmed Ghanmi received a Bachelor degree in civil engineering, a Master degree in applied mathematics, and a PhD in computational fluid dynamics from Laval University, Québec, Canada. He is currently a senior defence scientist at the Defence Research and Development Canada – Centre for Operational Research and Analysis. His research interest includes military operational research and analysis applied to joint targeting, materiel acquisition, supply chain, operational energy, risk analysis, and decision support. He has published numerous papers in international referred journals and conference proceedings, and has authored several technical reports. Dr Ghanmi has chaired different North Atlantic Treaty Organization research groups, led various technical projects in defence research and analysis and chaired sessions in different international conferences.