A Preference Structuring Framework for Appraising Complex Engineering Programs

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Abstract

Appraising and selecting a preferred supplier for the acquisition or development of systems under a complex engineering program is a multi-dimensional and multi-faceted decision. It comprises many, often competing, objectives and multiple attributes upon which to appraise a program and establish a measure of overall value. These objectives and attributes represent the many value dimensions of a program and stakeholder preferences, however they often conflict due to complicated relationships between one another. The need to include qualitative and quantitative attributes (factors) in the presence of uncertainty gives rise to additional complications.

This paper introduces a multi-attribute value based framework and stated preference approach to appraising competitively tendered contracts applicable to major programs. The framework comprises two stages, value analysis and preference structuring, and is applied to systematically structure and value complex decision problems in terms of qualitative and quantitative attributes. The preference structure modelling component is based on the statistical design of experiments to identify preference structures and support trade-offs between classes of attributes.

Key words: Complex Engineering Programs, Decision Analysis, Multi-attribute Value, Stated Preference Models.

1. Introduction

Managing the acquisition and development of a Complex Engineering Program is clearly a challenge. Appraising a tender within such a program to establish an objective measure of overall value and likely success on the basis of qualitative and quantitative attributes is equally, if not more, challenging. The scale of these programs is both enormous and multi-dimensional. They are characterised with high levels of ambiguity and uncertainty, and the presence of multiple, often conflicting, objectives and stakeholder values. These characteristics lead to difficulties and inconsistencies in identifying, structuring and measuring the values, attributes, and objectives of a program. Consequently, identifying and modelling the values and preference structures of decision-makers to allow trade-offs between attributes also becomes increasingly difficult. To manage these difficulties and challenges, decision-makers must identify and understand the relationships between the factors of a particular program that contribute value and lead to success.

The appraisal of complex engineering programs and selection of a preferred supplier should be considered on the basis of attributes and criteria that establish a coherent measure of value across all dimensions [1, 2, and 3]. Often, the viability, value and likely success of a program is largely considered on attributes (factors) and criteria that relate to cost, schedule, scope, risk, and technical feasibility. The reasons for this are clear and for the most part largely understandable. Quantitatively, they are easily measured. As such, judgment and decision making is perceived as being objective and therefore easily defendable. However, the consequences are that decisions ultimately collapse into "simple" trade-offs between cost, schedule and technology. From a business perspective this may appear reasonable, but it does not examine the underlying preference structures of stakeholders and decision makers across all the value dimensions of a program.

Increasingly, there is growing awareness that program appraisals based solely on financial and technical attributes do not represent total value, nor do they provide a coherent or reliable measure upon which to gauge a program's likely success, risk and overall value [4]. Consequently, it is necessary to broaden the appraisal framework to consider other attributes, including, supplier reputation and performance, managerial experience and competence and engineering capability. These do reflect additional risks and are value drivers that, when ignored, have led to in-effective governance of programs and subsequent failures despite being successful when measured in economic and technical terms [5]. However, including qualitative attributes into the appraisal is by no means trivial and often leads to difficulties with respect to providing consistent and meaningful results.

This paper proposes an integrated framework and behavioural modelling approach to structure complex decisions in the context of appraising major programs. It is referred to as Multi-attribute Value Analysis and Preference Structuring (MaVAPS). Whilst this paper outlines an overall approach for identifying, structuring, and modelling relationships between various attribute classes, its focus is centred around a description and application of experimental design to identify preference structures relevant to the appraisal of complex engineering systems and major programs.

2. The Appraisal Framework

A framework that provides a systematic, structured, and robust approach to assist decision-makers in making complex judgments will facilitate improvement in the appraisal process in terms of its reliability and effectiveness. The objective of this framework is to provide coherency, consistency, and a means for comparative judgments with respect to values, preferences and courses of action with outcomes and consequences. The framework should guide thinking about the facts, values and unique aspects of a given situation and provide a basis for understanding and managing the many complexities, dependencies and relationships required to appraise a program. This requires a structure that is both context dependent and requisite. That is, it represents a shared reality of the form and content which is sufficient to solve the problem [6].

Multi-attribute Value Analysis and Preference Structuring (MaVAPS) is a two stage integrated decision support framework. It is an extension of a previous developed concept that proposed stated preference modelling as a means to evaluate Competitive Tendered Contracts [1]. Figure 1 indicates the framework and principle elements, details of which are provided in [1, and 7].

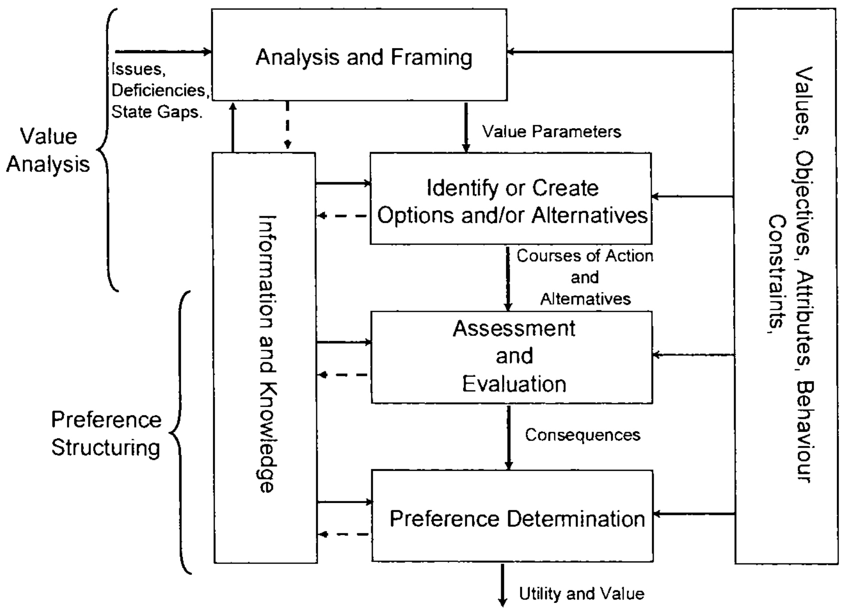

Figure 1 – Integrated Decision Making Framework.

Briefly, the framework draws on the principles and practices of Decision Analysis to first structure complex multi-attribute problems [2, and 8]. The outcome of stage 1 is a values and performance matrix upon which to design statistical experiments and model stakeholder preference structures. Stage 2 uses Stated Preference (SP) methods as derived from Random Utility Theory (RUT) to elicit and identify preferences based on the bundling of attributes related to a program, system, product or service [9].

Whilst the overall approach has some similarities with Multi-attribute Utility Theory (MAUT), there are structural differences. These include the use of statistical designs and Stated Preference (SP) models, during stage 2, instead of Subjective Expected Utility (SEU), to elicit preferences in regard to options or alternatives. This enables analysts to quantify preferences and develop behavioural decision models through the use of experimental designs to construct choice or preference sets.

3. Quantifying Choice and Preferences

Stated Preference (SP) methods provide a flexible and robust approach to elicit preferences with respect to programs, systems, products, and services. They are particularly useful for placing a value on non-market assets and services by identifying the attributes that stakeholders value the most, independent of monetary value. That is, in the context of complex programs, attributes such as, cost, quality, schedule, and supplier performance, etc are treated simultaneously to model the effect of changes across attribute levels. In addition, the method is not reliant on existing data, and each unique alternative or option is represented as a function of its attributes and respective levels or ranges. Consequently, it is possible to measure the preferences and attribute effects within "constructed" programs of alternatives to uncover additional value drivers.

In the context of program appraisals we assume that decisions made with respect to the selection of a preferred supplier can be modelled as a discrete choice using Stated Preference. Experimental designs are used to develop preference or choice sets that describe a suite of alternatives in terms of defined attributes, and their respective levels and ranges. They are generated to identify statistically efficient preference functions, whilst simultaneously keeping the number of combinations to manageable levels [10, and 12]. Often this requires the use of fractional factorial designs where only a portion, or "fraction", of all possible attributes and their respective levels is considered in the experimental design structure [9].

Sets of alternatives are evaluated by respondents, in our case stakeholders, suppliers, customers or program managers, to select the "best" alternative on the basis of their individual preferences. The preference function of stakeholders and individuals is assumed to be a random process and further assumes that each seeks to maximise utility. Utility is dependent upon both the influences of the program dimensions and its attributes being considered, along with the characteristics of preferences relevant to stakeholders and decision-makers. As such, there is a systematic (observed) and random (unobserved) component. These components, respectively, represent the behavioural elements common to decision-makers, and an aggregation of all unobserved influences that arise due to individual preferences [9]. Total utility is then, the summation of the systematic or observed and random or stochastic components. This is represented by:

$$U_{in} = V_{in} + \varepsilon_{in} \quad (1)$$

$$U_{jn} = V_{jn} + \varepsilon_{jn}, \; j = 1,....J. \quad (1a)$$

Equation (1) represents the overall utility that the *n*th individual, associates with the *i*th alternative. Similarly, equation (1a) provides a measure of utility for the *j*th alternative where J is the total number of alternatives. The term, V, represents the *i*th and *j*th components of observed utility, while the terms, ε_{in} and ε_{jn}, represent the error or unobserved components of utility. As such, utility is considered maximized for example, when alternative *i* is chosen in preference to alternative *j*. That is, $U_{in} > U_{jn}$. The probability that the *i*th alternative, *i* is chosen by the *n*th decision maker from the complete set of choices or alternatives, C under consideration is given by:

$$P(i \mid C) = P[U_{in} \geq U_{jn} \forall j \in C] = P[U_{in} = \max_{j \in C} U_{jn}] \quad (2)$$

$$P(i \mid C) = \frac{e^{(U_{in})}}{\sum_{j=1}^{J} e^{(U_{jn})}} = \frac{e^{(\mathbf{x}_i \boldsymbol{\beta})}}{\sum_{j=1}^{J} e^{(\mathbf{x}_j \boldsymbol{\beta})}} \quad (3)$$

Equation (2) represents the basic structure for determining the probability of a particular alternative or program structure being selected over all available options/alternatives. Operationalised models and assumptions with respect to error distributions allow numerical values to be calculated in accordance with equation (3). Here, $\mathbf{x}_i$ is a vector of alternative attributes and $\boldsymbol{\beta}$ is a vector of unknown parameters [11]. In terms of a program appraisal the resultant model provides a means for establishing the probabilities of preferences for particular program attributes.

4. An application of Preference Structuring

In this paper we provide an example and results from a concept study that applied the Multi-attribute Value Analysis Preference Structure (MaVAPS) framework to the appraisal of large scale technology based projects. The application has been deliberately kept simple in regard to the number of value dimensions, attributes, attribute levels/ranges and respondents considered and emphasises the use of experimental designs to identify preferences. For this concept study, we used 40 senior program and engineering managers with experience in delivering technology based systems for the defence and telecommunications sectors. SAS[1]® software was used to generate the experimental designs, questionnaires, and conduct statistical analysis. The following general steps were undertaken for the study.

1. Analysis and framing of decision Problem. Establish context of problem, constraints and identify key stakeholders;
2. Identify Value Dimensions, relevant attributes and indicative ranges/levels;
3. Determine number of choice sets required and develop a linear design;
4. Evaluate this linear design in terms of correlations, frequencies, orthogonality and statistical efficiency;
5. Create a choice design from the linear design, format and evaluate;
6. Generate questionnaires, elicit preferences, collect response data;
7. Data analysis, parameter estimation and model.

Our initial steps (1&2) sought a consensus on the purpose and objective of a program appraisal in an effort to frame and contextualise the study. To achieve this, we conducted interviews with several of the senior managers and also undertook a review of recent literature related to program appraisals. Whilst we found no readily accepted definition on the purpose and objective of an appraisal, there was evidence of a common theme. That being, the appraisal should provide an objective assessment of a suppliers' ability to perform well across all value dimensions of a program subject to constraints; cost, quality, schedule, etc [7, 13, and 14]. With respect to step 2, we concluded that most programs appeared to be appraised on the basis of between six (6) and ten (10) value dimensions, of which each comprises several attributes (factors). Typical value dimensions relate to economic or financial, technology, management capability, engineering expertise and capacity, organisational effectiveness, etc, or some variation. Generally, the associated attributes comprise a mix of qualitative and quantitative data that relate to delivered cost, operational and support cost, risk, past performance on similar programs, schedule, scope, financial stability, etc. [13].

The value dimensions considered for this study are Organisational Effectiveness, Economic/Financial and Technology. The three attributes are Company, Acquisition Cost, and Software, noting that the last two have discrete levels/ranges. The attribute of company infers the selection, or consideration, of a supplier based on a subjective determination of its perceived organisational effectiveness and performance in previously delivering similar systems. As such, we note the presence of both attribute classes; quantitative and qualitative. Table 1 provides the value and performance matrix from steps 1 and 2.

Table 1 – Value and Performance Matrix

Factor	Company	Value Dimension	Attribute	Levels/Ranges	Measure
x1	Supplier 1	Economic/Financial	Acquisition Cost	$105m, $110m, $120m, $125m	$
x3	Supplier 2	Economic/Financial	Acquisition Cost	$105m, $110m, $120m, $125m	$
x5	Supplier 3	Economic/Financial	Acquisition Cost	$105m, $110m, $120m, $125m	$
x2	Supplier 1	Technology	Software	Un-Precedented, Existing	
x4	Supplier 2	Technology	Software	Un-Precedented, Existing	
x6	Supplier 3	Technology	Software	Un-Precedented, Existing	

[1] SAS®, Statistical Analysis System, registered software.

Steps 3 and 4 use the value and performance matrix information in Table 1 to generate and evaluate linear designs. This example represents 6 factors relevant to the appraisal and requires a minimum of [3x (4-1)+3x (2-1) + 1] = 13 choice sets. 13 choice sets represent a saturated design and 512 [(4^3) x (2^3)] choice sets will be required for a full factorial design if we are to include all effects from interactions. In the interest of keeping the example simple and to achieve the greatest possible statistical efficiency, we seek a main effects (no interactions between attribute and their levels) design that is both balanced and orthogonal. As such, a linear design with a minimum of 16 choice sets is required, since 16 is divisible by 2, 4, 8, and 16. Using the SAS software a balanced, orthogonal and 100% efficient linear design was obtained. That is, no factors are correlated with one another, and each level and pairs of levels occur with equal frequency. In addition, no choice set is duplicated.

The SAS software is used during step 5 to create, code and format a choice design from the linear design. Tables 2 and 3 show respectively, the coded and formatted results for choice set # 2 which includes a constant alternative of "No Preference" within all choice sets. Its selection is likely to indicate that a stakeholder or decision maker (respondent) considers there is no value or benefit in selecting amongst the available alternatives.

Table 2 – Coded Design Matrix Output (Partial)

Choice Set	Company	Acquisition Cost	Software
2	Supplier1	4	1
	Supplier2	1	1
	Supplier3	3	2
	No Preferred	.	.

These coded values equate to combinations of attribute levels. For example, the first row of the coded design matrix represents choice set #2. Here, Company = Supplier1, Acquisition Cost = 4 represents an acquisition cost of $125m, and Software = 1 represents Unprecedented or yet to be developed technology. Similarly, for the third row Company = Supplier3, Acquisition Cost = 3 representing an acquisition cost of $120m, and Software = 2 represents existing or available technology. Table 3 provides the formatted choice set #2.

Table 3 – Formatted Design Matrix Output (Partial)

Choice Set	Company	Acquisition Cost	Software
2	Supplier 1	$125m	Un-precedented
	Supplier 2	$105m	Un-precedented
	Supplier 3	$120m	Existing
	No Preferred	.	.

The final task within step 5 is to evaluate the statistical properties of the choice design. Table 4 provides the results of this evaluation.

Table 4 – Design Matrix Evaluation Output (Partial)

n	Variable	Variance	DoF	Standard Error
1	CompanySupplier1	0.9444	1	0.97183
2	CompanySupplier1	0.9444	1	0.97183
3	CompanySupplier1	0.9444	1	0.97183
4	AcquisitionCost$105m	0.8889	1	0.94281
5	AcquisitionCost$110m	0.8889	1	0.94281
6	AcquisitionCost$120m	0.8889	1	0.94281
	AcquisitionCost$125m	-	0	-
7	TechnologyExisting	0.4444	1	0.66667
	TechnologyUnprecedented	-	0	-

The results indicate that all parameters can be estimated and that standard errors are reasonable. In Step 6 all 16 questionnaires were constructed using the SAS software. These were presented to the 40 program and engineering managers who saw all 16 choice sets, each of which contained 4 alternatives. Prior to the survey, a discussion was held with each manager (respondent) to describe each of the hypothetical suppliers in terms of their respective past performance and overall governance in successfully delivering major programs. The following represents choice set #2 as seen by respondent #1.

Form: #1 Choice set: #2 Subject: #1

1. Indicate your Preferred combination of technology, price and supplier for the acquisition/development of a Complex Engineering System:
   a. System delivered by ***Supplier1*** using ***unprecedented*** technology and costing ***$125 Million***;
   b. System delivered by ***Supplier2*** using ***unprecedented*** technology and costing ***$105 Million***;
   c. System delivered by ***Supplier3*** using ***Existing*** technology and costing ***$120 Million***; or
   d. No Preference.

The forty (40) respondents saw all 16 choice sets once only and indicated a ***single*** preference in terms of all available (designed) alternatives. This provided a total of 2560 observations, derived from 16 choice sets with 4 options with 40 respondents (i.e.16x4x40).

Table 5 – Choice Results (Partial)

Choice Set #	Subject #	Company	Acquisition Cost	Technology	Choice Results
2	1	Supplier 1	$125m	Un-precedented	2
		Supplier 2	$105m	Un-precedented	2
		Supplier 3	$120m	Existing	1
		No Preferred	.	.	2

Table 5 provides the coded results for choice set #2. The numeral "1" in the choice results column indicates the preferred option/alternative and the numeral "2" indicates those not selected. Therefore, we expect to see a single occurrence of the number 1 and three occurrences of the number 2 for each choice set. The survey results indicated that this is indeed the case. In this example, we observed that the respondent (subject #1) preferred the option/alternative indicated in the shaded row of Table 5. That is, they preferred supplier 3 for managing the acquisition/development of a complex engineering system comprising existing, or available, software at a cost of $120 Million. All responses were collected and subsequently analysed with SAS.

Table 6 – Model Parameter Estimates

Variable	DoF	Parameter Est	Standard Error	Chi-Square	Pr > ChiSq
Company:					
Supplier 1	1	2.2128	0.3461	40.868	< 0.0001
Supplier 2	1	2.1768	0.3463	39.499	< 0.0001
Supplier 3	1	2.4201	0.3440	49.491	< 0.0001
No Preference	0	0	.	.	.
Acquisition Cost:					
$105m	1	0.9963	0.1577	39.927	< 0.0001
$110m	1	0.8962	0.1588	31.834	< 0.0001
$120m	1	0.5396	0.1584	11.600	0.007
$125m	0	0	.	.	.
Software:					
Un-Precedented	0	0	.	.	.
Existing	1	0.2877	0.1053	7.4668	0.0063
	7				

In this illustration the Multinomial Logit (MNL) model was specified to determine part-worth utility parameters for the attributes under consideration. Results and estimates for each parameter, their standard errors, and associated statistics are summarised in Table 6, noting that all are significant. Variables indicated with zero degrees of freedom represent the constant alternative of "NoPreference" within the Company attribute, and a base (reference) level for the attributes Acquisition Cost and Software.

As expected the utility for a system with the lowest acquisition cost (price) is clearly greater than that for the more expensive proposals. However, at the lower range, the difference between utility for the least expensive and second least expensive proposals is marginal.

Parameter estimates for all three suppliers indicate some marginal utility and a possible advantage associated with using supplier 3. Suppliers 1 and 2 provide similar utilities indicating that any choice between these two is likely to be determined on the basis of cost.

In terms of technology, the results show a clear preference for systems that utilise existing, or readily available software as opposed to those requiring unprecedented, or yet to be developed software. This outcome could well be explained through current concerns, where the development of complex systems, particularly those with high levels of software often take several years to develop, and once fielded almost immediately require a technical refresh or run into obsolescence issues.

While the example presented in this paper is relatively simple it does demonstrate how the framework can assist decision-makers in making complex judgments in relation to the appraisal of complex programs. In particular, it provides a basis for determining and valuing programs and projects in terms of attributes and utilities that stakeholders value the most, regardless of attribute class.

5. Conclusion

This paper illustrates the application of an integrated decision support framework to support the appraisal of tenders relevant to the acquisition or development of complex engineering systems. This framework was produced in response to industry needs to improve the delivery of complex systems through competitively tendered contracts. The framework recognises the notion that value and success can not be measured purely in terms of financial or technical attributes and that successful delivery depends on other factors related to source selection and the governance of major programs.

The Multi-attribute Value Analysis and Preference Structuring (MaVAPS) approach described in this paper provides a basis for addressing these concerns. It utilises appropriately designed experiments to determine the preference structures of stakeholders and decision-makers, to identify the relationships between attributes (factors), their classes and their effects in appraising and selecting programs.

The key benefits of this approach include:

1. A systematic and robust approach to the identification of the stakeholder values, objectives, attributes and preference structures;
2. The inclusion of both quantitative and qualitative attribute classes to represent the many value dimensions of a program;
3. A formalised means to establish behavioural models of decision making and preferences as a result of variations in the ranges/levels of attributes,
4. A Structure for identifying and modelling the significance of program attributes and the effects of any interactions; and
5. Identifies potential trade-offs between attributes and their levels/ranges.

While the example presented in this paper is not very complex, it is sufficient to convey the central tenets of the experimental design technique as applied to complex decision making. The framework presented here may be extended to include more complicated preference structures and higher order interaction effects to identify trade-offs in terms of weighted attributes. In addition, models can be developed as a means to assist suppliers in estimating their chances of winning a tender.

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