Chapter 4 – METHODS

4.1 GENERAL

This chapter discusses the different methods of generating life cycle cost estimates and conducting cost analyses at various stages in the NATO PAPS cycle. It is not meant to be a prescriptive description of the methods which are best found by accessing the reference books and web sites but does provide guidance on the appropriate approaches to life cycle costing for each PAPS phase.

4.2 OVERVIEW OF METHODS

Most cost estimates require the use of a variety of methods. A different approach may be used for each area of the estimate so that the total system methodology represents a combination of methods. Sometimes a second method may be used to validate the estimate.

When choosing an estimating method, the cost estimator must always remember that cost estimating is a forecast of future costs based on a logical interpretation of available data. Therefore, availability of data will be a major factor in the estimator's choice of estimating methodology.

The best combination of estimating methods is the one which makes the best possible use of the most recent and applicable historical data and systems description information and which follows sound logic to extrapolate from historical cost data to estimated costs for future activities.

An example of this is would be to use data gathered through expert opinion combined with methods for simulation to obtain reliable data to conduct simulations on different support organisations. Linear programming might then be used to optimise a spares inventory for the chosen support organisation. These values can then be used in the parametric techniques employed in estimating the total life cycle costs for the programme.

The following table shows how the methods have been categorised for easy reference.

Table 4-1: Method Categorisation

Method Category	Methods
Optimisation	Linear programming Heuristics
Simulation	System Dynamics Discrete Event Monte Carlo
Calculation/Estimation	Analogy Parametric Bayesian Engineering Catalogue Rule of Thumb Expert Opinion
Decision Support	Analytical Hierarchy Process Multi-Criteria Decision Analysis

4.2.1 Optimisation Methods

Mathematical programming and heuristics are both common forms of optimisation methods. Linear programming is a subset of mathematical programming but deemed important enough to be described separately.

4.2.1.1 Linear Programming

Linear programming is a mathematical modelling technique designed to optimise the usage of limited resources. The usefulness of this technique is enhanced by the availability of highly efficient computer codes. A linear programming model consists of three basic elements:

- Decision variables that need to be determined.
- Objective (goal) that need to be optimised.
- Constraints that need to be satisfied.

Linear programming is particularly useful for large and medium scale problems in which there are many variables and many constraints to be considered. Therefore, the use of linear programming is often supported by computer software.

4.2.1.2 Heuristics

Methods based on heuristic approaches use standardised rules of thumb repeated many times in order to find a good enough solution to a problem. These types of models can be easier to apply than the mathematical programming methods. There are, one the other hand, no guarantees that the solutions found will be the optimal choices for solving the problem.

4.2.2 Simulation Methods

System dynamics and discrete event simulation are both forms of simulation models that allow a representation of the activities of a system over time. In each case, the simulations step through time and perform calculations for that point in time which will change the state of the system in some way. The end state at one point in time is the start state for the next.

4.2.2.1 System Dynamics

System dynamics works by using even time steps. It keeps track of how many items are in particular locations (stocks) in the system (items can be entities such as people, cash or can represent fluids). It works by allowing flow into and out of stocks through valves. The structure of the model allows the development of behaviour to control the flows, and to provide measures based on the state of the system (such as costs). One of the most powerful features of system dynamics is the visual structure of the model that helps users and developers to understand the relationships between elements of the model. This structure allows the representation of complex behaviour while using comparatively simple equations for each relationship.

System dynamics are usually good for building models with a wide scope and long run behaviours. They are generally quicker to build than discrete event simulations and also execute more quickly. The models do not usually contain stochastic elements although they can be repeatedly run with different input values to examine uncertainty around inputs. System dynamics models are good for life cycle costing where there can be a wide scope for cost drivers, large numbers of items and long duration.

4.2.2.2 Discrete Event Simulation

Discrete event simulation uses uneven steps in time with the model jumping to the point in time where the next event will occur. The event will cause a change in state of the system that can trigger other events to occur immediately and/or schedule another event to occur at a point in the future. The model keeps track of every entity in the system in terms of location and can store characteristics of each entity. Many of the models have animations that show the state of the system, although much of the actual logic is hidden below the surface of the model.

Discrete event simulation is good for building models with a narrow scope and relatively short-term durations. They generally take longer to build than system dynamics models and execute more slowly because each of the entities is represented individually. The model allows stochastic elements, using sampling from probability distributions to represent things like inter-arrival times and durations of activities. Due to the stochastic elements in the models, all experiments should make use of multiple runs in order to calculate means and standard deviations for the key output variables. Discrete event simulation is good for logistics models where it is important to understand how the system can deal with peaks and troughs in demand.

4.2.2.3 Monte Carlo Simulation

Monte Carlo simulation is used in defence cost analysis to generate frequency or probability distributions which are otherwise too difficult or impossible to generate mathematically, that is, using formulae. More specifically, all variables in a cost estimating model potentially affected by risk and uncertainty are first identified. Then, probability distributions are estimated or selected for each. This entails first choosing the type of distribution to apply and then estimating the distribution's parameters. Possible distribution types include:

Figure 4-1: Example of Typical Distribution Types.

Monte Carlo simulation generates random values for each of the uncertain variables over and over again, according to the type of distribution chosen, to produce a frequency or probability distribution of total costs for a weapon system or automated information system acquisition programme. Figure 4-2 shows a typical Monte Carlo output, based on 5000 selections or trials.

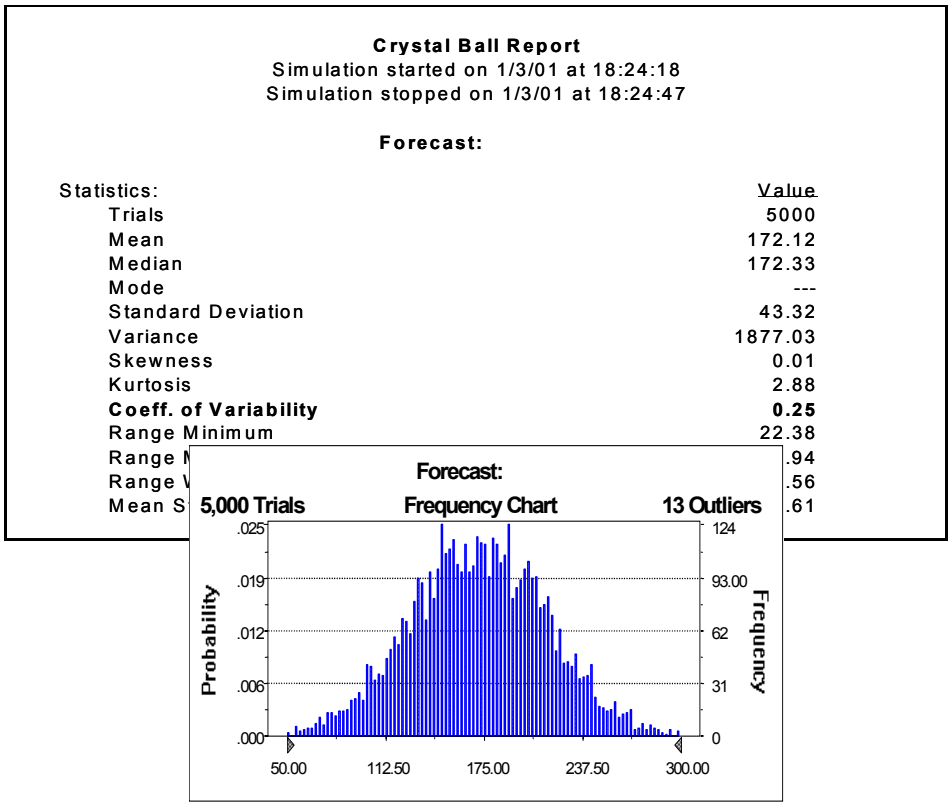

Figure 4-2: Example of Monte Carlo Output.

4.2.3 Calculation/Estimation Methods

4.2.3.1 Analogy

The analogous or comparative method assumes that no new programme represents a totally new system. Most new programmes originate or are evolved from already existing or simply represent a new combination of existing components.

The analogous method compares a new system with one or more existing systems for which there are accurate cost and technical data. The historic system should be of similar size, complexity and scope. The estimator/analyst makes a subjective evaluation of the differences between the new system of interest and historic systems. Normally, engineers are asked to make the technical evaluation of the differences between the systems. Based on the engineer's evaluation, the cost estimator/analyst must assess the cost impact of the technical differences.

It is not necessary to compare the new system to just one other analogous system. It may be desirable to compare some sub-systems of the new system to sub-systems of old system A, and other to sub-systems of old system B.

The advantage of the analogy method is that if a good analogy can be found, it allows for a lower level of detail, thus enhancing the credibility of the estimate.

The estimator should be cautious of using this technique without fully understanding the basis and the proper usage context. The major disadvantage of the analogy method is that it can be difficult to find a good analogy and the required engineering judgment.

An example of this method can be found at Sub-section 3.5.9.1.

4.2.3.2 Parametric

The parametric method estimates costs based upon various characteristics or measurable attributes of the system, hardware and software being estimated. It depends upon the existence of a causal relationship between system costs and these parameters. Such relationships, known as CERs (cost estimating relationships), are typically estimated from historical data using statistical techniques. If such a relationship can be established, the CER will capture the relationship in mathematical terms relating cost as the dependent variable to one or more independent variables. Examples would be estimating costs as a function of such parameters as equipment weight, vehicle payload or maximum speed, number of units to be produced or number of software lines of code to be written. The CER describes how a product's physical, performance and programmatic characteristics affect its cost and schedule.

The parametric or statistical method uses regression analysis of a database of similar systems to develop the CERs. Therefore parametrics rely on complex relationships and therefore require a considerable amount of data to accurately calibrate. Some of the commercially available cost estimating models do have historic public domain information attached and this enables the model to achieve reasonable results in the early phases of the procurement cycle when capability is known, but detailed requirements are poorly defined.

Parametric estimating is used widely in government and industry because it can easily be used to evaluate the cost effects of changes in design, performance, and programme characteristics. The major advantage of the parametric method is that it can capture major portions of an estimate quickly and with limited information. Parametric cost estimating, in essence, is usually a form of hedonistic regression analysis. More specifically, the cost of a weapon system, or component thereof, is typically postulated as a function of the technical, performance, and programmatic characteristics of that system. There are several advantages of this cost estimating technique:

- **Objectivity.** The cost-estimating relationship, ideally, is based on consistent, quantitative, non-subjective inputs, or values of the dependent and explanatory variables.
- **Ease of Use.** Values of cost, the dependent variable, can be easily calculated based on changes to any of the explanatory variables. This is useful for what-if, sensitivity analyses.
- **Tests of validity.** Standard outputs of regression analysis include F and t statistics which measure, respectively, the overall power of the set of explanatory variables in explaining changes in costs and of the significance of any one variable in explaining changes in costs.

A critical consideration in parametric cost estimating is the similarity of the systems in the underlying database, both to each other and to the system which is being estimated. Additionally, the database must be homogenous. A data element entry for one system must be consistent with the same data element entry for every other system included in the database. The major disadvantage of the parametric method is that it may not provide low level visibility and subtle changes in sub-elements cannot be reflected in the estimate easily.

An example of this method can be found at Sub-section 3.5.9.2.

4.2.3.3 Bayesian Techniques

Bayesian techniques deal with how a prior belief should be modified in the light of additional information e.g. later information or information from another source. A parameter to be estimated is known, on the basis of information available at the time, to have a certain value subject, since that information is

incomplete or of a probabilistic character, to a range of uncertainty i.e. there is a "prior probability distribution" of that parameter. Further information then becomes available which, of itself, suggests a different value and probability distribution for the parameter. Bayesian inference allows these two sets of data to be combined to give the most probable value (and least uncertainty) for the parameter in question i.e. the correct "posterior distribution".

Beliefs are expressed either as the probabilities of a finite number of discrete outcomes of a future event or else, as here, as the probability distribution of a continuous variable. The question to be answered becomes, therefore, that of how an initial estimate (the 'prior' distribution) is best modified in the light of additional information so as to obtain a refined estimate (the 'posterior' distribution).

Figure 4-3 presents the relationship between the inputs and outputs and shows how the cost estimates can be based on that which is known with some certainty and not on what can only be conjectured at the time the estimates are made. The approach also provides performance-based estimates from the earliest stage of the project life cycle and allows more precise design-based estimates to be derived as proven design data becomes available.

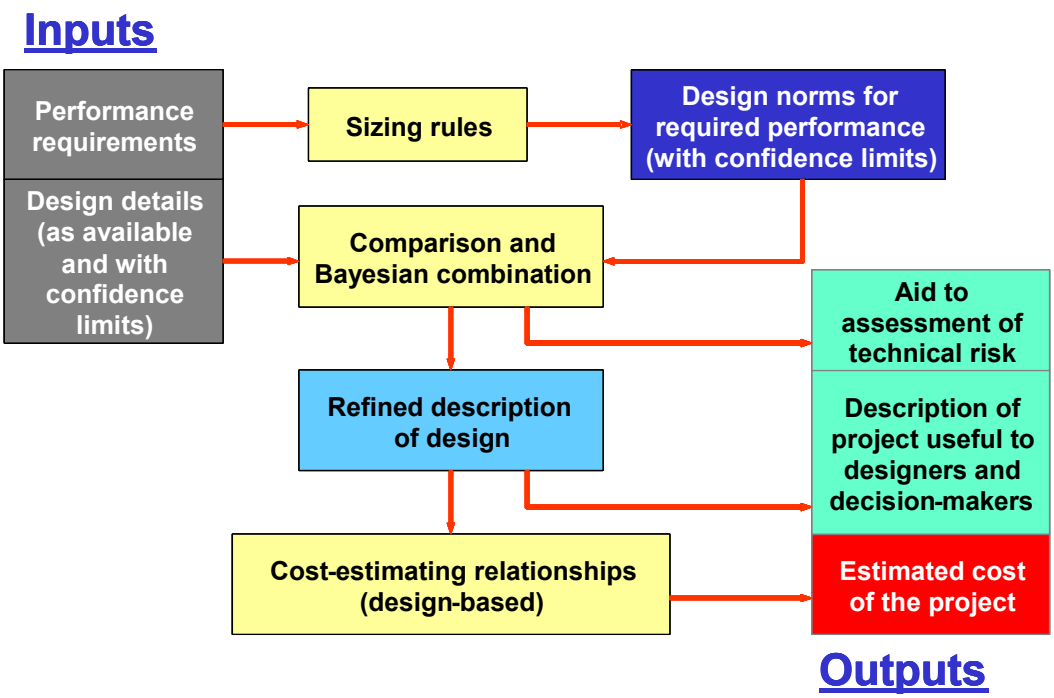

Figure 4-3: Bayesian Application to Cost Estimating.

Within the context of the techniques described above, such questions arise from design variables (on which the cost estimates are later to be based) being both supplied by the estimator and also derived within the model from the performance required of the equipment whose costs are to be estimated, as also input by the estimator. How this is done may be illustrated through an example.

Suppose that the estimator has supplied an estimate of the displacement of a ship as to be 10,000 ± 3,000 tons. This is the initial estimate i.e. the 'prior' distribution of displacement. The estimator has also supplied information concerning the performance required of the vessel in question. From that, the model computes, as a design norm, a displacement of 12,000 ± 4,000 tons.

It is now necessary to examine the compatibility of these two estimates.

In this case, the two estimates of displacement do not conflict. Rather, there is a high probability that they are both estimates of the same quantity i.e. of what will be the displacement of the vessel when designed fully and built. The question at issue becomes then what value of displacement should be used for the purposes of estimating the cost of this ship i.e. what 'posterior distribution should be taken forward into the next stages of the calculation.

There are various possibilities. They are:

(a) To use the estimate of displacement provided by the model i.e. that of 12,000 ± 4,000 tons;

(b) To use the estimate input by the estimator i.e. that of 10,000 ± 3,000 tons;

(c) To average the two estimates; or

(d) To combine the two estimates but to weight each according to its reliability as manifest by the uncertainty attached to each.

Clearly, the first approach (a) is incorrect since it concentrates solely on the estimate of lesser certainty and ignores that which is more certain.

The second approach (b) is more reasonable but unsatisfactory. The higher estimate is only somewhat less certain and it is inappropriate, therefore, to ignore entirely the indication given by the model that the displacement may well turn out to be higher than is supposed at present.

The third possibility (c) is yet more reasonable but it is still to be criticised. To average the two estimates (obtaining, thereby, a figure of 11,000 ± 2,500 tons) is to attach equal weight to both even though one is less certain than the other.

The fourth (d) (and Bayesian) approach is optimal. Weights attached to each estimate are those, which minimise uncertainty of the combined estimate and, so, make best use of all of the information available.

Details of the mathematics involved are not repeated here. However, the reader may gain an understanding of their basis by regarding each estimate as being (independently and hypothetically) the result of repeated sampling from the same (infinite) population comprising all possible values for, in this case, the displacement of the vessel in question. The estimate having the greater certainty is then the result of averaging more samples than was the case for the result having the lesser certainty. Accordingly the former is accorded more weight when all of the samples are pooled and a grand average computed.

In the present example the result of this Bayesian approach is an estimate of displacement of 10,720 ± 2,400 tons. Note that, as expected and as is reasonable, this inclines somewhat more to the more precise of the estimates being combined than their simple average. Note also that the uncertainty of this estimate is somewhat less than that resulting from simple averaging, again reflecting optimal use of all of the information available.

The utility of this approach may be illustrated further by considering the evolution of a project. At its earliest stages, prior to any design or development work, estimates of design characteristics, supplied by the estimator cannot be anything but imprecise. Through the Bayesian approach, the model will then rely upon the (the more certain) design norms, which it generates. As design and development proceed more certain information will become available to the estimator for input to the model and estimates will be based progressively more upon such data. When design and development are complete design characteristics will be known exactly. The model will then rely upon those alone thus a single model is able to respond appropriately, optimally and automatically to all of the circumstances encountered throughout the evolution of a project.

4.2.3.4 Engineering (bottom up)

The engineering or bottom up method of cost analysis is the most detailed of all the techniques and the most costly to implement. This technique starts at the lowest level of definable work within in the cost breakdown structure and builds up to a total cost. This type of estimate is used when detailed design data is available on the system. Two types of engineering estimates can be distinguished:

- An engineering estimate provided by a contractor. Making sure that the contractor has provided all the data and supporting information to clearly define the basis of the estimate.
- An engineering estimate provided by government personnel (an in-house prepared engineering estimate).

Engineering estimates prepared by contractors differ substantially from engineering estimates performed by government in at least two ways. First, the contractor prepared estimate is based on input from work units that will do the work and that have performed similar work in the past. Second, contractors are able to bring more detailed programme description data to the cost estimating process. For an engineering estimate provided by a contractor, an industrial engineer will estimate the labour hours, raw materials and parts required to complete the work. The industrial engineer may use a variety of techniques in estimating the direct labour and material cost of each discrete work element.

An engineering estimate prepared by a contractor do not usually include such elements as other government costs (e.g. other system and sub-system integration costs). It is also important to ensure that any engineering change costs are included in the government budget estimate submissions.

A contractor prepared engineering estimate will be used or evaluated by a government cost estimator. The following guidelines have proven useful in the past with respect to evaluating contractor prepared engineering estimates:

- Quickly find out the high cost areas or items and focus attention on them.
- If the evaluation is part of a source selection compare costs among contractors to spot unusually high or low costs for further investigation.
- If in time more than one cost estimate has been provided by the contractor see whether major changes were made to the cost estimate.
- Use audit report to check the validity of the rate and factors used by the contractor.
- In high cost areas, make sure the contractor has provided all substantiating information requested to generate a cost estimate.

Perhaps the most important guidance here is to require the contractor to submit cost data and substantiating information in a format that is clear, complete and ready for evaluation. The NATO generic cost breakdown structure developed by SAS-028 may help here.

In-house engineering estimates are mainly prepared to forecast out year cost for new systems. Government cost estimators usually obtain the necessary data through visits to and discussion with the prime contractors.

In-house engineering cost estimates differ from contractor prepared engineering cost estimates in several ways. For an in-house estimate fewer estimators, specialists and less information is available, especially when prior to production, when not much actual data is available. When the programme is in production, the differences should not be so significant.

The engineering cost estimate is most often used during the production an deployment phase. This technique encourages the contractor to do his homework early on and define all the work down to the lowest level of the cost breakdown structure.

4.2.3.5 Catalogue or Handbook Estimates

Handbooks, catalogues and other reference books are published that contain lists of off-the-shelf or standard items with price lists or labour estimates. The estimator can use these catalogue prices directly as unit values for standard components within a larger system.

4.2.3.6 Rules of Thumb

These refer to simple usually deterministic cost relationships. They are developed from an analysis of existing cost information.

Any rules developed should only be used at the early stages of project when actual specification and requirements are poorly defined.

4.2.3.7 Expert Opinion

An expert opinion may be used, when data required to use other techniques is not available. It is a judgemental estimate performed by an expert in the area to be estimated. Several specialists can be consulted until a consensus cost estimate is established. Surveying a number of experts independently to reach a consensus of opinion, the Delphi technique also may be used to provide a collective opinion.

An expert opinion can also be used to validate an estimate.

4.2.4 Decision Support Methods

4.2.4.1 Analytical Hierarchy Process

In grading or ordering the importance of a number of items in defence decision making, such as lists of operational tasks or lists of strategic requirements, Kenneth Arrow's "Impossibility Theorem" comes into play.[1] In a nutshell, the theorem indicates that no analytical technique exists that will simultaneously satisfy all commonly regarded fairness criteria in rank-ordering items in a list. Literally dozens of techniques for ordering preferences have been developed over the ages. These include the method of pairwise comparisons (used universally in the defence and commercial sectors), Borda's procedure (used by major league baseball in the U.S. for yearly selection of its most valuable player), and Tukey's algorithm, to name just a few. All techniques, however, as Arrow demonstrated, fall short of perfection.

Nevertheless, the demand for making selections and for ordering preferences remains unlimited. Hence, it is important to choose a method of ordering with good, robust statistical properties, such as those indicated above or below, realising, of course, that no technique is perfect.

The Analytic Hierarchy Process (see also 'Saaty Method'[2]) process is known as a soft operational research approach to quantify how important a criterion is compared to other criterion. This enables acquisition decisions to be approached using an auditable method that considers the importance of all the options against specific subjective and objective acquisition requirements.

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[1] Arrow co-shared the Nobel Prize in Economics in 1972 for this work, which was first undertaken in his Ph.D. dissertation a couple of decades earlier.

[2] The concept of AHP was developed, amongst other theories, by Thomas Saaty, an American mathematician working at the University of Pittsburgh.

It is used when making complex decisions involving many criteria. The process is particularly useful when conducting portfolio and options analysis. Some of the more complex models can provide a three dimensional view of the performance, cost and time aspects and present a graphical as well as a tabular output.

As the technique requires subjective judgement it is recommended that the process of allocating weightings and scorings should involve a team to avoid bias selections from any individual.

4.2.4.2 Multi-Criteria Decision Analysis

MCDA (Multi-Criteria Decision Analysis) is an established operational research technique with wide applicability. For example, in the UK, MACE (Multi-Attribute Choice Elucidation) is an adaptation of MCDA. It is a method for applying objective measurement to the relative merits of mutually exclusive acquisition options. Its principal application is in the assessment of bidder responses to tenders. The application of MACE should be focussed on the offer being made by a bidder. In certain circumstances investment appraisal may also play a part in the tender option assessment.

MACE translates key issues from the requirements for the options to be considered into logical items known as criteria. For each criterion MACE derives a numerical worth. The intermediate result is an assessment hierarchy of clearly defined and measurable criteria which is included in the RFI/ITT. Typically, each key user requirement in a NATO staff requirement is a candidate criterion.

Options are objectively marked against the criterion. Individual criterion marks are transformed and aggregated to produce numerical overall merit(s) for each option. The overall, and intermediate, merits are compared across the options, so informing the selection process.

MACE provides a methodical, objective, value adding, defensible and auditable assessment method, but it is only an aid to the decision making process. MACE may not always unambiguously isolate the best option, but when it does not it will provide reliable information to inform and support option selection. The ultimate decision on which option is to be selected is dependent on many factors, possibly including assessments using other methods. The factors (e.g. technical, commercial, financial, programme/risk management) to be included within a MACE assessment are determined on a case-by-case basis.

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4.3 SUMMARY OF FINDINGS

This section describes a summary of the methods that are being used by the participating nations, based on the analysis of the matrices, introduced in Chapter 1, that were completed by the participants. Figure 4.4 shows the results of this analysis graphically.

Method		Mission need	Pre-feasibility	Feasibility	Project Definition	Design & Developm.	Production	In-service	Disengage-ment
Optimisation	Optimization				○	○	○	○	○
Simulation	System Dynamics	○	○					○	○
	Discrete Event			○	○	◒	◒	○	○
Calculation / Estimation	Analogy	●	●	●	●	●	◒	◒	◒
	Parametric	●	●	●	●	●	●	◒	◒
	Bayesian		○						
	Engineering	○	○	◒	●	●	●	◒	◒
	Catalogue								
	Rule of Thumb	○	○	○	○	◒	○		○
	Expert opinion	●	◒	◒	◒	◒	◒	○	○
Decision Support	AHP	◒	○						
	MCDA					○			

Legend

blank	*No nation*
○	*1 nation*
◒	*2-3 nations*
●	*>3 nations*

Figure 4-4: Summary of Methods Used by the Nations.

The findings at Figure 4-4 clearly show that to generate a cost estimate all participating nations use many methods across each of the phases considered.

Looking at the categories of methods distinguished in this chapter, the calculation/estimation category is used in all phases. The analogy and parametric method are predominant and are used in (almost) every particular phase.

The engineering or bottom-up method is most popular in the phases (project definition, design and development and production) when major alternatives are compared and more detailed information is available.

In the very early phases decision support methods and system dynamics are becoming more popular. This is not surprising as these techniques can be employed using subjective judgement thus overcoming the lack of quantitative historical data.

In the design and development phase, the production phase and the in-service phase, simulation and optimisation methods are sometimes used to estimate support costs and the effects of alternative support scenarios. Not shown in the figure, but during the in-service phase activity based costing is widely used to capture actual costs.

4.4 RECOMMENDATIONS

Many cost estimates require the use of a variety of methods. It is often not possible to use a single method to estimate all the cost elements to be considered. Therefore the total life cycle cost estimate of a system will include the use and outputs from a combination of methods.

As shown in Figure 4-4 the participating nations use many different methods in each phase. It is therefore not possible to recommend a single method to estimate the life cycle costs for each phase of the life cycle.

The best cost estimating method is one that makes the best use of the data available. It is therefore recommended to employ a method that will provide as much detail as the availability of the input data will allow. Therefore, the availability of data is a major factor in the estimator's choice of estimating method.

It is also recommend that a second method is used in order to improve the confidence and to validate the life cycle cost estimate. In many cases, expert opinion or a simple rule of thumb can provide a good second estimate.

For multi-national programmes it is important that the method chosen can be used by all the nations involved, given the data available in each nation. This will probably result in a method being chosen that does not demand detailed design information and supporting data.

It is recommended that research be conducted continuously to enhance methods and models for life cycle costing.

Periodically, the US Department of Defence undertake an initiative to review the basis and techniques employed in cost estimating. This is supported by a number of academic groups and learned societies. However, these initiatives purely examine techniques that will be employed within the US. It would be beneficial to conduct a similar continual review across NATO and PfP nations.

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