

Acquiring Main Equipment

1. APPLICABLE RESEARCH QUESTION

In this chapter we address the research question:

If the relationships between a military strategy, its ends, ways and means are quantified and if the effectiveness of the force design elements is known, how will it aid decision-making about the acquisition of the future force design?

An important aspect of multi-criteria decision making such as prevails in the acquisition or main equipment environment, is that the model must aid the decision making process, which in turn, should seek to

- integrate objective measurement with value judgements; and
- make explicit, and manage, subjectivity¹.

2. FACTORS INFLUENCING ACQUISITION

In order to address the research question, it is necessary to analyse the acquisition process from a decision-making point of view. This would imply that we find the factors that influence the decisions regarding the acquisition of main equipment and verify whether they may be addressed by the information contained in the model that has been developed thus far.

An analysis of the acquisition process indicates that the following non-exhaustive list of criteria could be used to make decisions on whether to acquire new main equipment or not:

- Life-cycle Cost.
- Inherent Availability.

¹ Belton, V. and Stewart, T.J., *Multiple Criteria Decision Analysis - An Integrated Approach*. Boston, Ma: Kluwer, 2002, p. 3.

Chapter 4

- Weapon System Effectiveness.
- Changes in Opposing Force's Order of Battle.
- Project Contribution to a military strategy.
- Effectiveness and System Cost.

We regard the list above to be requisite as far as the model developed in the previous chapters is concerned. We acknowledge that there may be other factors that could be taken into consideration in decisions about acquisition, but none could be established that are related to the developed model. We shall now consider the above-mentioned criteria for deciding on whether to acquire new main equipment or not by analysing these factors one-by-one.

2.1. LIFE-CYCLE COST

We shall expound finding a force design element's life-cycle cost in the following steps:

- Life-Cycle Definition.
- Methodology for Estimating Life-cycle Cost.
- Cost Estimating Relationships.
- Life-Cycle Cost as a Decision Parameter.

2.1.1. Life-Cycle Definition

Intuitively, one would consider the force design element's cost to be a major factor in deciding whether such a system is worth having. However, Moss² holds that not only would the decision-maker consider the acquisition costs only; he/she would have to consider the cost of the system over its expected life cycle. Kirkpatrick³ proposes a force design element life-cycle similar to the life-cycle depicted in Figure 4.1.

A system's life-cycle cost is made up of all the costs within all the life-cycle phases as depicted in the figure. This also includes post acquisition and continuing design as an entity in the life cycle that needs to be budgeted for.

² Moss, M.A., *Applying TQM to Product Design and Development*. New York: Marcel Dekker, c1996, pp. 175–177.

³ Kirkpatrick, D., *Choose Your Weapon: Combined Operational Effectiveness and Investment Appraisal (COEIA) and its role in UK Defence Procurement*. London: Royal United Services Institute, 1996, pp. 60–62.

Research and development costs include the cost of technology evaluation, project definition and the development of prototypes in order to verify the viability of proposed solutions. Even if force design elements are purchased off-the-shelf, a certain amount of research and development cost will be incurred to write the system specification and to evaluate the various options available to the decision-maker.

Production costs include the investment cost to industry, system production, acceptance of the systems by means of in-service demonstration and the cost of investment to ensure that the system will operate smoothly. The latter cost involves the training of personnel and procurement of initial spares, munitions, support and test equipment, training simulators, documentation and support infrastructure.

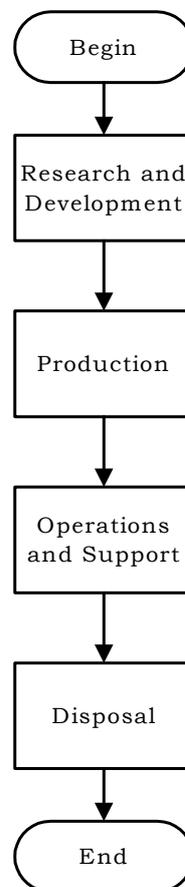


Figure 4.1: The Force Design Element Life-Cycle

The cost of operations and support involves operations costs such as personnel, fuel and lubricants, munitions, transport and stowage as well as the cost of continuation training and support costs for personnel, materials and facilities for first, second, third and fourth line maintenance respectively. The levels of maintenance may be defined as follows:

- First line maintenance is the maintenance of the force design element that takes place at the point of operation.
- Second line maintenance is the maintenance that takes place away from the point of operation such as typically happens in a brigade administrative area.
- Third line maintenance is the maintenance that takes place at a depot.
- Fourth line maintenance is the maintenance that takes place at a contractor's site.

Post acquisition and continuing design costs are costs that are incurred in improving the effectiveness of the force design element during its operating lifetime. Thus, this entity is considered to be part of the cost of operations and support.

The cost of disposal includes the cost of transport and stowage, dismantling, destruction and disposal, spares recovery and sales. Although this phase of the force design element's life-cycle may seem insignificant, this is in all probability not the case. To comply with, *inter alia*, legislation regarding occupational health and safety, the environment *et cetera*, may proved costly. A case in point is the disposal of ammunition. In South Africa, the method of dumping ammunition at sea has been prohibited by environmental legislation and, as a result, costly methods for dismantling and destroying ammunition had to be engineered.

2.1.2. Methodology for Estimating Life-cycle Cost

A basic methodology for finding life-cycle cost has been reported by Hoebner⁴. The TRI-TAC methodology, so named because of the fact that it was developed for three services, the US Navy, Army and Air Force at the tactical level of war, is partially depicted in Figure 4.2.

After having stated the objectives and made the necessary assumptions in close collaboration with the decision-maker about the system under consideration, the cost elements must be selected. That is, a cost breakdown structure must be drawn up. Such a cost breakdown structure comprises a structured array of elements defined first in terms of the life-cycle phases as depicted in Figure 4.1 and then in terms of end items to be costed. The structure must be designed to encompass the entire set of costs during the item's life span.

⁴ Hoerber, F.P., *Military Applications of Modeling – Selected Case Studies*, New York: Gordon and Breach, 1981, pp. 39–48.

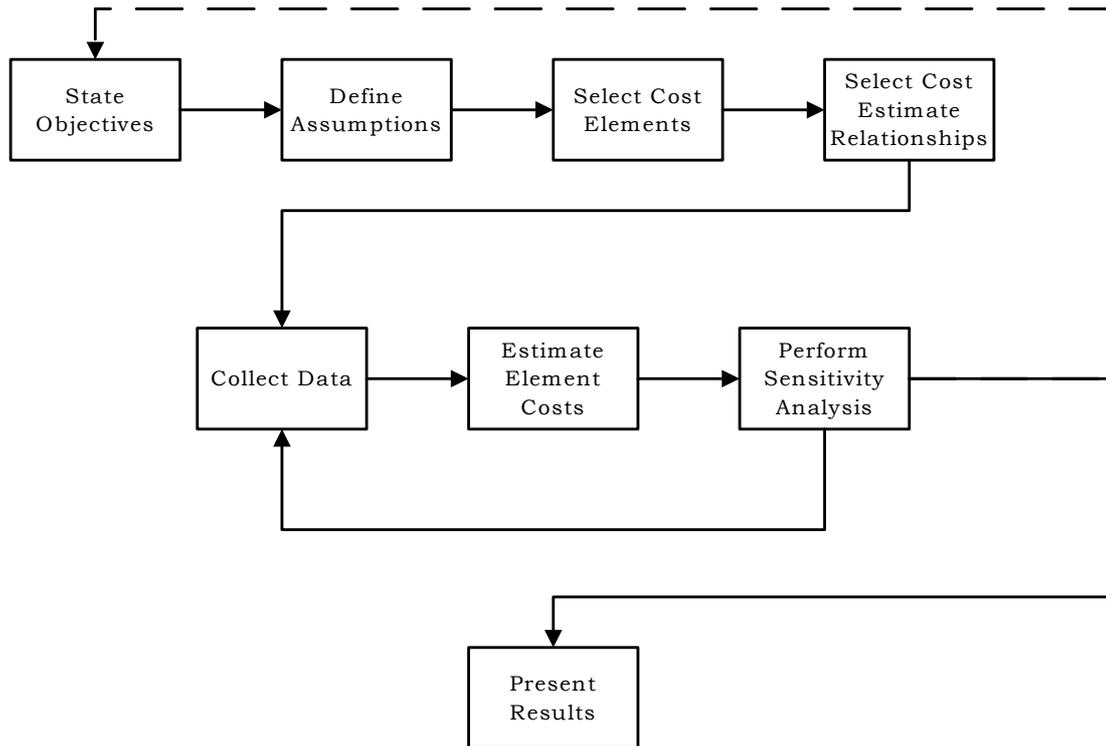


Figure 4.2: TRI-TAC Methodology for Estimating Life-cycle Cost

For every cost item a cost estimating relationship must be determined. This relationship must allow for the costing of all the cost elements defined in the previous step. We shall give examples of cost estimating relationships in the next section.

At this stage, data must be collected to allow for populating the cost estimation relationships. Where systems already exist, the systems manager may prove important in this step. However, for new systems the analyst must obtain data from the suppliers of the items, but in many cases, it will be required that the analyst must estimate the parameters and the cost estimating relationships him/her self.

Thereafter the item costs are estimated and aggregated for the complete force design element. In order to have a measure of the robustness of the life-cycle cost, sensitivity analysis on the whole of the model should be conducted. If the estimates are robust, these should be presented to the decision-maker. If not and depending on the findings, either the whole of the model should be revisited or more data should be acquired so that greater confidence may be placed on the estimates.

A point to consider is that, where a system will replace an older system, a suitable measure might be the difference between the life-cycle cost of the new main equipment, C_L^{New} , and the residual life cycle cost of the old equipment, C_L^{Old} where

$$C_{\delta} = C_L^{\text{New}} - C_L^{\text{Old}} \quad (4.1)$$

Now, if $C_{\delta} < 0$, the replacement of the old system by a new system may be justified purely on cost provided that the life-cycle of the new equipment exceeds that of the equipment to be replaced.

2.1.3. Cost Estimation Relationships

In order to have a better understanding of cost estimation relationships, two examples are given below. Firstly, Hoebner⁵ gives an example of a cost estimating relationship for a typical airframe to be

$$C = Ae^{B(\log V)^{-D}}WRST \quad (4.2)$$

where

C is the airframe development and design cost,

e is the base of the natural logarithms,

A , B and D are empirically derived constants,

V is the maximum aircraft velocity in knots at maximum power at 55 000 foot altitude,

W is the airframe weight in tons,

R is the hourly rate of engineering manpower,

S is a factor which discriminates between fixed wing and variable sweep wing aircraft, and

T is the fraction of the airframe that is made of titanium.

The general procedure for the development of a cost estimation relationship requires the formulation of hypotheses as to the cause and effect relationships between dependent and independent variables affecting costs. Although correlation does not prove cause and effect, when cause and effect cannot be proved, good statistical correlation may still justify its use⁶.

Jaiswal⁷ proposes such a cost estimating relationship for the system cost relating to a battery of guns

⁵ Hoerber, F.P., *op. cit.*, p. 49.

⁶ Banchar, B., *Design and Manage Life Cycle Costs*, Portland, Oregon: M/A Press, 1978.

⁷ Jaiswal, N.K., *Military Operations Research*, Boston, Ma.: Kluwer, c1997, p. 114.

$$C_s = m((1+e)(C_g + C_v)) + T(nC_r + f(C_g + C_v)pC_m) \quad (4.3)$$

where

C_g is the procurement cost of a gun,

m is the number of guns required,

n is the number of rounds allocated per gun per year,

p is the number of personnel required per gun,

C_r is the cost of a single round,

C_v is the cost of towing vehicles,

T is the planned life span of the equipment in years,

e is the cost of spares per gun,

C_m is the manpower cost per person per year, and

f is the annual maintenance cost of the guns and towing vehicles as a fraction of the cost of the guns and towing vehicles.

In the latter example, Jaiswal makes provision for the system cost of the guns, spares, maintenance cost, operating cost including the cost of towing vehicles, manpower and ammunition. If various systems are subjected to an evaluation and they are all equally effective, then the system that yields the lowest C_s would be the most cost-effective system.

2.1.4. Life-cycle Cost as a Decision Parameter

Jaiswal⁸ contends that the selection of a weapon or equipment from available systems depends on its effectiveness and its cost. Hoebner⁹ holds the same view, advocating the following three desirable attributes of a life-cycle costing model:

- It must be highly flexible.
- It must be accurate enough for decision-making both among, and within, system programmes where performance or effectiveness may be adequately specified; system effectiveness must be estimated on a corresponding time-

⁸ Jaiswal, N.K., *op.cit.*, p. 111.

⁹ Hoerber, F.P., *op. cit.*, p.57.

phased basis or the life-cycle cost must be converted to a static total, e.g., a ten-year system cost.

- It must be accurate enough in an absolute sense to aid in high-level choices among non-comparable systems or different parts of the military budget.

We shall address the effectiveness issues in later sections. As far as life-cycle cost is concerned, when

- new systems are being acquired, life-cycle cost, C_L , should be considered as a major criterion to make the relevant decision, and when
- old systems are to be replaced, the difference in life cycle costs, C_δ , would be a more appropriate criterion.

2.2. INHERENT AVAILABILITY

Recall that we have defined inherent availability

$$A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where MTBF denotes mean time between failures and MTTR denotes mean time to repair. We may restate this definition, in terms of all time, T^A , and the number of instances of corrective maintenance that we have observed, T^{LC} , to be

$$A_i = \frac{T^A - T^{LC}}{T^A}. \quad (4.4)$$

Suppose we measure A_i in fixed intervals. If the number of observations of corrective maintenance time increases per interval, then the inherent availability of the system is declining. Alternatively, if the number of observations of corrective maintenance time decreases per interval, then the inherent availability of the system is improving. A simulation of typical expected values for a generic system over time is depicted in Figure 4.3.

Moss partitions the bathtub curve into three distinct segments. First, the area, where the bathtub curves shows a declining number of failures per time interval, is called the infant mortality stage. Second, the area where the number of failures per time interval remains more or less constant is called the safe usage area. Third, the area where the number of failures per time interval increases is called the wear-out stage.

During the infant mortality stage the system is subjected to a large number of failures or teething problems. As maintainers come to understand the new equipment better and improve maintenance and other techniques, the system performance improves and settles at a minimum failure level that is related to the systems inherent design. As the equipment gets older, a tendency for failures to occur more frequently is normally observed. This is a result of the number of operating hours that is now reaching the end of the designed for life span of the equipment.

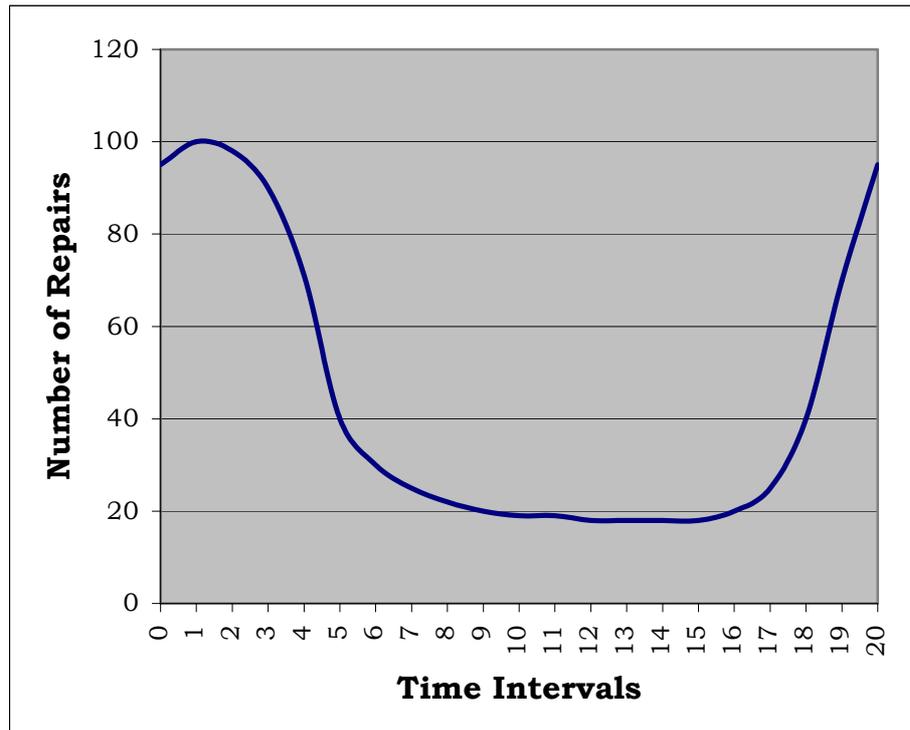


Figure 4.3: Simulated Bathtub Curve for a Generic System

Moss¹⁰ holds that for the purpose of failure analysis, the bathtub curve is only relevant to parts and not to assemblies. However, Wong and Lindstrom¹¹ contends that an overwhelming array of electronic parts exhibits completely different failure patterns and that the concept is outdated for electronic parts.

Although Wong and Lindstrom might be correct in their approach as the bathtub curve relates to electronic parts, it serves as a handy model to demonstrate how complex systems such as force design elements behave over time. The author has previously analysed failure data for Fast Attack Craft and the general shape of a bathtub curved was readily apparent.

¹⁰ Moss, M.A., *op. cit.*, p. 157.

¹¹ Wong, K.L. and Lindstrom, D.L., Off the Bathtub onto the Roller-coaster Curve, *Proceedings of the Annual Reliability and Maintainability Symposium*, USA, 1988.

Now, by observing the trend in the number of corrective maintenance occurrences observed, the point may be established when the system is entering the so-called wear-out stage. As the system approaches the wear-out stage, the decision-maker should be alerted to the fact and he/she will have to consider mid-life upgrade or the replacement of the system. Invariably this will lead to further decisions about acquisition.

We conclude that inherent availability serves as a measure to trigger the decision regarding whether it is necessary to replace existing systems or not. Indirectly inherent availability will also influence operational availability and as a result, it will, in turn, influence measures of effectiveness. Thus, a detrimental change in the value of inherent availability should eventually also effect the measure of effectiveness adversely.

2.3. WEAPON SYSTEM EFFECTIVENESS

Lavenberg and Squillante¹² hold that performance is one of the fundamental factors in the design, development and configuration of computer and communications systems. They conclude that performance evaluation has been and continues to be of great practical importance to the industry. According to Jaiswal¹³ the selection of a weapon or equipment from available systems depends on its effectiveness and its cost. We hold that, not only is performance an equivalent concept to effectiveness, but the notion that it is important in the design, development and configuration of all systems is supported.

Thus, the effectiveness of weapon systems is a major decision-making criterion when the acquisition of new main equipment is considered. In the previous chapter, we have demonstrated how measures for effectiveness at all levels of abstraction within a military strategy may be defined. This has resulted in establishing a quantitative decision-making measure to aid in deciding how scarce resources should be allocated in order to optimise weapon system effectiveness.

Furthermore, we have noted that as a force design element ages, its inherent availability generally decreases. The impact of this decrease in inherent availability will affect operational availability directly and adversely.

As inherent availability decreases, operational availability is achieved from a decreasing baseline and it may be predicted that, from a practical point of view, operational availability would also decrease. Suppose we fix dependability and capability both at some value, ε , then the effect of

¹² Lavenberg, S.S. and Squillante, M.S., Performance Evaluation in Industry: A Personal Perspective, *Performance Evaluation: Origins and Directions*, edited by Haring, G., Lindemann, C. and Reiser, M., Berlin: Springer, 2000, p. 3.

¹³ Jaiswal, N.K., *op.cit.*

decreasing operational availability on effectiveness is a linearly decreasing function where $E = \varepsilon^2$ for $A_o = 1$ and $E = 0$ for $A_o = 0$.

As $E = A_o DC$, this chain reaction will then also decrease this measure of effectiveness accordingly. However, age will not only affect operational availability within the measure of effectiveness, but will also affect the dependability and capability parameters adversely.

Recall that we measure dependability for single shot user systems by

$$D = f(R_1, \dots, R_n)$$

where R_i is the reliability of the i th sub-system and that we measure dependability of more complex systems with the ability to maintain itself by

$$D = \frac{T_U^M}{T_A^M}$$

where T_A^M is the number of observations during a mission whilst T_U^M is the number of observations when the system was ready to carry out its designed for purpose.

In the case of the measurement dependability, we note that any failures in the force design elements will impact on both measures. In the first instance, failures will affect the reliability of some of the sub-systems directly and in the second instance, failures will reduce T_U^M or the number of observations when the system was ready to carry out its designed for purpose. We see that more frequent failures as predicted by age alone will also affect the measure of dependability adversely.

We shall next consider the impact of ageing in main equipment on measures of capability relating to the main equipment under consideration. Consider a 76-mm quick firing naval gun complete with the associated fire control system. The system, which includes the crew, is subjected to a capability evaluation every eight months. Recall its capability is measured in terms of the percentage target triggered bursts achieved during a particular assessment firing. Typical results over a number of eight monthly evaluations are shown in Figure 4.4.

Note that there is a general decreasing tendency in the time-series under consideration. In this particular example, the linear regression is

$$y = 71.961 - 1.399x \quad (4.5)$$

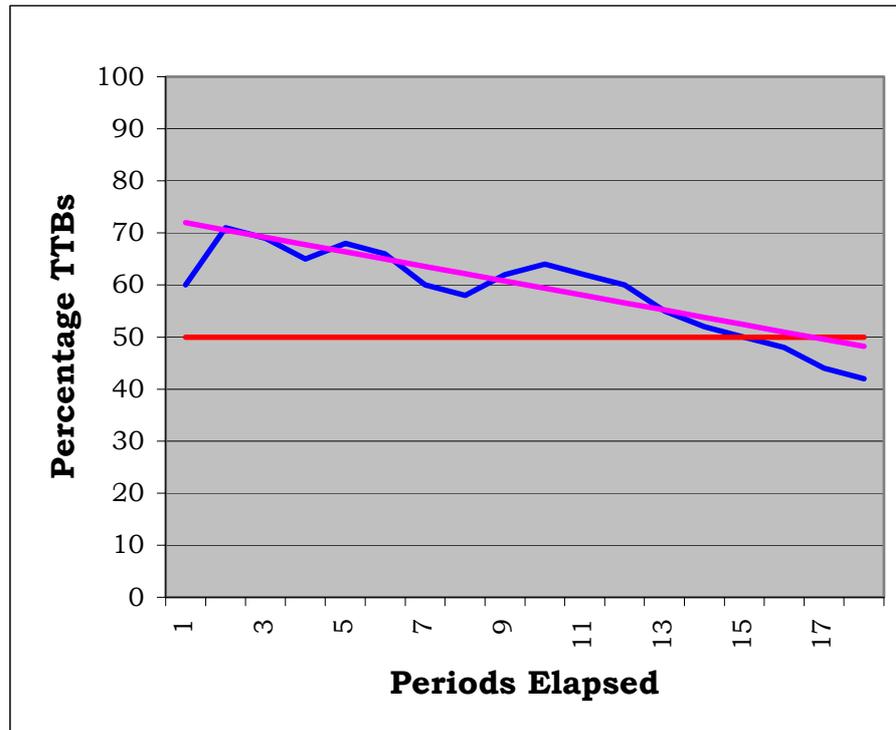


Figure 4.4: Typical Air Defence Results for 76-mm Naval Gun

where y represents the percentage target triggered bursts and x is the various successive time periods. The relevant statistics derived by means of SYSTAT 10.2¹⁴ is given in Table 4.1. Note that the linear regression analysis confirms the general decreasing tendency in the time-series data¹⁵.

The cause of the decreasing tendency in the percentage target triggered bursts may be attributed to several factors relating to the age of the equipment. Specifically, the following causal factors may be assumed to be present:

- Wear and tear on the main elevation and training gears within the mounting.
- Degradation of the performance of the gun control system with special reference to resolvers, synchros and potentiometers.
- Increased inaccuracies in the antennae control system and other target tracking equipment.

¹⁴ SYSTAT 10.2, *Statistics I*, SYSTAT Software Inc. c2002, p. 399–430.

¹⁵ Makridakis, S., Wheelwright, S.C., McGee, V.E., *Forecasting: Methods and Applications*, 2 ed., New York: John Wiley, 1983, pp. 217–219.

- Operating the gun without adequate estimators for muzzle velocity where excessive barrel wear has been experienced.

Dep Var: VAR02 N: 18 Multiple R: 0.876 Squared multiple R: 0.768

Adjusted squared multiple R: 0.753 Standard error of estimate: 4.237

Effect	Coefficient	Standard Error	Standard Coef	Tolerance	t	P (2-tail)
CONST	71.961	2.084	0.000		34.538	0.000
VAR01	-1.399	0.192	-0.876	1.000	-7.270	0.000

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Regression	948.780	1	948.780	52.853	0.000
Residual	287.220	16	17.951		

*** WARNING ***

Case 1 is an outlier (Studentized Residual = -3.783)

Durbin-Watson D Statistic 0.929

First Order Autocorrelation 0.302

Table 4.1: Statistical Analysis of Data in Presented in Figure 4.4

Although none of the above causes for the degradation of the gun's performance may be attributed to failures, the equipment has, due to wear and tear, become less capable of executing its designed for task and as a result, the measure of capability is indicating less capability. Given a minimum acceptance level of 50% target triggered bursts, as a result, (4.5) predicts that the system's level of capability will become unacceptable after the sixteenth eight monthly evaluation. In reality, the system could be labelled unacceptable after the fifteenth eight monthly evaluation.

We have indicated how the ageing of the main equipment influences the measure of effectiveness. At the force design element level, this is most pronounced whereas the measures of effectiveness at the operating system and task force levels respectively will be less affected unless a general state of ageing equipment exist within the operating system or the task force.

We conclude by stating that measures of weapon system effectiveness as developed in here contribute to the decision-makers fact based decision base which contributes significantly to supplying objective information.

2.4. CHANGES IN OPPOSING FORCE'S ORDER OF BATTLE

The changing of the perceived opposing force's order of battle has implications for the military planner. Recall Moss's¹⁶ example of effectiveness of a fighter aircraft where its effectiveness could be the probability that the system would be effective

$$P_S = P_d P_i P_k \quad (4.6)$$

where P_d is the probability that the own aircraft will detect the incoming enemy fighter as it comes within attacking range, P_i is the probability that he will intercept the enemy fighter and P_k is the probability that he will kill the enemy aircraft when he fires his weapon.

Moss holds the position that P_S is a function of own and enemy equipment and personnel effectiveness. For example, suppose the opposing force's fighter aircraft are replaced by new aircraft with better stealth capabilities, then we would expect probability that the own aircraft will detect the incoming enemy fighter as it comes within attacking range, P_d , will be reduced.

Suppose we have, based on (4.6), defined a system design effectiveness index, P_{ae} . Moreover, we define a system design effectiveness index, P_{be} , for the opposing force's aircraft based on its ability to

- conceal itself from our detection equipment;
- evade our intercept efforts; and
- escape or destroy our aircraft when it is being intercepted.

An index of own aircraft's *system application effectiveness*, P_a , could be calculated by

$$P_a = \frac{P_{ae}}{P_{be}}. \quad (4.7)$$

It follows that for any subsequent change in either of the two fighter aircraft, the system design effectiveness indices, P_{ae} and P_{be} , will have to be re-evaluated. This will lead to a new assessment of own aircraft's system application effectiveness, P_a .

Consider the capability requirements for armour under battle conditions not to expose themselves for longer than twenty seconds at a time. This requirement is based on

¹⁶ Moss, M.A., *op. cit.*, pp. 147–148.

$$C_t = \begin{cases} 1 - \frac{t-t_0}{t_{\max}} & \text{for } t-t_0 \leq t_{\max} \\ 0 & \text{for } t-t_0 > t_{\max} \end{cases} \quad (4.8)$$

where C_t is the capability of a tank troop to manage exposure time, t_0 is the time the tank troop broke cover and t is the time the tank troop was under cover again and where $t_{\max} = 20$ is the maximum exposed time that a tank might be exposed under battle conditions. The twenty second exposed time is based on information about the state of the art regarding anti-tank weapons. Suppose a potential opposing force develops a new infantry anti-tank weapon that will allow their infantry to find and fix our tanks and fire at them within fifteen seconds, then in (4.8), we need to set $t_{\max} = 15$.

Moreover, suppose that a potential opposing force changes its maritime strike aircraft armed with ballistic weapons for aircraft armed with air-to-surface missiles. This would render an air defence capability measure based on target triggered bursts against aircraft-like targets invalid. The experiment to determine the percentage target triggered bursts will have to make use of missile-like targets.

The methods that we have described above serve as some examples that will allow for research to amend the capability parameter of effectiveness of force design elements in order to estimate the impact of changes in the opposing force's order of battle.

We conclude by the observation that changes in the opposing force's order of battle will impact on the effectiveness of the appropriate own force design elements. This needs to be researched in order to set new capability requirements, measure the force design elements against the new requirements and initiate acquisition action in order to rectify the imbalance that resulted from changes in the opposing force's order of battle.

2.5. PROJECT CONTRIBUTION TO THE MILITARY STRATEGY

In the acquisition community, it is standard practice to acquire main equipment by employing project management methods¹⁷. Every acquisition is seen as a project and, in line with project management methodology, the necessary funding, staffing and other resources are allocated to the project. However, given the scarcity of resources, not all projects could always be executed at once. Thus, we need a measure to aid management in determining project priority. The contribution that a

¹⁷ Willcock. Brig Gen P.B., SD, SM, MMM., Director Air Force Acquisition, Department of Defence, Personal Interview, 21 May 2003. Pretoria.

project would make in terms of the force design's effectiveness to execute a military strategy is, *inter alia*, a suitable project measure.

2.5.1. Nature of Project Objectives

In acquiring main equipment, project objectives are normally restricted to

- acquiring or maintaining single force design elements; or
- maintaining a number of force design elements by addressing sub-systems that are in use in all of the force design elements under consideration.

An example of the first type of project objective is to replace an existing force design element such as a fighter aircraft with a new generation one. The South African replacement of the Cheetah fighter aircraft with the Grippen fighter aircraft is an example of such a type of project objective.

This type of project objectives may also be limited to a sub-system within a particular force design element. For example, such a project would entail the replacement of an existing air-to-air missile on the Cheetah fighter aircraft by a more capable air-to-air missile.

On the other hand, such project objectives may be to acquire a completely new force design element. For example, South Africa may decide to add an Air Early Warning aircraft to its inventory or the United States may decide to add a surface tracking satellite to its military inventory.

The latter type of project objective is normally to replace a sub-system that forms part of more than one force design element in order to maintain or enhance the force design's effectiveness. An example is the acquisition of a tactical UHF radio that is more robust against opposing force's communications intelligence efforts or the acquisition of a new 76-mm ammunition for Fast Attack Craft and Armour units in order to enhance armour penetrating capabilities against hardened targets.

We shall deal with the two types of project objectives sequentially and in the order that we have stated them above.

2.5.2. Acquiring or Maintaining a Single Force Design Element

From the discussion in 2.5.1 it is clear that a project may relate to all or some of the force design. Thus, a measure of the contribution that a project would make in terms of the force design's effectiveness to execute a military strategy should have a common reference so that all projects may be measured against the same scale.

Suppose the contribution a project is going to make in producing a new ground air defence system is made against the force design element's contribution to the defence operating system. Furthermore, suppose that the contribution a project is going to make in producing a new artillery system is made against the force design element's contribution to the indirect fire operating system. As the defence operating system and the indirect fire operating system are not directly comparable concepts the suppositions regarding the two projects will not allow for the direct comparison of the two projects.

However, if both projects are measured against their respective contributions that they would make in terms of the force design's effectiveness to execute a military strategy, then the related objectives of the two projects become directly comparable.

Furthermore, modern management practice¹⁸ demands that the continuous improvement of the quality of processes and products must be accorded the highest priority. Combat ready or effective force design elements are the products of force preparation processes. Their single most important attribute is combat readiness or effectiveness. Therefore, we may equate effectiveness to the quality of products. Thus it would be to the military's advantage to measure the improvement in the effectiveness of force design elements achieved by the various projects as part of the measurement of the respective contributions that they would make in terms of the force design's effectiveness to execute a military strategy.

In Chapter 2 we have established that the degree to which a particular force design element contributes to a military strategy relative to the other force design elements, w_f is

$$w_f = \sum_{\delta \in M_5(f)} \tilde{v}_{\langle \delta \rangle} \quad (4.9)$$

where $M_5(f)$ is all the vertices in the set M_5 corresponding to the force design element F or the particular force design element to be considered and $\tilde{v}_{\langle \delta \rangle}$ is the contribution to a military strategy of the relevant vertices in the set M_5 .

Now, we assume that the project team is able to specify the effectiveness of the force design element to be acquired or maintained and that the specified project measure of effectiveness is

$$E_f^P = A_O^P D^P C^P \quad (4.10)$$

¹⁸ Walton, M., *Deming Management at Work*, New York: Perigee, c1991, pp. 17–18.

where A_o^P is the specified operational availability, D^P is the specified dependability and C^P is the specified capability of the force design element under consideration.

We are now in a position to quantify the improvement or difference in effectiveness for a force design element that is to be achieved over the life span of the acquisition project,

$$\Delta_f = E_f^P - E_f. \quad (4.11)$$

We define a measure of the increase in contribution that a project would make in terms of the force design element's effectiveness or improvement in quality to execute a military strategy to be

$$\Theta_f = w_f \Delta_f. \quad (4.12)$$

2.5.3. Maintaining more than one Force Design Element

Suppose a project is aimed at n force design elements, then a measure of the increase in contribution that a project would make in terms of the force design elements' effectiveness or improvement in quality to execute a military strategy is

$$\begin{aligned} \Theta^P &= \sum_{f \in P} w_f \Delta_f \\ &= \sum_{f \in P} \Theta_f \end{aligned} \quad (4.13)$$

where P is the set of n force design elements under consideration.

2.6. AFFORDABILITY

From (4.1) we know that C_δ is the difference in the life-cycle cost between the life-cycle cost of new main equipment and the residual life cycle cost of the equipment to be replaced. We determine C_δ for all supplier options that guarantees the minimum requirements for (4.13) and test whether the options are affordable by projecting the C_δ over the expected life of the new main equipment and comparing it with the budget allocation for the particular force design element. Note that if $C_\delta \leq 0$, it points to a supplier option that is cheaper or will cost the same as the present situation. Also, if $C_\delta > 0$, it points to a supplier option that is more expensive than the present situation.

Figure 4.5 depicts the situation with respect to a supplier option where $C_\delta > 0$. Options that exceed the operating budget allocation may be discarded at this stage. However, note that in our example, except for the

costs directly attributable to the acquisition project, the life cycle cost is generally below the operating budget allocation. Thus, if this supplier is decided on, additional funds will have to be made available. In the South African context, such additional funds are made available in the capital acquisition budget.

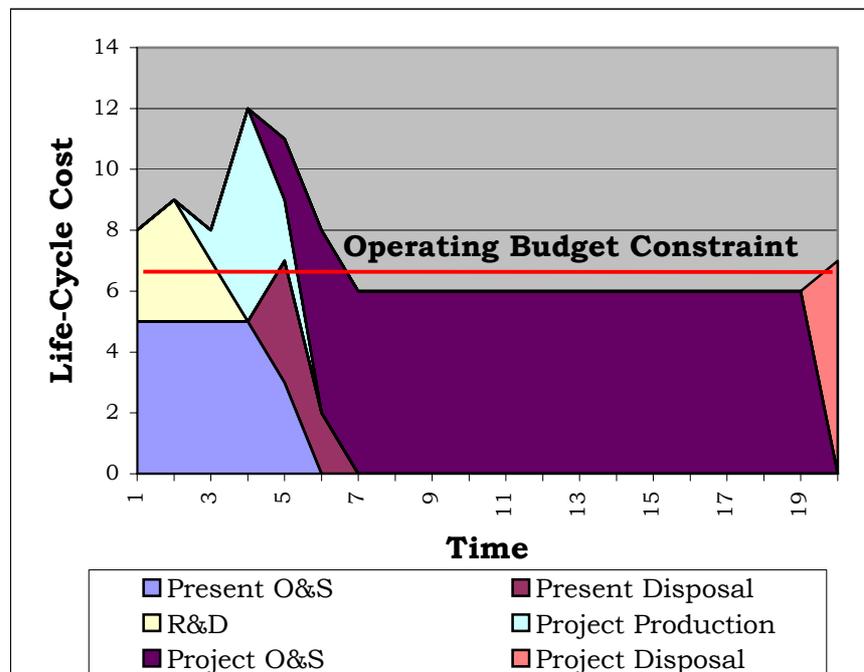


Figure 4.5: Life Cycle Cost with respect to Time

By discarding supplier options that are not affordable, a set of feasible options will remain for further analysis.

2.7. EFFECTIVENESS AND SYSTEM COST

In this sub-section we shall develop measures to enable management to

- decide on supplier options for a particular project; and to
- prioritise acquisition projects.

2.7.1. Deciding between Supplier Options

Jaiswall¹⁹ categorically states that the selection of a weapon system depends on its effectiveness and cost. Thus, if a number of systems are to be considered for replacing an existing system, the increase in effectiveness of the various system options could be considered against their respective supplier option costs.

¹⁹ Jaiswal, N.K., *op.cit.* p. 111.

Suppose we plot the increase in effectiveness guaranteed by the supplier and the supplier option cost of the main equipment to be acquired on two axes, for a feasible set of supplier options, as depicted in Figure 4.6.

A gradient measure may be expressed as

$$\beta = \frac{E_S}{C_S} \quad (4.14)$$

where E_S is the supplier guaranteed increase in effectiveness and C_S is the supplier option cost of the new main equipment. This measure is generally referred to as the *bang for the buck* measure²⁰.

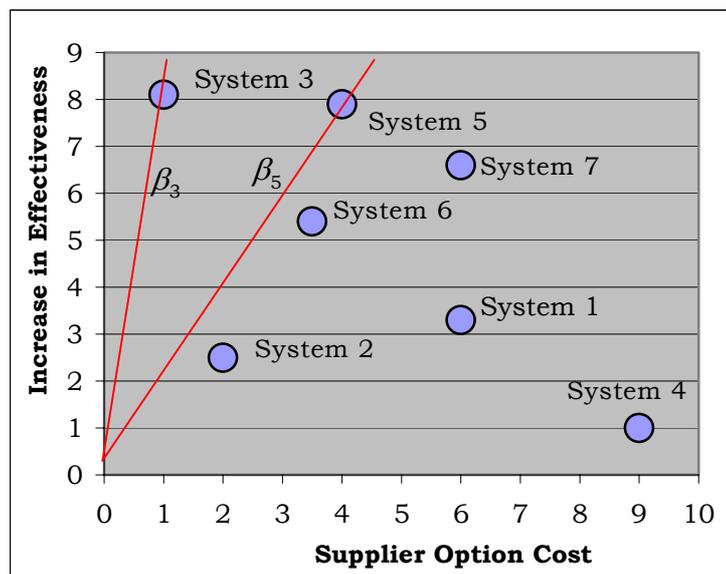


Figure 4.6: Supplier discrimination on Supplier Option Cost versus Guaranteed Increase in Effectiveness

From this diagram we note that, in terms of the gradient measure, system 3 is dominant over the other systems. This is so because system 3 provides the largest increase in effectiveness against the cheapest supplier option cost. Now, suppose that system 3 was not in contention, then system 5 would be the dominant system. It provides the biggest E_S at the third cheapest C_S .

Suppose $\beta_i = \beta_j$, then β_i and β_j will not allow for discrimination between the two supplier options. In such a case, we shall need an alternative measure in order to make a decision about which supplier option to accept.

²⁰ Keoane, D., More bang for our bucks, *new statesman*, 28, 30 November 2001; Latynina, Y., RSPP Reform, More Bang for the Buck, *The Moscow Times.com*, 23 April 2003; Willcock. Brig Gen P.B., *op. cit.*

The necessary discrimination could be done after using (4.14) by incorporating a measure of the distance from the origin in Figure 4.6. Such a distance measure is

$$d = \sqrt{E_S^2 + C_S^2} \tag{4.15}$$

where the larger of d_i or d_j will be taken into account when a decision about which supplier option to accept, is made and we have that $\beta_i \approx \beta_j$.

An alternative measure is defined based on the idea that the optimal supplier option would be one where $C_S = 0$ and where $E_{\max} = \max(E_{S_1}, E_{S_2}, \dots, E_{S_n})$. We define a distance measure to decide which supplier option to accept to be the distance between $(0, E_{\max})$ and (C_S, E_S) expressed as

$$\delta = \sqrt{C_S^2 + (E_{\max} - E_S)^2} \tag{4.16}$$

This concept is shown graphically in Figure 4.7.

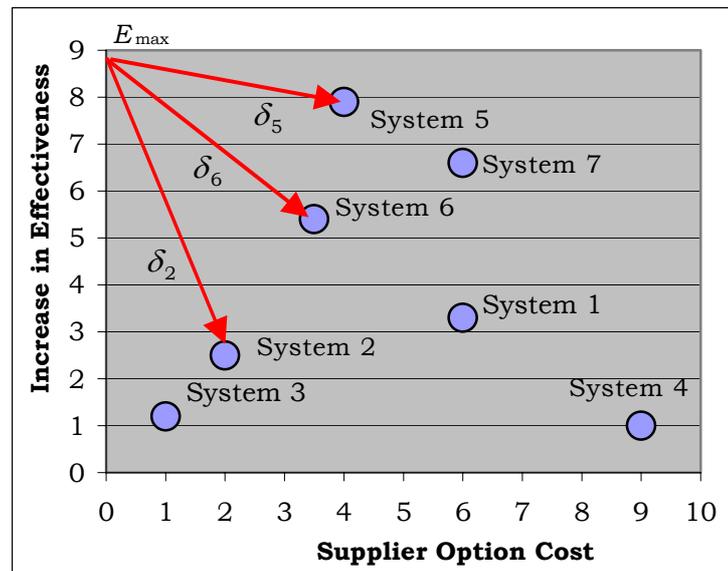


Figure 4.7: Alternative Measure for Choosing a Supplier Option

Again, if $\delta_i \approx \delta_j$, we shall need a second measure to discriminate between the i th and the j th supplier options. In this case, $\beta_i \neq \beta_j$, E_S , C_S or a combination of them may be used.

To illustrate these concepts, we have generated random values for E_S and C_S for thirty supplier options. Both sets of data were generated in the interval $[0,10)$. Thereafter we have computed β_i and δ_i respectively. We

have also subjected the thirty supplier options to AHP and SMART multi criteria decision analysis. The values and rankings obtained are depicted in Table 4.2.

Supplier Options	E_S	C_S	Calculated Value				Rank Order			
			β_i	δ_i	AHP	SMART	β_i	δ_i	AHP	SMART
	a	b	c	d	e	f	g	h	i	j
S1	5.622356	2.034352	2.763708	4.710883	0.044987	6.794002	5	3	4	5
S2	9.272205	4.731022	1.959874	4.768807	0.046502	7.270592	9	4	3	2
S3	9.095570	9.316529	0.976283	9.348772	0.029831	4.889520	17	23	18	17
S4	2.220781	4.130716	0.537626	8.694469	0.027353	4.045033	25	19	22	23
S5	8.756438	9.747779	0.898301	9.811330	0.027291	4.504330	19	25	24	21
S6	4.435303	1.662012	2.668635	5.684428	0.042719	6.386646	6	7	8	9
S7	9.796632	7.202815	1.360111	7.203203	0.039384	6.296908	13	12	12	10
S8	1.680431	1.488340	1.129064	8.325027	0.035023	5.096045	14	18	14	16
S9	1.496290	3.520400	0.425034	9.084855	0.027316	3.987945	26	20	23	24
S10	2.402395	7.472968	0.321478	10.56553	0.016138	2.464714	28	27	28	28
S11	2.233316	9.521799	0.234548	12.20672	0.008417	1.355759	29	30	30	30
S12	6.033289	9.763299	0.617956	10.49060	0.019025	3.134995	23	26	26	26
S13	3.668743	4.908573	0.747415	7.909883	0.028981	4.380085	22	17	20	22
S14	9.708833	9.212626	1.053862	9.214059	0.032046	5.248103	16	21	16	15
S15	7.182226	5.051564	1.421783	5.722727	0.039072	6.065331	12	8	13	11
S16	2.561976	0.962780	2.661020	7.372495	0.039531	5.799598	7	14	11	13
S17	2.837816	0.844394	3.360772	7.084024	0.040779	5.996711	4	11	9	12
S18	4.834232	1.909692	2.531419	5.386960	0.043050	6.462270	8	6	7	7
S19	9.107160	5.264209	1.730015	5.319385	0.044128	6.921476	10	5	6	4
S20	5.476179	0.956106	5.727583	4.497948	0.048342	7.260036	3	2	2	3
S21	8.498129	5.697898	1.491450	5.861036	0.040765	6.400115	11	9	10	8
S22	9.871335	1.173477	8.412036	1.173477	0.060829	9.348929	2	1	1	1
S23	5.042815	6.022569	0.837320	7.719193	0.029204	4.510123	21	16	19	20
S24	7.599812	6.835751	1.111774	7.203284	0.034052	5.382031	15	13	15	14
S25	2.308936	5.590951	0.412977	9.404713	0.022479	3.358992	27	24	25	25
S26	5.634875	9.870511	0.570880	10.741260	0.017447	2.882182	24	28	27	27
S27	1.228763	7.574539	0.162223	11.492070	0.012241	1.827112	30	29	29	29
S28	8.173258	9.102279	0.897935	9.259316	0.027804	4.535490	20	22	21	19
S29	5.508541	5.959414	0.924343	7.385702	0.030830	4.774563	18	15	17	18
S30	3.532585	0.401502	8.798426	6.351453	0.044433	6.565542	1	10	5	6

Table 4.2: Simulated Values for Thirty Supplier Options

In the analysis, we have set $E_{\max} = 10$ to calculate δ_i and, in order to maintain the relative importance of E_S and C_S as implied by (4.14) and (4.16) we have set both to 0.5 to calculate values in terms of the AHP and SMART multi criteria decision analysis.

We have used Spearman's rank correlation coefficient as a measure of the strength of the rank order for supplier options for any two methods. The correlation matrix

$$\mathbf{R}_s(ij) = \begin{bmatrix} 1 & 0.878 & 0.956 & 0.937 \\ & 1 & 0.959 & 0.948 \\ & & 1 & 0.986 \\ & & & 1 \end{bmatrix} \quad (4.17)$$

resulted, where, for $i = j$, the i th rows and the j th columns correspond to β_i , δ_i , the AHP and SMART solutions for $i = j = 1, 2, 3, 4$ respectively.

As the number of supplier options exceeds 10, the test statistic $R_{S_{ij}} \sqrt{n-1} \sim n(0,1)$ may be used²¹. We have tested the following hypothesis:

H_0 : There is no rank correlation between the two methods.

H_1 : There is rank correlation between the two methods.

For all correlation coefficients in (4.17) we have rejected H_0 on the 5% level. Thus, there is significant correlation between the four methods to decide on supplier options.

However, if we consider the calculated values appertaining to the supplier options, it yielded the Pearson correlation matrix

$$\mathbf{R}(ij) = \begin{bmatrix} 1 & -0.698 & 0.734 & 0.709 \\ & 1 & -0.962 & -0.955 \\ & & 1 & 0.994 \\ & & & 1 \end{bmatrix} \quad (4.18)$$

where for $i = j$, the i th rows and the j th columns correspond to β_i , δ_i , the AHP and SMART solutions for $i = j = 1, 2, 3, 4$ respectively.

We have used (4.18) to distinguish between the correlation strengths appertaining to the four methods for deciding on supplier options. We may test on the α -level whether the found r_{ij} and r_{ik} for $j \neq k$ is significantly different or not. Note that the negative correlation coefficients in (4.18) are the result of the preference for the supplier option where δ is small whereas we prefer large values in the other methods. As a result, it is valid to use the absolute value of these correlation coefficients in testing whether the coefficients are significantly different or not.

²¹ Steyn, A.G.W., Smit, C.F., Du Toit, S.H.C. and Strasheim, C., *Modern Statistics in Practice*, Pretoria: J.L. van Schaik, c1994, p. 615.

In Table 4.3 a technique given by Steyn *et. al.*²² to test whether the correlation coefficients in (4.18) are of the same magnitude or not, is depicted. We test the hypothesis

$$\begin{aligned} H_0 : \rho_{ij} &= \rho_{ik} \\ H_1 : \rho_{ij} &\neq \rho_{ik} \end{aligned} \quad (4.19)$$

against the test statistic Z and rejection criteria as stated.

Serial	i,j	i,k	$z(r_{ij})$	$z(r_{ik})$	df	$Z = \frac{z(R_{ij}) - z(R_{ik})}{\sqrt{\frac{1}{n_{ij}-3} + \frac{1}{n_{ik}-3}}}$	Reject if $z < -1.96$ or if $z > 1.96$
	a	b	c	d		e	f
1	1,2	1,3	0.8640	0.9375	27	-0.2699	Accept
2	1,2	1,4	0.8640	0.8853	27	-0.0779	Accept
3	1,3	1,4	0.9375	0.8853	27	0.1919	Accept
4	2,1	2,3	0.8640	1.9776	27	-4.0914	Reject
5	2,1	2,4	0.8640	2.9360	27	-7.6127	Reject
6	2,3	2,4	1.9776	1.8848	27	0.3410	Accept
7	3,1	3,2	0.9375	1.9776	27	-3.8215	Reject
8	3,1	3,4	0.9375	2.9460	27	-7.3797	Reject
9	3,2	3,4	1.9776	2.9460	27	-3.5581	Reject
10	4,1	4,2	0.8853	1.8848	27	-3.6725	Reject
11	4,1	4,3	0.8853	2.9460	27	-7.5716	Reject
12	4,2	4,3	1.8848	2.9460	27	-3.8991	Reject

Table 4.3: Hypothesis Test in terms of (4.19)

We note that only in the case of serials 1, 2, 3 and 6 in Table 4.3, we have accepted the null hypothesis. Thus, the correlation between (4.14) and the AHP on the one hand and the correlation between (4.14) and SMART on the other hand may be considered the same at the 5% level. Likewise, the correlation between (4.16) and the AHP on the one hand and the correlation between (4.16) and SMART on the other hand may be considered the same on the 5% level. Furthermore, from (4.18) we note that the correlation coefficient between AHP and SMART, $R_{34} = 0.994$. Therefore, from a statistical point of view, one cannot choose between the AHP and SMART methods as their behaviour is very strongly correlated.

The remainder of the correlation coefficients are all significantly different from each another. Moreover, correlation coefficients between (4.14) and the other three methods are lower than the other correlation coefficients. This would indicate that (4.14) does not behave consistently with the other methods. Thus, from a statistical point of view, (4.14) might be a weaker method to use.

²² Steyn, A.G.W., *et. al.*, *op. cit.*, p. 497.

If we consider Figure 4.6, then, if the i th and j th supplier options are such that $\beta_i \approx \beta_j$ and $\beta_i < \beta_j$, then β_j will be the preferred supplier option. Suppose $E_{S_i} \ll E_{S_j}$ and $C_{S_i} \ll C_{S_j}$, then (4.14) will not use that fact to discriminate between the i th and j th supplier options whereas the other methods do. This would account for the inconsistent behaviour when using (4.14). To illustrate, in Table 4.2 supplier option S19 was rated tenth by using (4.14) whereas it was rated fifth by using (4.16). At the same time supplier option S16 was rated seventh by using (4.14) whilst it was rated fourteenth by using (4.16). In this case, $E_{S_{19}} \gg E_{S_{16}}$. This demonstrates the remarks above. Thus, in deciding on a preferred supplier option, the use of (4.14) is not recommended.

Because of the simplicity of the method and the ease with which the situation can be visualised in most cases we prefer the measure δ to the AHP and SMART methods for deciding between supplier options.

Moreover, note that rank reversal is possible when (4.16) is used and the accuracy of $E_{\max} = \max(E_{S_1}, E_{S_2}, \dots, E_{S_n})$ is uncertain. Suppose we have two supplier options with (C_{S_i}, E_{S_i}) and (C_{S_j}, E_{S_j}) respectively and the resultant $\delta_i \neq \delta_j$. Then, in order to find \tilde{E}_{\max} such that $\delta_i = \delta_j$, we solve for \tilde{E}_{\max} in

$$C_{S_i}^2 + (\tilde{E}_{\max} - E_{S_i})^2 = C_{S_j}^2 + (\tilde{E}_{\max} - E_{S_j})^2$$

and we have that

$$\tilde{E}_{\max} = \frac{E_{S_j}^2 + C_{S_j}^2 - E_{S_i}^2 - C_{S_i}^2}{2(E_{S_j} - E_{S_i})} \quad (4.20)$$

and a measure of the robustness of the rank order difference between δ_i and δ_j is given by

$$\lambda = \frac{|E_{\max} - \tilde{E}_{\max}|}{E_{\max}}. \quad (4.21)$$

Note that λ is a measure of the size of the error allowable in E_{\max} , E_{S_i} , C_{S_i} , E_{S_j} and C_{S_j} respectively before rank reversal shall occur. It enables us to conduct single parameter sensitivity analysis to determine the size of the maximum allowable error in the applicable variables. The maximum allowable error for E_{\max} is λE_{\max} whereas the maximum

allowable error for the remainder of the variables is such that the error in that variable would result in $E_{\max} = \bar{E}_{\max}$.

For example, if we wish to find values for C_{S_i} where these values will cause rank reversal, $C_{S_i}^*$, we may rewrite (4.20) in the form

$$E_{\max} = \frac{E_{S_j}^2 + C_{S_j}^2 - E_{S_i}^2 - (C_{S_i}^*)^2}{2(E_{S_j} - E_{S_i})} \quad (4.22)$$

and solve

$$C_{S_i}^* = \sqrt{E_{S_j}^2 + C_{S_j}^2 - E_{S_i}^2 - 2E_{\max}(E_{S_j} - E_{S_i})}. \quad (4.23)$$

If $C_{S_i}^*$ is an imaginary number, then C_{S_i} may assume any value without causing rank reversal. Otherwise the limits of the values that C_{S_i} may assume without rank reversal is known and the decision-maker is sensitised to the accuracy requirements associated with C_{S_i} .

2.7.2. Prioritising Acquisition Projects

Apart from deciding on which system to acquire, sometimes the priority of the project also needs to be assessed. That is, which projects do we execute first and which projects do we execute later. This decision is normally required because of budget constraints.

We assume a set of projects, each with a chosen supplier option. Every project influences the ability of the military to execute a military strategy. The relevant measure, Θ^P , is contained in (4.13). The linear program to be solved when prioritising n projects for a particular time period is

$$\text{Maximise } Z = \sum_{i=1}^n \Theta_i^P x_i, \quad (4.24)$$

with the cost constraint

$$\sum_{i=1}^n C_{P_i} x_i \leq b \quad (4.25)$$

where C_{P_i} is the cost of the i th project, $C_{P_i} = C_{S_i}$ and b is the capital acquisition budget for a time period and

$$x_i = 0 \text{ or } 1 \quad (i = 1, \dots, n). \quad (4.26)$$

Without loss of generality, we assume that $\Theta_i^P > 0$ ($i = 1, \dots, n$), $C_{P_i} > 0$ ($i = 1, \dots, n$), $b > 0$ and the ordering

$$\frac{\Theta_1^P}{C_{P_1}} \geq \frac{\Theta_2^P}{C_{P_2}} \geq \dots \geq \frac{\Theta_n^P}{C_{P_n}}. \quad (4.27)$$

Note that the ordering (4.27) allows for the problem to be solved by inspection. Salkin and Mathur²³ give an in depth description of the various methods to solve the 0-1 knapsack problem.

The capital acquisition budget would normally not allow for all projects to be undertaken at once. Money would be made available over a number of years. In the South African context, a capital acquisition plan may be scheduled over more than two decades with available resources planned for every financial year. Thus, we have a series of 0-1 knapsack problems to solve. It must be noted that it is rare for projects to be completed within one financial year. Therefore, it might be necessary not to consider particular financial years but rather some financial periods in which it is feasible to complete major projects.

Even so, the knapsack problem will only give an optimal solution for the projects scheduled in a particular time period. It will perform sub-optimally over a number of time periods as it will choose projects to schedule that will fit into the budget for the time period under consideration when sufficient funds are not available to allow for the scheduling of projects with a larger ordering in (4.27).

However, if we relax (4.26) to the upper bound

$$x_i \leq 1 \quad (i = 1, \dots, n) \quad (4.28)$$

and the lower bound

$$x_i \geq 0 \quad (i = 1, \dots, n) \quad (4.29)$$

then the amended knapsack problem will schedule the last project only partially in the time period under consideration. This would allow for optimising the objective function over successive time periods.

Suppose we need to schedule projects per financial year. Then we amend (4.28) to

$$x_i \leq p_i \quad (i = 1, \dots, n) \quad (4.30)$$

²³ Salkin, H.M. and Mathur, K., *Foundations of Integer Programming*. Amsterdam: North-Holland, c1989, pp. 567-578.

where p_i is the proportion of the i th project that may be completed in a financial year and (4.29) to

$$x_i \geq q_i \quad (i = 1, \dots, n) \quad (4.31)$$

where q_i is the minimum proportion of the i th project that is feasible to do in any given financial year.

This allows for an initial linear program to be formulated. In successive years, the coefficients in (4.24) and (4.25) will have to be adjusted to reflect the planned project activities of the previous years. This will preserve the ordering in (4.27) and therefore ensure the inclusion of the uncompleted projects in the optimal solution set until they are completed. Once a project has been scheduled and the necessary contract placed on the supplier, the project must be removed from the program and the right hand constraint of (4.25), b , amended to allow for the committed funds.

To sum up, we now define the linear program

$$\begin{aligned} \text{Maximise} \quad & Z = \sum_{i=1}^n \Theta_i^p x_i \\ \text{with} \quad & \\ & \sum_{i=1}^n C_{P_i} x_i \leq b, \quad (\text{Cost Constraint}) \quad (4.32) \\ & x_i \leq p_i \quad (i = 1, \dots, n) \quad (\text{Upper Bound}) \\ \text{and} \quad & \\ & x_i \geq q_i \quad (i = 1, \dots, n). \quad (\text{Lower Bound}) \end{aligned}$$

The following algorithm should be followed to schedule projects so as to maximise Z .

- Step 0: Set up equations in (4.32) for the first financial year.
Go to Step 1.
- Step 1: Solve the problem and schedule projects accordingly.
Go to Step 2
- Step 2: Extract the completed projects from equation (4.32) as necessary.
Amend coefficients for ongoing projects.
Go to Step 3.

- Step 3: If all projects are scheduled fully or the end of the planning horizon has been reached, then STOP. Else amend (4.32) to allow for new annual budget allocation. Then Go to Step 1.

The series of knapsack problems will maximise the effectiveness of the military to execute a military strategy over successive time periods. We may expect that, in the early time periods, the rate at which the degree to which the effectiveness of the force design increases will be faster than in later time periods.

3. MANAGEMENT INFORMATION DERIVED FROM THE MODEL

We may derive three sets of management information from the model, *viz*,

- early warning information that the management of certain force design elements might pose a larger risk than in the past;
- information and solutions to discriminate between suppliers of main equipment; and
- information and solutions to prioritise projects.

The early warning information that the management of certain force design elements might pose a larger risk than in the past is contained in the measurement of inherent availability and the effects of the ageing of equipment on operational availability, dependability and capability of force design elements. The study of potential opposing force's order of battle enables the assessment of own force's capability to deal with changes in their order of battle. This proves to be another source of early warning that the management of certain force design elements might pose a larger risk than in the past.

The selection of appropriate suppliers of main equipment is aided by measures to discriminate between the various supplier options whereas the linear program that is constituted by (4.24), (4.25) and (4.30) will optimise the corporate management's requirement to schedule projects so as to have a military that can execute a military strategy.

4. CONCLUSION

In this chapter we have researched the question:

If the relationships between a military strategy, its ends, ways and means are quantified and if the effectiveness of the force design elements is known, how will it aid decision-making about the acquisition of the future force design?

We have shown that, if the relationships between a military strategy, its ends, ways and means are quantified and if the effectiveness of the force design elements is known, then it will aid decision-making by allowing the relative importance of the force design elements to be taken into account when decisions about the future force design is made. Furthermore, by adding the information derived from the measurement of weapon system effectiveness, the management of projects may be optimised.