PERFORMANCE MEASURES FOR COMBAT-READY FORCES IN THE MILITARY

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Introduction

The development of performance indicators in the military is dependent on the measurability of its associated strategies. Von Clausewitz ([1832] c1976) argues that nations are either at war or preparing for war. It follows that military forces should have a strategy for conducting war, also called a military strategy, and a strategy for preparing for war, loosely termed a force preparation strategy.

A closer analysis shows that whereas a military strategy has to do with the art and science of employing the armed forces of a nation to secure the objectives of national policy by the application of force or the threat of force (Joint Chiefs of Staff, 1994), the force preparation strategy has to do with the supply of the means to conduct the military strategy. The method by which the latter strategy is conducted is normally accepted to be the use of supply chains that supply, *inter alia*, commodities, weapon systems and human resources.

As the achievement of the force preparation strategy bears directly on the achievement of the military strategy, performance indicators should ideally measure the achievement of both strategies.

Military Strategy

In order to develop a methodology for the measurement of the achievement of both strategies, the following realist definition of a military strategy is given:

> *Military Strategy* is a plan at the military strategic level of war that consists of a set of military strategic ends, ways and means and the [enabling] relationships between them (Engelbrecht, 2003)

In today's context, the ends of the military strategy are the objectives set by government for achievement by the military. Thus, war, in a modern sense, encompasses the achievement of the nation's territorial integrity against aggressors, the execution of international obligations and aid to other state departments as required by the military's civil control.

An interpretation of this definition is that the means of a military strategy enable the ways that, in turn, enable the achievement of the ends. This interpretation allows for the design of a methodology to develop performance measures for the military strategy and, in turn, quality measures for the supply chains that underlie the force preparation strategy.

Methodology

The methodology to establish performance measures for the two strategies was developed by following the four steps below.

Step 1. A military strategy is cast in a ranked tree where the vertices represent the ends, ways and means of the strategy in a top down manner whilst the arcs represent the enabling relationships between them. The degree of participation of lower order vertices in enabling their common higher order vertex is determined and the ranked tree populated accordingly.

Step 2. Measures for the probability that combat units will be effective to conduct their stated roles are developed. These are also called effectiveness indicators. The information is stored on the appropriate vertices. Provision for interdependence between combat units is also made. Reasons for non-performance are saved with the effectiveness information.

Step 3. A composite indicator is constructed by means of a weighted sum of effectiveness indicators where the weights correspond with the degree of participation developed in Step 1. The composite indicator allows for effectiveness performance indicators regarding the military strategy, military missions and tasks as well as operating systems within task forces.

Step 4. Finally, the reasons for non-performance are used to calculate Tachuci's loss function (Farnum, 1994) regarding the logistic and human resource support functions in the military.

A Tree-view of a Military Strategy

Further analysis of the definition of a military strategy given previously leads to a ranked tree where the vertices depict the military strategy, its ends, ways and means. In the South African context, the way in which the strategic ends are enabled is achieved by a two-tier decomposition. At the higher level, missions are formulated that may achieve the strategic ends and, in turn, missions are decomposed in military tasks that would constitute the more detailed mission plan. Enabling the conduct of military tasks is achieved by operating systems such as command and control, indirect fire, protection and other operating systems. In turn, operating systems are decomposed into military units also termed user systems.

The arcs in the ranked tree depict the enabling relationships of the military strategy. For example, artillery, ground attack aircraft and ships capable of shore bombardment enable an indirect fire operation system.

The following scheme denotes the vertices in the ranked tree:

- The root of the tree with rank 0 signifies the military strategy and is denoted by $\langle R \rangle$.
- The vertices of rank 1 signify military strategic ends where the i th such vertex is denoted by $\langle i \rangle$.
- The vertices of rank 2 signify military missions where a vertex relating to the j th mission that appertains to the i th end is denoted by $\langle ij \rangle$.
- The vertices of rank 3 signify military tasks where the vertex relating to the k th task that appertains to the j th mission is denoted by $\langle ijk \rangle$.
- The vertices of rank 4 signify operating systems where the vertex relating to the l th operating system that appertains to the k th mission is denoted by $\langle ijkl \rangle$.
- The vertices of rank 5 signify user systems where the vertex relating to the m th user system that appertains to the l th operating system is denoted by $\langle ijklm \rangle$.

Let $\langle \varphi \rangle$ be any vertex in the ranked tree. Then the contribution that a particular vertex makes to the enablement of its predecessor vertex is $v^{\langle \varphi \rangle}$ where, for every vertex $\langle \varphi \rangle$, its n successor vertices should attract values $v_i^{\langle \varphi i \rangle}$ such that

$$\sum_{i=1}^{n} v_i^{\langle \varphi i \rangle} = 1 .$$

By definition, $v^{\langle R \rangle} = 1$. The total contribution that a vertex $\langle \varphi \rangle$ makes to the military strategy's enablement, $V^{\langle \varphi \rangle}$, is the product of all its predecessor vertices, for example, $V^{\langle ijk \rangle} = v^{\langle R \rangle} v^{\langle i \rangle} v^{\langle ij \rangle} v^{\langle ijk \rangle}$. Furthermore, given the ranked tree, a particular user system might be represented in more than one terminal vertex. For example, a frigate may appear as a terminal vertex in a branch in the rank tree that represents a shore bombardment task and also as a terminal vertex in a branch that represents the neutralisation of an opposing force's naval units. Thus the i th user system's (US) total contribution to the attainment of a military strategy, given that it is represented in m terminal vertices is

$$\mathrm{X}_i^{US} = \sum_{j=1}^{m} v_j^{\langle ijklm \rangle} . \qquad (1)$$

Three groups of methods to find values for $v^{\langle \varphi \rangle}$ have been determined, *viz*., analytical methods such as linear programming and non-linear programming models, heuristic methods such as simulation and war games and multi-criteria decision analysis using the Simple Multi-attribute Rating Technique and

Analytical Hierarchy Process models. The latter set of methods allows for more rapid analysis whereas the first two sets of methods allow for better quantifiable results.

Effectiveness Indicators

Blanchard and Fabrycky (1990: 360) define *system effectiveness* as the probability that a system may successfully meet an overall operational demand within a given time and when operated under specified conditions. In short, system effectiveness is the ability of a system to do a job for which it was intended.

The Weapons System Effectiveness Industry Advisory Committee (WSEIAC) first defined effectiveness during the 1960s in a state-space environment. By *state-space* is meant the state of a weapon system, that is, the weapon system is either functioning properly or it is not functioning properly. Thus the WSEIAC nomenclature determines that a system's state is defined by its condition at a given time. Their work became the established basis for evaluating effectiveness in the US Army (US Army Material Command, 1971). They define system effectiveness as follows:

> *System Effectiveness* is a measure of the extent to which a system may be expected to achieve a set of specific mission requirements. It is a function of the system's availability, dependability and capability.

In turn, availability, dependability and capability were defined by the WSEIAC in the following manner (US Army Material Command, 1971: 2-21 to 2-23):

> *Availability* is a measure of the system condition at the start of a mission. It is a function of the relationships among hardware, personnel and procedures.
>
> *Dependability* is a measure of the system condition at one or more points during the mission, given the system condition at the start of the mission.
>
> *Capability* is a measure of the system's ability to achieve the mission objectives, given the system condition during the mission. Capability specifically accounts for the performance spectrum of the system.

The basic WSEIAC definition of effectiveness may therefore be written as

$$E = aDc \tag{2}$$

where

$$a = [a_1, a_2, \ldots, a_n] \tag{3}$$

is the availability vector with a_i the probability that the ith combination of the m sub-systems is in state i,

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \tag{4}$$

is the dependability matrix with d_{ij} the probability of a system state transition from state i to state j for the corresponding initial and later states, and

$$c = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}$$

is the capability vector with c_j the capability of the system for performing the mission, given that the system is in state j.

The WSEIAC model is not a self-contained, directly applicable mathematical equation for effectiveness. It is a framework for effectiveness quantification that will allow for all system-mission combinations provided that their respective criteria for availability, dependability and capability are rewritten into the format of equation 2. For example, an aircraft's dependability might depend on the reliability of its sub-systems whereas the dependability of a mechanised infantry battalion might depend on the reliability, maintainability and sustainability of its sub-systems.

If the relationship between the m sub-systems and the size, n, of the vectors and matrix in equation 2 are considered, it is noted that $n = 2^m$ shall hold. Thus, n shall behave exponentially as m becomes large. Now suppose a tank regiment comprises four echelons of thirteen tanks each. To find the effectiveness of the regiment based on the state of the 52 tanks shall necessitate $n = 2^{52} \approx 4.5 \times 10^{15}$ entries in the vectors a and c each and n^2 entries in D. It is concluded that when m is large, the analytical application of the WSEIAC framework becomes prohibitive.

In order to find a more useable measure for effectiveness we consider the systems-space as opposed to the state-space of the force design element under consideration. To this end, we need to reformulate the definitions of availability, dependability and capability so that they may be applied directly to the weapon system or force design element under consideration (Engelbrecht, 2003:103).

Operational Availability, $P(A_O)$, is the probability that a weapon system is operationally available when called upon to execute a mission. The time of the commencement of the mission is regarded as a random event.

Dependability, $P(D|A_O)$, is the probability that, whilst on a mission, a user system will not suffer a catastrophic failure, that is, the system shall not abort its mission due to some failure.

Capability of a weapon system, $P(C|D \cap A_O)$, is the probability that a user system is capable of effecting its designed for function given that it is available and dependable.

From these conditional probabilities and taking the Blanchard and Fabrycky definition of system effectiveness into account, effectiveness is defined by

$$P(E) = P(A_O)P(D|A_O)P(C|D \cap A_O) \tag{5}$$

which may be simplified to simply read

$$E = A_O DC \tag{6}$$

where E, A_O, D and C denote $P(E)$, $P(A_O)$, $P(D|A_O)$ and $P(C|D \cap A_O)$ respectively.

If we consider equation 6 as it relates to user systems, we note that A_O and D are directly influenced by the maintenance of the product systems that make up the user systems; and that $C = f(x_1, \ldots, x_n)$, where x_i is the ith capability of the product systems including main equipment and personnel as integrated by applicable doctrine. Therefore, in the case of both A_O and D, they are measures of the proportion of "up" time of user systems under different circumstances. As a result

$$A_O = \frac{T^U}{T^A} \tag{7}$$

where T^U denotes up time and T^A denotes the designated period under consideration. For n sub-systems that make up a larger complex system the operational availability of the user system is calculated by

$$A_O = \sum_{i=1}^{n} w_i A_{O_i}^S \tag{8}$$

where w is the relative importance and $A_{O_i}^S$ is the operational availability of the i th sub-system. By devising a simple random sampling method, accurate estimators for A_O may be found. As user systems are, for most of their life cycle, in a preparation phase, more than sufficient sampling events will occur.

Estimators for D might be found in a similar fashion. However, actual mission time is normally of shorter duration and in some cases the number of sampling events might prove to be insufficient. However, experiments to measure dependability may be planned to coincide with planned tactical exercises in the field.

The definition of measures of capability is varied and dependent on the type of user system under consideration. However, in order to develop measures of capability, the following should guide the model builder:

- The sub-systems that make up the user system.
- The roles assigned to the user system.
- The organisation of the user system.

Let a fighter aircraft's air-to-air combat capability be C_A and its ground attack capability C_G. The actual measurement is normally done by experiment. For example, accuracy of bombing a given target may underlie C_G. Then the relative contributions of the two roles to the fighter aircraft, w_A and w_G for the air-to-air combat and ground attack roles, respectively, are found by analysis. The fighter aircraft's capability is now given by

$$C_F = w_A C_A + w_G C_G . \tag{9}$$

On the other hand, complex organisations that reside within larger user systems may cause more complex weighted sums. For example, weights associated with capability measures for tanks found by using the Analytical Hierarchy Process method are shown in Figure 1.

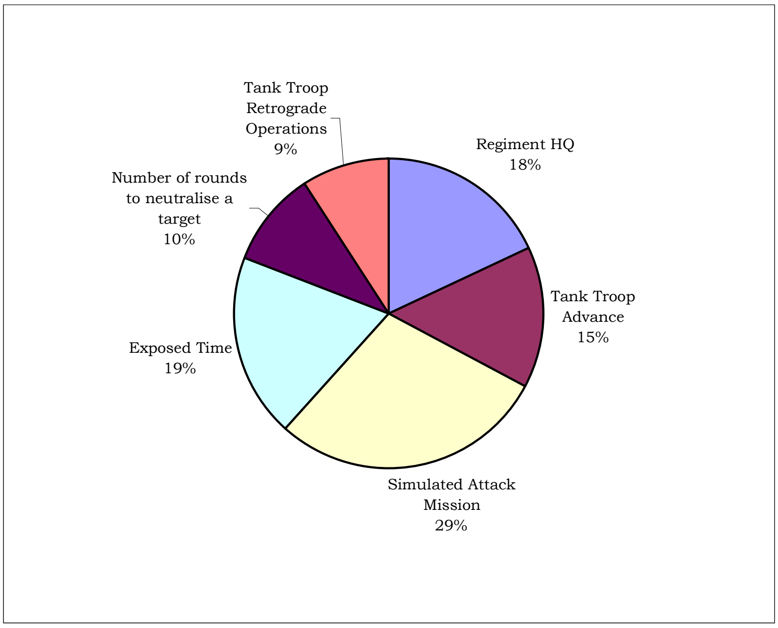

Figure 1: Capability Weights for a Tank Regiment

The weighted sum for the capability of particular tanks must be summed at troop, squadron and regimental levels and, in addition, be viewed in conjunction with capability measures for supporting elements and command and control arrangements.

Performance Indicators

Performance indicators regarding the performance of the military in executing its military strategy may now be defined. Consider the mth user system or military unit. Given the discussion thus far, its contribution, $\upsilon^{\langle ijklm\rangle}$, to particular operating systems, $\langle ijkl\rangle$, as well as its effectiveness, E^{US}, are known. Thus the probability that a user system will be effective in enabling its role in a particular operating system is

$$E^{US} = A_O DC \tag{10}$$

whilst the probability that a set of t user systems will be effective in enabling the kth operating system is

$$E_k^{OS} = \sum_{m=1}^{t} \upsilon_m^{\langle ijklm\rangle} E_m^{US} \,. \tag{11}$$

Likewise, the probability that a set of t operating systems will enable a military task or task force objective is

$$E_k^{TF} = \sum_{l=1}^{t} \upsilon_l^{\langle ijkl\rangle} E_l^{OS} \,, \tag{12}$$

the probability that a set of t military tasks will enable a military mission is

$$E_j^{M} = \sum_{k=1}^{t} \upsilon_k^{\langle ijk\rangle} E_k^{TF} \,, \tag{13}$$

the probability that a set of t military missions will enable a strategic end is

$$E_i^{E} = \sum_{j=1}^{t} \upsilon_j^{\langle ij\rangle} E_j^{M} \,, \tag{14}$$

the probability that a set of t strategic ends will enable a military strategy is

$$E^{S} = \sum_{i=1}^{t} \upsilon_i^{\langle i\rangle} E_i^{E} \,. \tag{15}$$

Note that the relevance of equation 15 could be restated as the probability that the military could conduct its military strategy effectively. Also, equations 10 to 15 are performance indicators regarding the conduct of the military strategy.

Supply Chain Quality Indicators

Performance indicators regarding the force preparation strategy may be derived from the same measuring scheme as that of the performance indicators for the military strategy. Two major groups of supply chains exist, *viz.*, supply chains for human resources and supply chains for items of supply including commodities and weapon systems. Both supply chains have associated qualities or sub-processes that impact on the quality of delivery.

It is important to note that, in accordance with military practice in South Africa, the provision of the means for military forces impacts on their operational availability only. Maintaining and sustaining deployed forces are the responsibility of the forces themselves, that is, organic logistical elements are included in military forces. Therefore, performance indicators for dependability measure the performance of the forces themselves and not the performance of the supply chain. Also, quality indicators could be measured in terms of a loss in operational availability. To this end, Taguchi’s loss function quantifies the loss to society due to lack of product quality (Farnum 1994, 428) and was chosen as the preferred supply chain quality indicator.

First, consider logistic and human resource supply chain costs, C, to operational availability caused by them that could be attributed to the non-exhaustive list in Table 1. Thus, when a user system is evaluated for operational availability, reasons for non-performance, in accordance with such a table, are recorded. These will serve as categories of instances of “down” time.

Note that these failure categories are not mutually exclusive. For example, a tank may not be “up” due to several factors such as a logistic delay in spare parts to fix something whilst the driver is on leave and the tank commander is ill. In this case, the down time is attributable to all of C^{L}, C^{LD}, C^{H}, C^{HC} and C^{HL}.

Logistics	**Denoted**	**Human Resources**	**Denoted**
Logistic Supply Chain	C^{L}	Human Resource Supply Chain	C^{H}
System design	C^{LC}	Poor Health	C^{HC}
Preventative maintenance philosophy	C^{LP}	Individual training	C^{HT}
Logistic delays	C^{LD}	Leave policy	C^{HL}
		Poor discipline	C^{HP}

Table 1: Cost of Failure Categories

The total loss attributed to the quality of the force preparation strategy and its execution in operational availability would be

$$C^{\tau} = 1 - E^{US} \tag{16}$$

where $0 \le C^{\tau} \le 1$.

Let all $C^{\psi}, \psi \in \{L, LC, LP, LD, H, HC, HT, HL, HP\}$, be variables that assume values reflecting the number of instances of down time experienced due to their associated failure category. Furthermore, suppose n observations are made over a specified period of time. Then the proportion of down time relating to the various failure categories would be given by

$$p^{\psi} = \frac{C^{\psi}}{n}. \tag{17}$$

By expressing Taguchi’s loss function in terms of proportions,

$$\begin{aligned} T^{\psi} &= k\sqrt{p^{\psi^2} + p^{\psi}\left(1 - p^{\psi}\right)} \\ &= k\sqrt{p^{\psi^2} + p^{\psi} - p^{\psi^2}} \\ &= k\sqrt{p^{\psi}} \end{aligned} \tag{18}$$

where k is a scaling variable.

By combining the relative contribution of the user system under consideration with its measured loss function value, the risk to the supply chain is quantified simply by likelihood, p^{ψ} from equation 17, and impact, X^{US} from equation 1, and

$$R^{\psi} = p^{\psi} \mathrm{X}^{US}. \tag{19}$$

Equation 19 will aid decision makers to, *inter alia*, prioritise efforts to remedy problems in terms of their effect on the probability to execute the military strategy.

Model Performance

The measures developed are considered to be logically consistent. The following serve as motivation:

- The measures are monotone nondecreasing functions.

- Small changes in the inputs result in comparably small changes in the results.
- Results are consistent when major parameters are varied.

Furthermore, the model requires inputs and computational capabilities that are readily available. It tracks the military's core strategies and provides commanders with quantified performance information that can be linked to their respective objectives directly.

The measures described here can be regarded as composite in the sense that they are derived from two separate entities, the contribution of vertices at various levels in the ranked tree as well as the effectiveness of user systems at the terminal vertices. The advantage of this method is that the resultant measures focus on the relevant strategy and that is generally considered to be a major requirement for measures (Kaplan and Norton, 1996: 38). However, inadequate conceptualisation may cause serious flaws in the use of such measures. To ensure adequate conceptualisation, the methodology was constantly reviewed during the research and the researchers are confident that the model is requisite (Phillips, 1982) as no new intuitions about the methodology emerged.

Concern was expressed during the research that variance in the measurement of E and in the determination of $v^{\langle ijklm \rangle}$ could obscure results to the extent that, for example, equation 19 might not be sufficiently robust to determine priorities for effort to address problems in the execution of strategy. Care was taken to ensure that the probability that ambiguity may arise in measuring of these entities was minimised. The model was implemented in the South African Army and in the South African Navy and is considered plausible by them. The use of the model in the two Services proved valuable and a decision to extend it to the whole of the SANDF is currently being considered.

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