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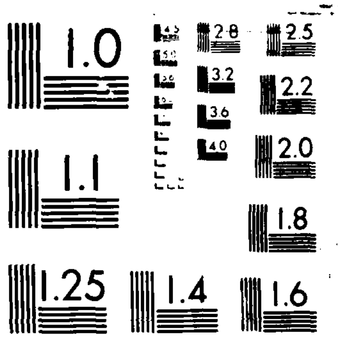
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TOWARD AN AXIOMATIC GENERALIZED VALUE SYSTEM

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper proposes and develops a structure for assigning value, consistently, to the varied and diverse targets that populate the Airland battlefield. These values will be used as inputs to allocation and decision modules in a systemic Corps-level Airland Research Model under development at NPS. Key elements of the proposed structure are that the values of noncombatant targets must be derived from the values of combatant targets that are supported, and that the effect of time increments and delays on value is incorporated through exponential discounting.

ABSTRACT

This paper proposes and develops a structure for assigning value, consistently, to the varied and diverse targets that populate the Airland battlefield. These values will be used as inputs to allocation and decision modules in a systemic Corps-level Airland Research Model under development at NPS. Key elements of the proposed structure are that the values of noncombatant targets must be derived from the values of combatant targets that are supported, and that the effect of time increments and delays on value is incorporated through exponential discounting.

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1. INTRODUCTION

The Airland Battle is an emerging doctrine of the US Army. This doctrine envisions an extended battlefield, not confined to a narrow belt around the forward edge of the (main) battle area (FEBA). Inherent in this doctrine is a concept of target value analysis which attempts to identify targets on the extended battlefield in terms of their values, which may be situationally dependent. Such analysis is crucial to the successful conduct of the Airland Battle, since the battlefield environment is target rich, but asset limited, and therefore these limited assets must be allocated to maximize effectiveness.

A group of faculty and students at NPS is currently involved in research whose goal is the development of methodologies appropriate for modelling Corps-level combat under this still-emerging doctrine. The essential goals of this project, which is titled the Airland Research Model, are the development of:

a. A two-sided, force-on-force model at the Blue Corps, Red Front level.

b. A primarily systemic (no human intervention) decision architecture, but with the provision to selectively insert human decision-makers if required for the development of rule-based systems.

c. A generalized network methodology and multidimensional coordinate system to represent transportation systems, terrain, communication links, and both fixed and mobile combat assets.

d. A resolution determined by the function and situation being modeled.

e. An ability to represent planning based on future-time extrapolation of the possible results of plan execution.

f. Detailed audit trails of cause/effect relationships between decisions made and the results of decision executions.

The primary focus of model development to date has been on command and control (C^2)/decisionmaking methodology, since the pivotal element of any closed (no man-in-the-loop) combat model is the decision rules used by the simulated elements. One of the major general thrusts of our research revolves about degree to which such decisions can be represented as quantitative, multi-attribute optimizations, as opposed to representation in terms of expert systems/artificial intelligence/heuristic processes. This question is especially relevant for decisions that involve force allocations or task prioritizations. Such decisions are extremely complex, and current models often contain very ad-hoc schemes that seem to compare "apples and oranges."

We envision that, in the Airland Research Model, the starting point for any combat decision process will be the unit mission, expressed in terms of a desired future network state or sequence of future states, and a list of which enemy units must be fought. Each command headquarters will need to dynamically generate missions for each of its subordinate units in the hierarchy, and this mission generation process must establish both a desired end state and an associated time frame for each subordinate. (The modelling of this dynamic mission generation process will be one of the most critical (and difficult) research areas of the project.) As part of this overall process, command headquarters will also need to generate schemes of maneuver and force allocations against dynamically generated enemy avenues of approach. A planning filter (or filters), based on the area of interest and area of influence, will need to be available to identify all enemy units and assets that **can** affect the mission. Lastly, algorithms must be developed that produce rank-orderings and target priority lists for enemy units and assets; and that allocate maneuver, fire support, interdiction and other assets against the targets on the list.

This note is concerned with a fundamental aspect of the development of these rank-ordering and target list-producing algorithms, specifically whether a feasible mechanism exists for producing such lists by a quantitative optimization, as opposed to by the expert systems approach. At the heart of such a quantitative optimization algorithm would, of necessity, lie a **Generalized Value System (GVS)**, i.e. a system capable of assigning a "value" to each candidate target for the list. Determining generalized value for the Airland battle is not a trivial procedure, for several reasons:

a. The Airland Battlefield consists of greatly dissimilar targets, e.g. combat units, logistical depots, bridges, etc.

b. There do not exist acceptable value systems for other than combat and fire support units (and even these are subject to debate).

c. Interdiction warfare is based on a concept of threat stemming from potential for future usage, as opposed to current killing ability.

This report proposes an **axiomatic** generalized value system for the Airland Research Model and then examines the feasibility of the proposed system. The advantage of an axiomatic system is that the values of all potential targets are derivable from some basic set of principles. Therefore ad-hoc assignments are unnecessary, and comparisons between unlike systems are consistent. The values provided by this proposed axiomatic value system would then form the basis for target allocation decisions. We would emphasize that, at this time, we are not proposing the decision logic to allocate weapons to targets, only a mechanism by which a common value system can be applied to a proposed target list, after which the allocation procedure can then be logically applied.

2. FUNDAMENTAL CONCEPTS

The development of the axiomatic value system begins with several fundamental premises, which are really the assumptions which underlie the entire proposal. The first major premise is that:

> The purpose of an army is to wage war, and therefore the only elements/units that have inherent value are fighting elements, i.e. maneuver and fire support.

Before the reader is tempted to lay this report aside as a return to the dark ages of combat modeling, where only fighters were modeled, it is important to understand that this does NOT mean than combat support and combat service support units have NO value. For the second major premise in our system is:

> The value of CS/CSS units derives totally from the increase or decrease in value they provide to the combat (inherent value) units they support.

Thus, under our concept, while ammunition storage and transport units may have value, an army made of solely of ammunition storage and transport units is of no value. (The reader may wish to reflect on this comment.) Of course, these conceptual statements yield no information on how this derived value can be calculated. We shall consider this latter question in subsequent sections.

Lastly, we would point out that the value of combat units in contact stems primarily from their ability to destroy opposing forces. In contrast, the value of units which are not in contact, or of logistics support in the pipeline, derives from the **potential** for usage at some time in the future. (Consider of what value a reserve would be if the commander involved had decided that, under no circumstances he would commit that force.) Thus, we shall adopt as our final major premise the view that:

> Uncommitted units and usable, but unused, support are analogous to financial assets which mature at some time in the future - that is their current value is a **discounted** version of their nominal (inherent or derived) value.

This approach has several factors to recommend it, not the least of which are that discounting of future assets is a well recognized and accepted procedure, and that normal discounting, i.e. by a fixed percentage per time period, corresponds to exponential decay of value, an almost trivial computation in a model.

3. PRINCIPLE DEFINITIONS AND TERMS

In this section we introduce the main terminology with which we shall discuss our value system. As we noted above, we presume that value must, in the final analysis, relate to combat ability. This motivates our first definition:

> **Basic Inherent Value** is that value possessed by a maneuver or fire support unit, in contact, as a direct result of the unit's ability to conduct combat operations.

We shall assume that this quantity can be computed for any given combat unit, since our intent in this report is to propose a methodology by which the values of all other entities on the battlefield can be derived from the basic inherent values of combat units. We recognize that a major research effort remains in agreeing upon the algorithms for computing basic inherent value, however, addressing that question in more than a cursory way is beyond our scope. However, whatever algorithms are finally decided upon for this computation, the value will depend on what we refer to as the state of the unit. This state is, at present, a somewhat fuzzy, multidimensional quantity, which we assume will depend, as a minimum, upon the:

(a) Number of operational weapon systems,
(b) Effective personnel strength,
(c) Available ammunition, and
(d) Available POL

of the unit being considered. (Note that inherent value is very similar to an index of firepower potential (IFP) or firepower score.) We shall hereafter denote the state of a unit and the associated value, at time t, by $\mathbf{s}(t)$ and $V(\mathbf{s}(t))$, respectively. (Bold face type is used here to signify a potentially multidimensional quantity.)

Immediately following the definition of basic inherent value, we also have have the following definition:

> **Basic Derived Value** is that value possessed by a CS/CSS unit because of it's ability to either increase or maintain the value of a combat unit. This value is computed as if the support were able to be provided instantaneously when required.

Thus, if we were to denote the state of the supported unit, without the CS/CSS support as $\mathbf{s}_1(t)$, and with support as $\mathbf{s}_2(t)$, then the basic derived value of the CS/CSS unit would simply be

$$V(\mathbf{s}_2(t)) - V(\mathbf{s}_1(t))$$

(Mechanisms by which these can be computed will be discussed later.) Observe that basic inherent value is defined for units in contact with the enemy, and basic derived value as if the supporting unit were colocated with the combat unit. Neither need be the case. Thus, we add the following definition:

> The **Situationally Dependent Value** of a unit is its basic value, either inherent or derived, decremented by an exponential factor based on the time interval before that unit is available for commitment or can provide support.

Thus a unit which would have a basic (either inherent or derived) value of $V(s(t_0))$ if it were available at time t_0, but which will not be available until some time $t > t_0$, will have the situationally dependent value at time t_0 of:

$$V = V(s(t_0))\, e^{-A(t-t_0)} .$$

While this formulation does require a determination of the time decay constant (A), we propose that this is not a major obstacle. For inherent in the Airland battle doctrine is the concept of the Area of Interest - that area, at each echelon, in which the commander focuses his intelligence collection assets to acquire targets and determine enemy capabilities and intentions. Furthermore, this area of interest is expressable in terms of both distance and time, e.g. a division commander's area of interest may be nominally on the order of thirty-six hours. Thus, this division would look to acquire targets thirty-six hours before they reach the FLOT. Our final premise is that this leads to an extremely simple algorithm for determining the decay constant, i.e. chose the decay constant so that a unit entering the area of interest at the maximum distance (time) from the FLOT has only negligible value, e.g. 10%. Thus the discount figure for division-level targets would be determined from the equation:

$$\exp(-36*A) = 0.10, \text{ or } \quad A = .063 \text{ hour} \quad .$$

Under this approach then, a target maneuver unit located twelve hours from the FLOT would have a situationally dependent value of 46% (exp(-0.063*12)) of its inherent value, while a maneuver unit only six hours from the FLOT would have a situationally dependent value of 68% of its inherent value.

4. INSTANTANEOUS VERSUS AVERAGED VALUE

We would now note that value, as we have discussed it thus far, is a function solely of the state of the units involved at a single time (t), i.e. it is an instantaneous value. For certain analyses, this is certainly the most important single measure. For example, in trying to determine the probability of success of a breakthrough attack against a fairly shallow defense, the single most important measure would seem to be the relative combat power (value) of the units at the FEBA. However, we also note that the state of committed units is not constant, but changes continually (due to attrition, expenditure of POL and ammo, etc.). Therefore, for many questions, especially those involving the probability of success of extended operations, average value may be more meaningful measure. In order to remain consistent with our concept of exponential future discounting, we would then propose the following as the measure of average value:

$$G_A(V) = A \int_0^{\infty} V(s(t))\, e^{-At}\, dt \quad ,$$

where the current time is $t=0$. (The decay factor A in front of this integral is for normalization purposes, i.e. so that if $V(s(t))$ is constant, then

$$G_A(V) = V \quad ,$$

and, if $A \to \infty$, then

$$G_A(V) = V(0) \quad ,$$

i.e. if the dimension of the area of interest shrinks to zero, the average value reduces the current instantaneous value. We would also note that, if A is derived as discussed above from the area of interest, that the portion of the integral from times beyond the area of interest should be negligible.)

5. DERIVING VALUES FOR LOGISTICAL UNITS

As discussed above, the values of CS/CSS units derive from their effects on the values of the units they support. In this section, we present some initial thoughts on algorithms for computing values for logistical units. While not covering all cases, these nevertheless represent the type of algorithms that will be necessary for computing values for noncombat (i.e. CS/CSS) units. Logistical units are the easiest of the CS/CSS units to value since the functions of logistics in combat can be interpreted as a network of reservoirs (supply dumps) and pipes (transportation assets) whose function is to deliver a certain flow rate to the units in contact. Key parameters are the capacities of the reservoirs and pipes. The main purpose of the reservoirs is to function as shock absorbers in the face of fluctuating demands and replenishment rates, and in view of limited transportation capacity.

We first observe that, in the absence of logistical support, the value of combat units, even when not in contact, decreases monotonically over time. This decay, which is depicted in Figure 1, is due to the consumption of supplies, the

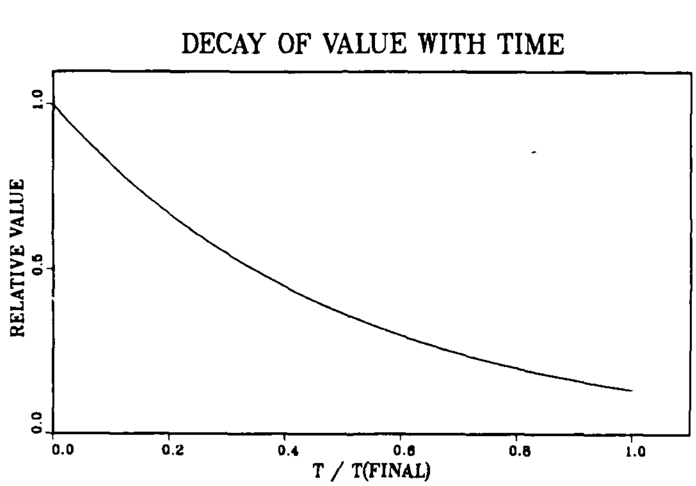


Figure 1

wearout of equipment, and the nonbattle attrition of personnel. The use of the term decay is deliberate, since we expect that, at least to a first approximation, this decrease in value could be modeled either by:

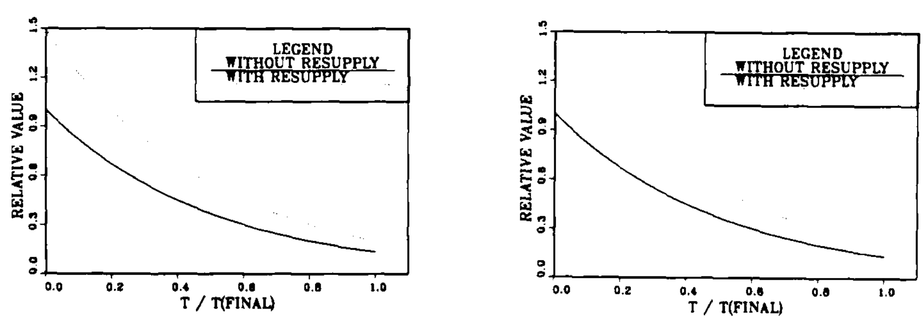
$$V(s(t)) = V_0 e^{-bt} \quad \text{, or } V(s(t)) = V_0 e^{-bt^2} \text{ ,}$$

where the value of b would depend on the unit's mission, environment, etc. A fundamental assumption in our approach is that the consumption, etc., that causes the change in state which leads to this decay can be estimated for a variety of conditions. This, of course, is really little more than assuming the validity of consumption factors such as are found in FM 101-10-1.

Logistical units act to change this decay in one of two general ways:

1. When the logistical unit is colocated with the supported unit, so that the support is immediately available, the effect will be to either raise the basic curve or decrease the slope of the decay, or both. This is indicated in Figure 2a (In theory, if the logistical unit had infinite support capacity, the decay curve would become flat.)

2. When the logistical unit is not colocated, then the support arrives at some time in the future. This will cause a discrete jump in the value of the supported unit at that time, following which the value will again decay until further support is received, etc. This behavior is shown in Figure 2b.



(a) (b)

Figure 2

Lastly, note that for logistical units, the average value, G_A, is essentially an exponentially weighted average of the area between the two respective curves in Figure 2.

Thus far, our approach has viewed logistics as a homogenous mixture provided to the users. This, of course, is not really realistic. Ammunition, for example, is provided in a somewhat different manner than POL, and the effect of ammunition resupply on a unit's value need not be the same as the effect of POL resupply. In addition, since the Airland model need not assume either side knows full ground truth on the other, we must also have procedures to assign value to a known logistical asset in the absence of knowledge about the location or condition of other assets. Thus we need to create an algorithm for determining the value of one specific type of logistic support, in the absence of full specific information on the other types. To do this, we introduce the concept of the (logistics) state network.

The logistics state network is related to ideas of state transitions, although the changes involved need to be random. Specifically, we assume that the state of a unit is given by an n-dimensional vector, and consider the possible changes that alter the unit's state from

$$\mathbf{S}_1 = (a_1, a_2, \ldots, a_n)$$

to

$$\mathbf{S}_2 = (b_1, b_2, \ldots, b_n) .$$

This transition will alter the value of the unit. The following methodology then determines how much of this change to ascribe to the change from a_1 to b_1, from a_2 to b_2, etc.

The process begins by establishing a network of nodes and arcs, where the nodes are generated sequentially from the initial node $\mathbf{S}_1$. The immediate neighbors of this node correspond to those states that are reachable by changing precisely one of the a_i to the corresponding b_i. The next level is generated by those states that represent replacement of precisely two of the a_i's, etc. Nodes are connected by an arc if and only if the corresponding states differ in precisely one position. The process continues until $\mathbf{S}_2$ is reached. A sample network for a three dimensional state vector is shown in Figure 3.

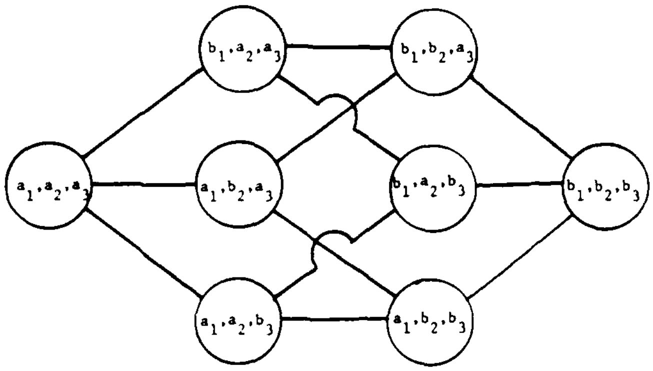


Figure 3

Note that every node at the i^{th} level (where $i=0$ corresponds to S_1) generates precisely (n-i) arcs to the next level, that there will be exactly n! different paths from S_1 to S_2, and, that, for each component of the state vector, only one arc on each path will represent changes due to that component. Each node represents some intermediate state between S_1 to S_2, with a corresponding value somewhere between $V(S_1)$ and $V(S_2)$. The value assigned to any arc will be the difference between the values of the end nodes for that arc. Then, we can compute the value of each component as the average of the values along all arcs of paths corresponding to a change of that component. (Note this will require multiple counting of arcs that occur on more than one path.) A sample complete such network is displayed in Figure 4, with the values of each of the nodes (arcs) written above that node (arc). For this network, using the methodology just described, the portions of the total increase in value:

$$V(S_2(t)) - V(S_1(t)) = 300$$

due to each of the three components of the state vector would be:

First Type: $(2(150) + (150+75) + 2(50))/6 = 104$

Second Type: $(2(50) + (50+150) + 2(125))/6 = 92$

Third Type: $(2(100) + (200+25) + 2(100))/6 = 104$

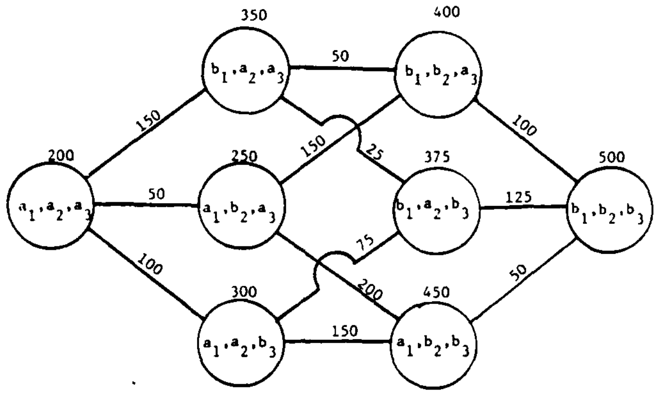


Figure 4

In closing this section, we note that, if desired, the above simple average could be replaced by a weighted average in the presence of additional information about the probability of certain intermediate states being actually reached, e.g. if a known POL shortage exists.

6. EXAMPLES

We conclude by presenting two examples of the use of the proposed value system methodology. Consider the attacking forces shown in Figure 5, which we assume have the following basic inherent values at full strength (in all areas) when in contact:

Motorized Rifle Battalion (+)	350
Motorized Rifle Battalion	250
Tank Battalion	400
Tank Battalion (-)	300
Artillery Battalion	600

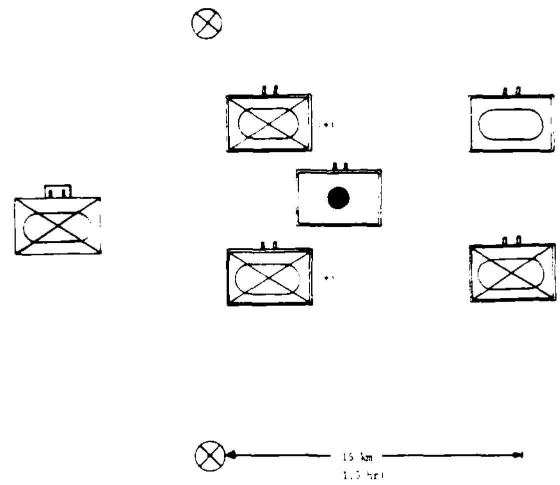


Figure 5

The forward two motorized rifle battalions and the artillery battalion are committed, while the two second echelon battalions are a minimum of 1.5 hours from commitment. Further, we assume for simplicity that maneuver units lose 30% of their value per hour committed, while artillery units lose 15% of their value per hour committed. (In this scenario, reconstitution, repair, and resupply are not considered.) Lastly, we assume that the defending task force commander has a three hour area of interest (which equates to a decay constant of 0.77). Thus, the current situationally dependent value of all the units shown is:

$$V_0 = (350 + 350 + 600) + (250 + 300)*e^{-(.77)*1.5}$$

$$= 1300 + 550*e^{-1.16}$$

$$= 1472$$

We now suppose the defending task force commander has available an asset (e.g. an on call air strike) with the capability to cause one of the following:

a. 50% decrease in the basic inherent value of a committed maneuver battalion

b. 35% decrease in the basic inherent value of a committed artillery battalion

c. 40% decrease in basic inherent value plus one hour delay (due to confusion, etc.) to one uncommitted maneuver battalion

d. 0% decrease in basic inherent value plus two hour delay (due to road damage) to both uncommitted maneuver battalions

The immediate values associated with these various options are, respectively,

Option a: $175 = (350*.50)$

Option b: $210 = (600*.35)$

Option c: $68 = (300*e^{-1.16} - (300*.60)*e^{-(.77)*2.5})$

Option d: $135 = (550*e^{-1.16} - 550*e^{-(.77)*3.5})$

Therefore, if the sole criteria for allocating this asset were to produce the maximum immediate decrease in value, the best choice would be to attack the opposing artillery battalion. However, other criteria may be equally appropriate. For example, suppose the objective were to minimize the average value of the total opposing force over the interval in question. If the attacking force were to commit its second echelon forces as soon as possible, then, over time (assuming t=0 to be the time in Figure 5), the value of the attacking force (without the air strike) would obey the formula:

$$V(t) = \begin{cases} 700*e^{-.36t} + 600*e^{-.16t} + 550*e^{-.77*(1.5-t)}, & 0 < t < 1.5 \\ 700*e^{-.36t} + 600*e^{-.16t} + 550*e^{-.36*(t-1.5)}, & 1.5 < t \end{cases}$$

Formulas for the value of the attacking force under each of the strike options above can be similarly derived. For the sake of brevity, only the one for the value under the third option (strike the uncommitted tank battalion) is shown here:

$$
V3(t) = \begin{cases} 700*e^{-.36t} + 600*e^{-.16t} + 250*e^{-.77*(1.5-t)} \\ \qquad + (300*.6)*e^{-.77*(2.5-t)} & , 0 < t < 1.5 \\ 700*e^{-.36t} + 600*e^{-.16t} + 250*e^{-.36*(t-1.5)} \\ \qquad + (300*.6)*e^{-.77*(2.5-t)} & , 1.5 < t < 2.5 \\ 700*e^{-.36t} + 600*e^{-.16t} + 250*e^{-.36*(t-1.5)} \\ \qquad + (300*.6)*e^{-.36*(t-2.5)} & , 2.5 < t \end{cases}
$$

Using these equations, curves describing the values, over time, of the total attacking force for these various options were computed and are displayed in Figure 6. Note that now under the objective of minimizing the average value of the total opposing force attacking the road network appears to be the best option.

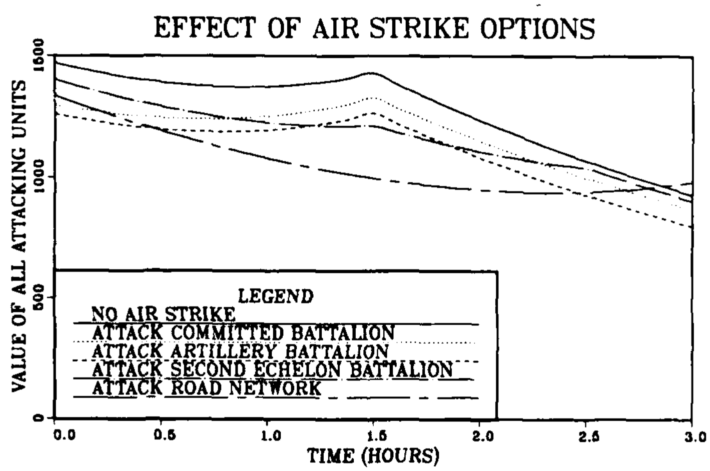


Figure 6

Lastly, however, we note that we expect that decisions in the model may frequently require computation of more than one set of value curves. For example, this would be necessary when the decision-making objective has been stated in the form of a constrained optimization, e.g. minimize the average value of the total attacking force, subject to the condition that the value of committed units never exceeds 1200 during the battle. Figure 7 displays the values, over time, of only the committed attacking forces, i.e. those actually in contact. Note the decision rule described above would exclude all the options lying above the threshold line indicated in Figure 7.

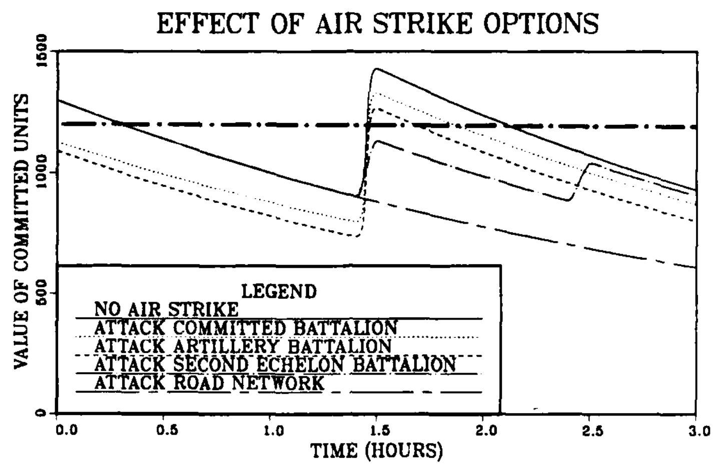


Figure 7

Our second, example illustrates the use of our methodology for logistics. In this example, we consider an artillery battalion whose basic load of ammunition would last twenty-seven hours under normal expenditure conditions. We assume that, over this time, the basic inherent value of the artillery battalion is solely a function of the ammunition on hand (i.e. no other losses); that the consumption of ammunition will remain uniform until all onhand ammunition is expended; and that, as a function of the number of basic loads of ammunition on hand, the value of the artillery battalion follows the curve shown in Figure 8. (Note the expression postulated for this curve was:

$$V = 300*(1.5 - 1.4*e^{-1.03*B^2})$$

where B was the number of basic loads of ammunition on hand.)

VALUE AS FUNCTION OF AMMO

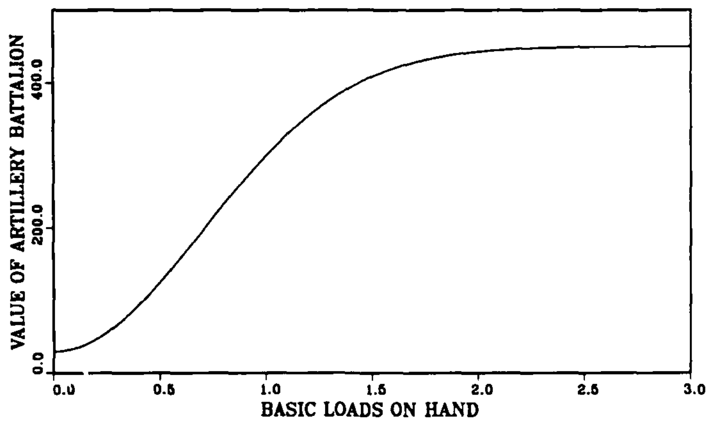


Figure 8

We now assume that at t=0 the battalion has on hand one basic load of ammunition, and consider the value of an ammunition resupply equal to a second basic load. Figure 9 displays two curves for the value of the battalion as a function of time. The lower curve is the value without delivery of the resupply, while the upper curve is the value with the resupply on hand. Thus, at any time, the basic derived value of the ammunition resupply is simply the difference between the upper and lower curves.

VALUE AS FUNCTION OF AMMO/TIME

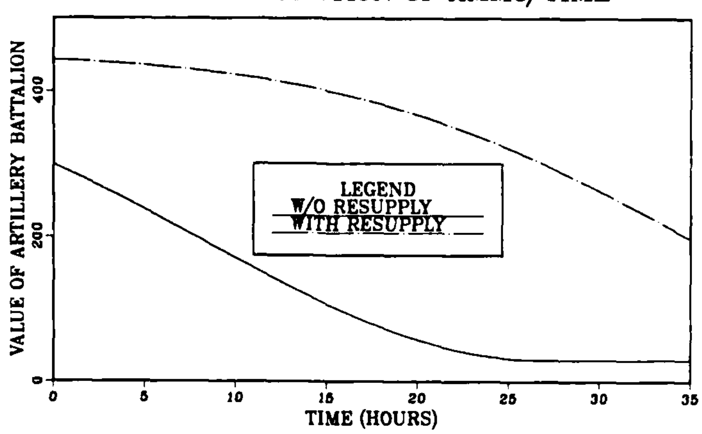


Figure 9

Following the same procedure as with combat units, the situationally dependent value of the resupply ammunition is determined by exponential discounting of the basic derived value based on the difference between the current time and the time when the resupply would actually arrive. The resulting curves are shown in Figure 10 for the case where the resupply is expected at t = 12 hours and the area of interest corresponds to 36 hours. As expected, the basic value of the ammunition grows as the battalion expends its on-hand ammunition. Furthermore, the situationally dependent value also increases, although for early times the exponential discounting will clearly affect this value.

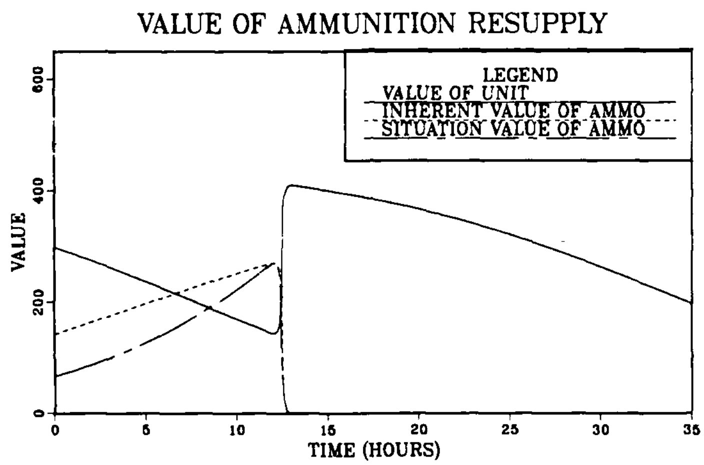


Figure 10

Lastly, Figure 11 shows the effect of interdiction on value, by displaying the situationally dependent values of the ammunition for resupply at both t = 12 and t = 18 hours. At any time, the value of the additional six hours delay is just the difference between the two curves. (Note there is no value assigned to interdiction for time greater than 12 hours since if the ammunition is not interdicted by then, it will have been delivered.)

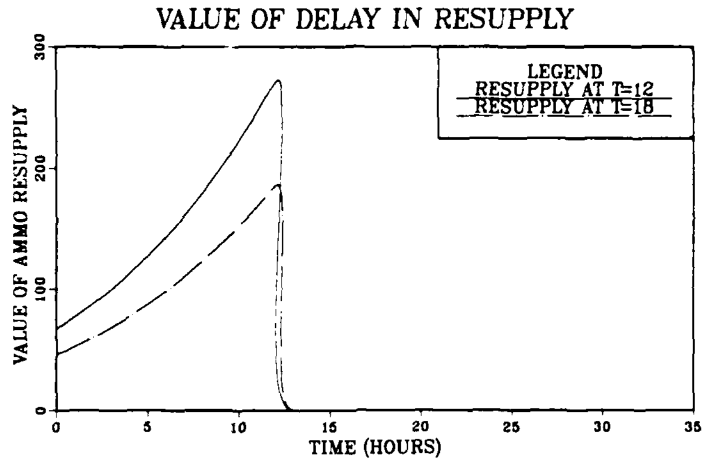


Figure 11

7. SUMMARY

In this paper we have proposed and developed a structure for assigning value, consistently, to the varied and diverse targets that populate the Airland battlefield. The values thus assigned are intended to be used as inputs to various target selection and weapon allocation decision modules in a Corps-level Airland Research Model under development at NPS. The key elements of the proposed value structure are that the values of noncombatant targets must be derived from the values of combatant targets that are supported, and that the value of time is reflected in the use of exponential discounting of value. A great deal of research still needs to be done to incorporate and refine this structure. Specifically, as alluded to in the paper, while the actual decisionmaking processes in the Airland Research Model will likely take the form of constrained optimizations, the actual form of the rules to be used is, for most decisions, not currently defined. Also, the value system we have proposed depends on realistic algorithms for computing what we have defined as the basic inherent values of combat units based on what we have called their state. Additional effort remains in the development of these algorithms. Despite the research still required, the structure proposed in this paper offers significant promise of being able to allow implementation of quantitative, systemic decisionmaking in the Airland Research Model.

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