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A GENERAL FRAMEWORK AND METHODOLOGY FOR ANALYZING WEAPON SYSTEMS EFFECTIVENESS

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ABSTRACT: Weapon systems effectiveness depends on many complex, interrelated factors, some of which are tangible, many of which are subjective and not measurable. These factors are often called Measures of Effectiveness (MoEs). However, weapons exist to perform mission-related tasks. As such, they can be characterized by Measures of Performance (MoPs), metrics that are objective and measurable. At the platform level, the MoPs are supported by the individual components from which it is constituted. However, the state of platform components and, hence its MoPs, can change through the course of a mission depending on factors both externally triggered as well as internally generated. After summarizing a taxonomy originally developed to support ballistic live-fire analysis, this paper outlines the development of a formal procedure for mapping the physical performance of components within complex system-of-systems (MoPs) to mission-based, warfighter utility in military operations (MoEs) for weapons systems analysis. This procedure seeks to unify five related approaches: the Vulnerability/Lethality Taxonomy for relating mission utility, system performance, system components, and combat interactions; the DMSO Functional Descriptions of the Mission Space (FDMS, formerly CMMS) within the overall Military Domain Representation Framework (MDRF); the ASD/C3I Operational Architecture (OA) within the overall C4ISR Architecture Framework; the NPS/TMCI Concise Theory of Combat for relating combat processes, combat interactions, and tactical deterrence; and the DMSO/AMSO/NIMA Integrated Natural Environment representation of terrain, oceanography, air and space weather.

1. Introduction

Today as the U.S. Army develops its future warfighting requirements, it does so in the context of a doctrine, training, leader development, organization, materiel, and soldier (DTLOMS) structure [1]. The U.S. Army Training and Doctrine Command (TRADOC) has been appointed the "gatekeeper" of the Army's requirements process. All mission success for both warfighting and other militarily supported activities must derive from the DTLOMS context.

The U.S. Army Materiel Command (AMC) is the Army's major command tasked with the responsibility of developing (nearly) all equipment. So, of the six DTLOMS elements, AMC supplies materiel to the warfighter. And what role does materiel play in terms of mission support? We suggest that materiel supplies the capabilities required for successful prosecution of the tasks associated with the mission(s). Two key issues associated with the capabilities, then are a) what are the capabilities required for mission success, and b) can the requisite capabilities be delivered and sustained for the mission duration?

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14. ABSTRACT

Weapon systems effectiveness depends on many complex, interrelated factors, some of which are tangible, many of which are subjective and not measurable. These factors are often called Measures of Effectiveness (MoEs). However, weapons exist to perform mission-related tasks. As such, they can be characterized by Measures of Performance (MoPs), metrics that are objective and measurable. At the platform level, the MoPs are supported by the individual components from which it is constituted. However, the state of platform components and, hence its MoPs, can change through the course of a mission depending on factors both externally triggered as well as internally generated. After summarizing a taxonomy originally developed to support ballistic live-fire analysis, this paper outlines the development of a formal procedure for mapping the physical performance of components within complex system-of-systems (MoPs) to mission-based, warfighter utility in military operations (MoEs) for weapons systems analysis. This procedure seeks to unify five related approaches: the Vulnerability/Lethality Taxonomy for relating mission utility, system performance, system components, and combat interactions; the DMSO Functional Descriptions of the Mission Space (FDMS, formerly CMMS) within the overall Military Domain Representation Framework (MDRF); the ASD/C3I Operational Architecture (OA) within the overall C4ISR Architecture Framework; the NPS/TMCI Concise Theory of Combat for relating combat processes, combat interactions, and tactical deterrence; and the DMSO/AMSO/NIMA Integrated Natural Environment representation of terrain, oceanography, air and space weather.

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This paper deals with these key problems. We start, however, by defining a framework within which we can place the key elements needed for analyzing weapon systems effectiveness. After describing the elements and the links by which they are connected, we will review the state of tools and methods available today. Finally, we will focus on some evolving methodologies which we believe to be critical in a) defining missions and mission Measures of Success (MoEs) and b) the key linkages required to tie materiel Measures of Performance (MoPs) to mission MoEs.

2. Framework Structure

During the mid-1980s, ballistic Live-Fire legislation [2] brought increased attention to the testing and prediction of ballistic live-fire phenomenology. An outgrowth of the efforts to rationalize the comparison of tests and prediction was the Vulnerability/Lethality (V/L) Taxonomy [3-8]. This framework was developed from a *platform-centric* perspective (*e.g.*, the numbering system is related to the platform being described). Later, we assert that this analysis strategy can be applied to multiple platforms engaged both in cooperative and adversarial roles (*e.g.*, groups of communications platforms).

2.1 Four Classes of Metrics

In what follows we employ the core levels of the V/L Taxonomy as described in Refs. 6 and 7. This concept characterizes a military platform (tank, aircraft, self-propelled gun, *etc*.) in terms of four classes of metrics. The classes are illustrated in **Fig. 1** as four abstract levels or mathematical spaces. For example, if emulating a ballistic live-fire event, **Level 1]** represents the complete geometry/material of the striking munition, the complete geometry/material of the platform, and the encounter geometry (*e.g.*, hit location and kinematics); this information can be represented by a vector containing the initial conditions needed to compute the resulting damage to the platform. **Level 1]** is shown as an ellipse filled with bullets (•), with each bullet representing one possible encounter vector.

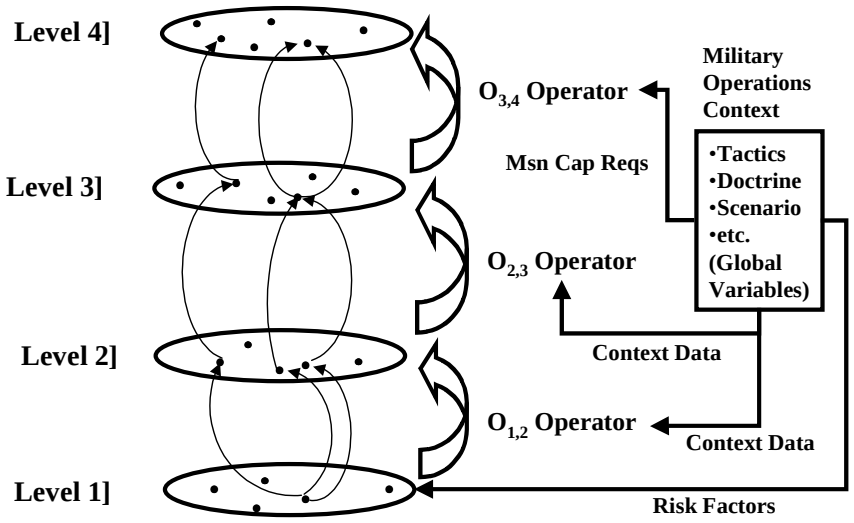

Figure 1. The V/L Taxonomy Illustrated *via* a Mapping Abstraction.

The ellipses represent mathematical spaces. The bullets (•) contained within the spaces represent vectors. The connecting arrows represent operators that map a vector at one level to a vector at the next sequential level. On the left, the descriptors for the various levels and operators are listed. On the right, a box labeled **Military Operations Context** provides descriptors of the external military environment (mission, terrain, threats, *etc*.) within which the platform must perform.

The second ellipse, labeled **Level 2],** represents the space of combinations of working and nonworking components on the platform. A single vector at this level lists the current status of each platform component.

The third ellipse, labeled **Level 3],** represents the measurable capabilities of the platform. For a fighting vehicle, this typically consists of its abilities to move, communicate, sense, engage, and replenish. Again, each bullet represents a vector that describes some particular state of the platform capabilities. **Level 3]** metrics can be considered measures-of-performance [MoPs].

The fourth ellipse, labeled **Level 4],** represents mission utility. In effect this metric represents whether the platform is either able or not to meet the requirements of the military campaign. **Level 4]** metrics are measures-of-effectiveness [MoEs].

In **Table I**, we list each level, indicate that a vector associated with that level has a corresponding subscript, and then describe the information typically represented by the vector. Except for the **Level 4]** vector**,** $\mathbf{v_4}$, each of the vectors in **Levels 1]** through **3]** is observable, measurable, and testable. This is important for supporting verification, validation, and accreditation (VV&A) activities that correspond to these metrics. In terms of our ballistic example, a vector at **Level 1]**, $\mathbf{v_1}$, defines the threat, the platform under test, and the kinematics of delivery. The results of the live-fire test generally lead to damage to particular components on the platform. The complete status of each component (*i.e.*, killed, not-killed) is represented by vector $\mathbf{v_2}$. As a vehicle is tested for its ability to move or fire a gun, the capabilities of the platform are represented by the vector $\mathbf{v_3}$. Platform utility, typically not measurable, is represented by the vector $\mathbf{v_4}$. For more on the properties of these vectors, see Ref. 7.

Table I. Composition of Vectors at Each **Level** or Class (from Ref. 7).

Level	Vector	Vector Descriptor
1]	$\mathbf{v_1}$	**Platform Geometry & Material, Risk/Repair Geometry & Material, Encounter Geometry**
2]	$\mathbf{v_2}$	**Status of Platform: *i.e*, Working and Nonworking Components**
3]	$\mathbf{v_3}$	**Platform Capability: *e.g.* Move, Communicate, Sense, Engage, and Replenish**
4]	$\mathbf{v_4}$	**Platform Utility: *e.g.* Does Platform Survive? (from Level 2]), Can Platform Perform Specific Mission Tasks?**

2.2 Three Classes of Operators

How are these vector levels linked? Mathematically, they are related by operators or transformation processes that map a vector at **Level n]** to a vector at **Level n+1].** The mathematical operators described are at the heart of the analysis process. Alternatively, the operators can be viewed as tests or experiments performed in the field. The linkage or corroboration between the results of analytical operators and field tests provide the basis for all rigorous VV&A activities. **Figure 1** also shows how the four levels of metrics are linked.

The four levels are connected abstractly by operators written as $\mathbf{O_{p,q}}$. This notation leads to the convention

$$\mathbf{v_q = O_{p,q}\{ v_p \}.} \qquad (1)$$

Since the operators only connect sequential levels,

$$\mathbf{v_{p+1} = O_{p,p+1}\{ v_p \}.} \qquad (2)$$

As noted above, live-fire tests are represented by the $\mathbf{O_{1,2}}$ Operator. The test of platforms to derive capabilities can be represented by the $\mathbf{O_{2,3}}$ Operator. Mission operations (or effectiveness) are represented by the $\mathbf{O_{3,4}}$ Operator.

To the right of the four ellipses shown in **Fig. 1** is found a box labeled Military Operations Context (MOC). This construct has been added to recognize that each of the operators takes input from the operations context in which a platform performs. In effect the MOC is defined by the DTLOMS concept (minus the M) noted above, and represents all of the factors external to the platform itself. For example, during a live-fire test, the volatility of ammunition that may be ignited is dependent on the ambient temperature for a given day–hence, the context data feed to the $\mathbf{O_{1,2}}$ mapper. Similarly, with the $\mathbf{O_{2,3}}$ capability mapper, the ability of a platform to move or acquire is a function of the terrain and weather variables– hence the context data connection to this mapper. Finally, the MOC clearly defines the mission activities or tasks that the platform will have to perform in order to achieve mission success. The required task levels are fed to the $\mathbf{O_{3,4}}$ Operator from the MOC as well.

By extending this construct to a time domain (see Section **3.5**) covering the period of a mission, the MOC can be thought of as supplying a series of mission tasks (as well as mission risks). The $\mathbf{O_{3,4}}$ Operator maps platform capabilities to mission outcomes. Simultaneously the $\mathbf{O_{1,2}}$ Operator maps component changes at **Level 2]**.

Mission outcomes are the basis for defining mission success. This particular mapping may represent the greatest analytic challenge facing the Army today. For a notional example on how mission success is determined by a platform current *versus* required capability, see **Fig. 4**, Ref. 7.

Finally we emphasize that in this abstraction the **Level 2]** vectors are the primary vectors from which all capabilities (and, hence, utilities) are derived and upon which all component-change mechanisms operate.

3. Generalizing the Structure

3.1 Component Change Mechanisms

Though originally conceived as a damage operator for representing ballistic phenomenology, the $\mathbf{O_{1,2}}$ Operator has been generalized across a range of damage and risk mechanisms including the description of reliability, availability and maintainability (RAM) [9] as well as electronic warfare and chemical threats [10]. In addition to causing damage, the $\mathbf{O_{1,2}}$ Operator can also represent repair or fix operations and, hence, supply or replenishment. A partial list of actions that fit the $\mathbf{O_{1,2}}$ framework is given in **Table II**. Thus, the $\mathbf{O_{1,2}}$ Operator is the general operator by which all platform components change state from working to nonworking (or *vice versa*) as a mission proceeds for a broad set of phenomenologies and events.

Table II. Some of the phenomena that can be emulated by the $\mathbf{O_{1,2}}$ Change Operator

Ballistic Interactions	**Electronic Jamming**
Chemical Interactions	**Cosite Interference**
Directed Energy Interactions	**Fair Wear & Tear**
High-Power Laser Interactions	**Battle Damage Repair**
Nuclear Interactions	**Logistics Resupply**
Logistics Burdens	**Fatigue***
Reliability	**Heat Stress***
Physics of Failure	**Sleep ***

*** Personnel Related**

3.2 Causal *vs.* Decompositional Structures

As noted above, the framework illustrated in **Fig. 1** was developed out of a need to model ballistic live-fire events with increased accuracy and resolution. As such it was conceived as a set of actions that (necessarily) take place in a time-forward, or causal, sequence. The numbering of the levels reflects the time-order of events. In fact earlier illustrations of the V/L Taxonomy were constructed with **Level 1]** at the top of the diagram and **Level 4]** at the bottom. Clearly all physically realizable events must obey causality.

Figure 2 illustrates the four levels with two arrows. The arrow going up represents the causal way in which the levels are linked; *i.e*, actions initiated at **Level 1]** cause component changes at **Level 2]**. Component status at **Level 2]** determines platform capabilities at **Level 3]**. Platform capabilities at **Level 3]** affect utility at **Level 4]**.

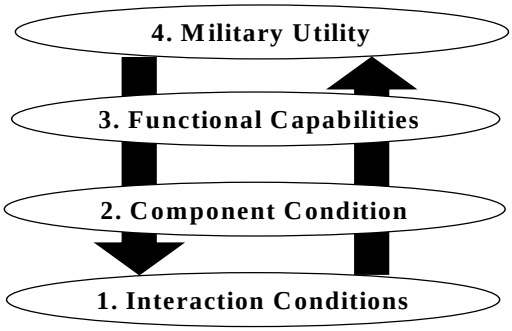

Figure 2. Top-Down *vs.* Bottom-Up Structuring:

The processes and events reflected by the taxonomy occur in a time forward and sequence in a numerically increasing order, *i.e.* bottom-up. For states to exist at the higher numeric levels implies decompositionally a top-down set of relationships. The operators connecting each level must therefore be constructed using top-down (or inferential) methods based on observation, hypothesis, testing, observation, etc.

Although all physical events run time forward, the physical and engineering hypotheses needed to establish cause and effect relationships must be constructed inferentially backwards. This is, in effect, the scientific method and therefore there is long-established precedence for this process. It is sometimes referred to as top-down or decompositional methodology. In a top-down context, **Level 4]** is clearly the highest level, and **Levels 3]**, **2]** and **1]** are logically subordinate. The downward-pointing arrow, therefore, shows that there is a decompositional relationship from the higher levels of the Taxonomy to the lower. Given the realization that the V/L Taxonomy is in fact a top (**Level 4]**) down (to **Level 1]**) construct, **Figs. 1** and **2** have been reconfigured as shown.

3.3 Mission-Based Utility

To pursue the issue of weapons effectiveness, it is first important to establish the detailed mission context, and desired mission outcome(s) (MoEs). In **Fig. 3**, we show the mission outcome space of **Level 4]** notionally in three textures. **Level 4]**, the collection of all possible mission outcomes, can be sorted into three categories; those exhibiting clear mission success, shown on the right in uniform shading, those exhibiting clear mission failure, shown on the left in horizontal hatching, and those showing ambiguous outcomes in the middle in vertical hatching. After the nature of the mission space and acceptable outcomes (MoEs) is established, the $\mathbf{O_{3,4}}$ Operator should be inferred linking platform capabilities at **Level 3]** to platform utility at to **Level 4]**. This process notionally leads to a single operator which, depending on the capability vector at **Level 3]** and the requirements arising from the mission, will map to one of the three outcome subspaces of **Level 4]**.

So far, we have established a detailed mission context, the measures of success, and the capabilities required to bring about the desired outcomes(s). We haven't as yet specified how those capabilities will be acquired. We also observe that the bold arrows all

point up; that is to remind us that the operators, when constructed, are causal and map up. However, they are each constructed using a top-down, or inferential, strategy. At this point we have notionally described a process that establishes the critical link of MoPs to MoEs. This elusive relationship is the corner stone of Cost/Benefit (C/B) studies and Analysis of Alternatives (AoAs) as well.

After the $\mathbf{O_{3,4}}$ Operator is established, then an exhaustive exercise of the mapping can be established to develop the statistical relationship between performance and effectiveness. Further, these relationships establish specific capability metrics associated with mission success. Armed with these insights, it is finally appropriate to develop specific platform configurations at **Level 2]** which can serve as candidates for achieving the performance levels specified in the success space of **Level 3]**. Confirmation of adequate platform performance at **Level 3]** can be achieved either through an engineering simulation of the $\mathbf{O_{2,3}}$ Operator and/or an appropriate set of performance tests of an actual platform.

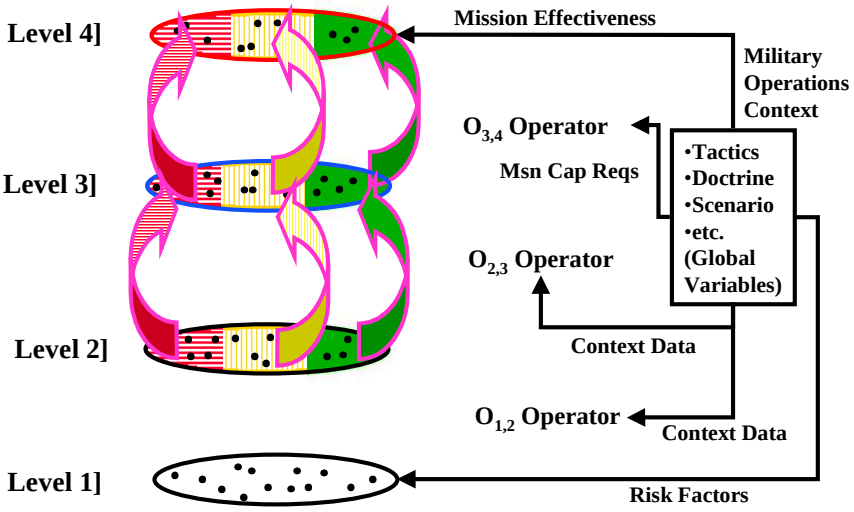

Figure 3. Mission-Based Utility.

In this construct, the materiel requirements process begins with establishing mission outcomes at **Level 4]** including the subset of failures (left horizontal cross-hatched), success (right side uniform) and ambiguous (center vertical cross-hatched). Once appropriate MoEs are established, the $\mathbf{O_{3,4}}$ Operator is inferentially constructed showing which capability combinations at **Level 3]** map to which subsets of **Level 4]**. Next, based on those capabilities identified at **Level 3]** which map to success at **Level 4]**, specific system designs can be established at **Level 2]**, potentially appropriate to delivering the required capabilities.

Having established a set of candidate platform designs at **Level 2]** which supply the required performance at **Level 3]** which results in mission success at **Level 4]**, we must establish the robustness of the designs. As described above, the mission context not only prescribes the capabilities needed for mission success, it also defines the threats, environment, logistics burdens, by which the component population at **Level 2]** will erode. Thus, an appropriate set of $\mathbf{O_{1,2}}$ Operators must be exercised to achieve robustness over the time extent of the mission spectrum.

3.4 System-of-Systems

This process can also be extended to "system-of-systems." For analyses in which multiple platforms are being played, each platform requires its own four-level vector description. We turn our attention to **Fig. 4**. In the bottom left we consider a set of **n** systems shown diagrammatically as individual taxonomies. In fact each platform has a **Level 2]** instantiation, and, for the moment, in isolation of every other platform, a set of capabilities at each respective **Level 3]** and corresponding utility at **Level 4]**. But the reason we fight as a team, obviously, is that seldom does one platform generate sufficient

capability to perform a mission by itself. Thus, in the sense of the inferential top-down utility process described above, how can we take a number of platforms embodying individual (read independent utilities) and combine them? The answer is, simply, individual platform utilities cannot be properly combined to infer joint utility!

The estimation of joint platform utility must begin at **Level 2]** for each platform. Although not yet described in detail here (see Section **4.3**), capabilities at **Level 3]** for individual platforms have been estimated for many years by using what amount to network models. Other than for communications applications, typically these network models have considered only the (sub)nets within a platform. But by expanding (horizontally) the notion of network connectivity to include component interconnects both within and among platforms, a network-centric, multi-platform system is instantiated. **Figure 4** notionally illustrates this super platform as a **Combined Level 2]**, populated by $\mathbf{Cv_2}$ vectors. Since platforms when cross-networked invariably demonstrate changed capabilities beyond some simple sum (or difference) of individual capabilities, the actual performance will be reflected at the Combined **Capability Level 3]**. This integrated construct can then be mapped to a **Combined Level 4]** utility space.

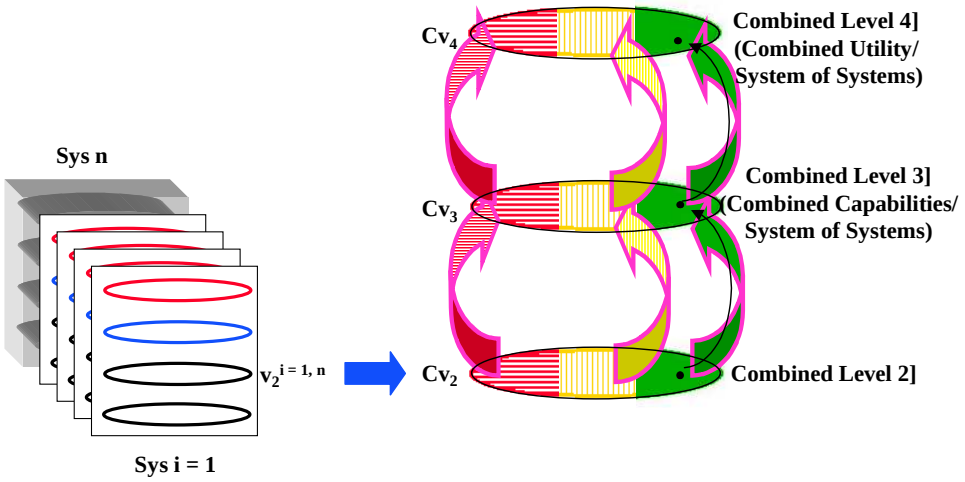

Figure 4. System-of-Systems.

This approach is especially relevant to analyses of C4I systems. The $\mathbf{O_{1,2}}$ map (evaluating jammers, worms, *etc*.) is worked for each cooperative networked platform. An appropriate $\mathbf{O_{2,3}}$ map is then computed across the gamut of linked systems. After aggregate MoPs are computed, the $\mathbf{O_{3,4}}$ utility mapping is performed for the joint platforms in mission context. But it should be emphasized that the notion of networked is applicable beyond C4I modeling. Multiple components, both within and among platforms, can be abstractly networked for many classes of linkage to include: mechanical, electrical, thermal, visual, hydraulic, acoustic, as well as electromagnetic.

3.5 The V/L Taxonomy as a Dynamic State Vector

When considered in the context of a mission, the Taxonomy framework illustrated in **Fig. 4** should be considered dynamic. That is, as a platform(s) proceeds through time, the military operations context will cause two kinds of activities. One, the capabilities of a platform will be challenged with a sequence of tasks. Two, a series of risk factors (e.g. bullets, wear out) will cause degradation to the system(s) (component) infrastructure. This notion is a compact, yet detailed way of thinking about mission activities. The metrics of the four levels and the connecting operators are, in fact, the pieces of simulation based acquisition (SBA) and how the pieces relate to each other.

4. Review of Framework

4.1 Three Kinds of Operations

In this context of SBA, we can see that there are three major classes of modeling and testing that, though different in detail, reoccur in virtually every study. They are:

1) How platform(s) macro performance leads to military success/failure.

2) How platform(s) atomic (read component) structure leads to platform(s) macro performance.

3) How risk/repair factors change the platform atomic structure.

It is our conjecture that the elements of SBA can be broken down and placed in one of these three categories. This observation has important ramifications that include assessing the completeness of operations research (OR) studies, the sharing of various tools/databases, and the achievement of global modeling coverage. In fact, we believe that this four-level structure, connected by three classes of operators, forms the foundation for an Operational Architecture for military systems analysis. The computation routines to be found in many codes can be parsed by this framework to see how a more complete top to bottom analysis framework can be built and integrated.

4.2 Aggregation of Damage

As noted above, **Level 2]** is the primary level in this architecture. All capability and utility are derived from the component structure. All $\mathbf{O_{1,2}}$ component change operators act to change **Level 2]** as well. To evaluate properly a particular risk or repair interaction, the result of all prior interactions must be accounted for; thus, the next event sees the platform in its current, not pristine, condition.

By contrast, nearly all risk effects estimated across the Army community, whether at the phenomenology level or at the aggregate wargame level, assume interactions with "pristine" platforms. That is to say, whenever an interaction occurs, there is no prior damage. This is true for the vulnerability community where, for example, the voluminous Joint Munitions Effectiveness tables covering numerous threat/target pairings are all for first-hit or independent-hit interactions. For example, it would likely be the exception for a chemical deposition study to be performed on a fighting vehicle in which prior ballistic damage existed (*e.g.* perforation of the crew compartment).

This framework illustrates that component damage (or repair) is, in fact, cumulative, and that a dynamic state vector is required to remember the current state for proper processing of the next $\mathbf{O_{1,2}}$ risk/repair mechanism.

4.3 Maturity of Levels and Operators

How much of the Framework described is supported by reliable algorithms (with supporting data) and computer implementation?

As noted above, the V/L Taxonomy arose about 1985 as a new stochastic vulnerability model SQuASH was developed.[3] The taxonomy was actually backed out of the early code efforts, not the other way around. Over the ensuing fifteen years, a suite of C-based vulnerability codes supported by a special portable environment has been developed. Called Modular UNIX-Based Vulnerability Estimation Suite (MUVES) [11], this single supporting structure is used to compute tank direct-fire interactions, anti-air encounters, and indirect-fire artillery and bomblet events. These capabilities are also provided for personnel vulnerability evaluation by a model called Operational Requirements for Casualty Assessment (ORCA) [12], which uses the same taxonomy. Due to the detailed nature of the threat/target interactions, high-resolution geometry and material information are required. Support for these calculations is provided by BRL-CAD® to enable the calculations [13,14]. But beyond the ballistic damage mechanisms included in the code (principally penetrator and fragment effects), none of the other $\mathbf{O_{1,2}}$ risk/repair mechanisms listed in Table II are resident. A great deal about these listed operators are known across the community. It is the exception, rather than the rule, that these mechanisms are linked through performance operators of the $\mathbf{O_{2,3}}$ class, or ever interleaved with various operators to estimate cumulative damage and performance degradation.

For the past decade or so, ARL/SLAD and AMSAA have developed various fault-tree based $\mathbf{O_{2,3}}$ mapping procedures [9, 15-16]. Yet, other engineering models exist. Again connectivity

between component state (**Level 2]**) metrics and platform(s) performance metrics is unusual.

In terms of explicit forms of the $\mathbf{O_{3,4}}$ Operator, we are familiar with few examples. Operational utility is normally prosecuted by means of wargames where the form of the mappings from performance to utility is implicit to the code. Force-on-Force model MoEs have focused mainly on loss exchange ratios (LERs), figures of merit probably best suited to massed forces decisively engaged. Relevance of LERs to future US military interactions is now a matter of debate.

However, there is precedent for the generation of $\mathbf{O_{3,4}}$ Operators in an explicit form. Early examples include efforts in the Air Force [17, 18] and more recently in the Army human performance community [19-23] where the decompositional methods have been developed most fully at the man-machine interface. Clear, complete linkages of systems-of-platforms and higher to complex, mission-specific MoEs seem not to be plentiful.

5. Defining the Warfighter Context

This section describes a formal procedure for describing warfighting utility at **Level 4]** as well as an approach for constructing the $\mathbf{O_{3,4}}$ Operator. This approach, called the Military Domain Representation Framework (MDRF) seeks to generalize and unify the V/L taxonomy discussed above, the DMSO Functional Descriptions of the Mission Space (FDMS), the C4ISR architecture framework, the Concise Theory of Combat, and the DMSO Integrated Natural Environment. The procedural steps are as follows:

1) Create scenarios to provide mission context.
2) Select an organizing principle for Combat Interactions.
3) Use hierarchical Strategy-to-Mission-to-Task (S-M-T) decomposition to organize the Combat Processes.
4) Use hierarchical Order-of-Battle decomposition to complete assignment of Task-Organized forces to Combat Processes.
5) Establish Task-based fault tree for Mission success using Measures, Conditions, and Standards.
6) Construct integrated Use-Case-Threads to sequence execution of Combat Processes leading to Combat Interactions.
7) Compute Measures (of performance), under prescribed Conditions, and compare to Task-based fault tree Standards to determine the Mission outcome of a Combat Process following a Combat Interaction.
8) The outcome of a specific Combat Process affects other Combat Processes one of two ways:
   a) First, as a direct input to a subsequent task and
   b) Second, by rolling up the S-M-T fault trees to where the branches connected to completed Task and the branches connected to the affected Task join (there may be many branches and many joins).

   In many cases, the influence will be implicit through a change in Conditions imposed on the Task rather than explicit through an input.
9) Warfighting utility is then expressed in terms of how the noted outcomes either enable or constrain Task execution within a Mission context. Resounding victory in many (but not enough) branches may not lead to overall Mission success; conversely, resounding defeat in many (but not critical) branches may still lead to overall Mission success.

We emphasize that the essence of Command and Control is to re-organize, re-sequence, change the S-M-T decomposition and/or the Table of Organization and Equipment (TO&E) to adapt to the new Conditions imposed by the various outcomes. Changes in the S-M-T will (likely) change the Measures and Standards assigned to an individual Task, including those Conditions that are under the exclusive control of the side executing the Task.

5.1 Scenarios

Clauswitz defined war as ". . . the continuation of policy by other means." It is the scenario (and associated mission context) which defines the "policy", describes the "other means," and ultimately determines which of the possible "continuations" constitute winning. For differing scenarios and missions, the exact same physical outcomes can represent anything from resounding victory to abject defeat.

It is at this point that many, perhaps most weapons systems analyses fall short – almost before beginning. In those instances, the scenario and mission context is little more than a set of initial

conditions and performance parameters for a list of interacting platforms, sensors, and munitions. The AoA scenario specifies a set of:

- **Level 1]** munitions,
- **Combined Level 2]** system-of-systems delivery components, and
- **Combined Level 2]** system-of-systems target components.

A range of $\mathbf{O_{1,2}}$ damage capability (to the target components) is assumed or computed. The number of **Combined Level 4]** sorties and **Level 1]** munitions to achieve a specified target attrition fraction is computed. The resulting force structure is then a tradeoff between the number of required **Combined Level 2]** system-of-systems delivery components and the **Combined Level 4]** sortie rate. Alternatively, for a given number of **Combined Level 2]** system-of-systems delivery components and ceiling **Combined Level 4]** sortie rate, the analysis determines what $\mathbf{O_{1,2}}$ damage capability is required.

The required operations tempo to achieve a specified target attrition percentage is then computed, perhaps as a number of **Combined Level 4]** sorties. **Level 4]** sorties are then transformed into numbers of required **Level 1]** munitions and **Level 2]** delivery components. Alternatively, for a fixed number of **Level 2]** delivery components (hence ceiling **Level 4]** sortie rate), $\mathbf{O_{1,2}}$ damage capability is required.

The problem is that the number of targets killed (or the rate killed or normalized as loss-exchange-ratio, LER) is no longer a complete measure of what constitutes winning. In contemporary combat, the US warfighter is faced with demands for:

- a near infinite loss-exchange-ratio (destroy opposing forces in place and drive him from the field, all at zero casualties by own forces),
- a near zero collateral casualty and damage rate (interdict enemy force using school buses as transport without a single injury to any child riding to school.),
- against an asymmetric adversary (state-of-the-art capabilities in narrow niches with a willingness to accept substantial own and collateral casualties to inflict numerically small casualties on US forces),
- all on a time-line driven by commercial communications technology (the collateral damage from a morning strike is broadcast on CNN within a few hours – in many cases inside the timelines for battle damage assessment and Air Tasking Order (ATO) generation – thus materially changing the political calculus of targeting in a multi-national force).

In many situations, the combat objective is to (favorably) shift a complex, multi-national political calculus rather than to attrite an enemy to an ultimate point. It is very unlikely that Iwo Jima level, own-force losses would be considered acceptable today in the US – almost independent of the political or military gain. Traditional killer-victim scoreboards and loss-exchange-ratios are still of value – primarily as a means to avoid paths leading to mission failure due to excess losses by own forces. However, in many (perhaps most) contemporary missions, these traditional measures provide little insight to mission success.

The Military Domain Representation Framework notion of scenario is a focused subset of a full campaign description – beginning with a "Road to War" and hierarchically decomposed from National Command Authority orders to the level of war and physical granularity required to conduct the more traditional weapons system analysis of alternatives. This approach explicitly states (at the top level) the political objectives and operational constraints which constitute winning.

What constitutes a "full campaign description", of course, must be sized to the scope of the analysis being performed. For a major system-of-systems which amounts to fundamental restructuring of a Service (*e.g.*, the US Army Future Combat Systems), then the level of detail in a Defense Planning Guidance Illustrative Planning Scenario would be appropriate. For weapons system analysis of lesser scope, the scenario detail should be correspondingly less.

The MDRF notion of scenario requires:

- a clear statement of the political objectives and operational constraints which constitute winning (and losing),
- excursions that cover the likely range of scenario (not performance) excursions,
- a focus on the distribution of possible outcomes, especially the sensitivity to variance rather than the traditional focus on expected value,
- sufficient top-level information to provide the needed mission context for the decompositions in subsequent steps.

Finally, the scenario should provide similar detail and content for both own and opposing forces. Understanding what constitutes winning and what constitutes losing for the OPFOR is just as important as it is for OWNFOR.

5.2 Combat Interactions

Having established the top-level context information in step 1, step 2 skips to the bottom-level of how the forces collide. In the traditional analysis of weapon systems effectiveness, battle damage (usually in the form of a kill/no-kill dichotomy) is essentially the only recorded combat interaction. However, the real combat involves a range of interactions that determine the eventual outcomes – not just damage outcomes, but other types of outcomes that affect mission success.

The Military Domain Representation Framework (MDRF) employs "The Concise Theory of Combat" framework developed by the Naval Postgraduate School and The Military Conflict Institute to categorize interactions. This framework distinguishes between Combat Processes and Combat Interactions. Combat Processes are the tactics, techniques, and procedures each side employs to conduct combat. To use a sports analogy, Combat Processes are essentially the playbook each side uses on the other.

The Concise Theory of Combat [24] identifies thirteen distinct types of Combat Interactions that describe the military outcomes. These outcomes arise when Combat Processes are employed. Seven of these Combat Interactions are externally directed on opposing forces by own forces:

- Demoralization,
- Destruction,
- Suppression,
- Neutralization,
- Disruption,
- Deception, and
- Information Acquisition.

At best, traditional loss exchange ratios represent only one of these (destruction). The Concise Theory further defines six Combat Interactions that are internally directed by own forces to assist own forces:

- Motivation,
- Command-control,
- Communication,
- Movement,
- Protection, and
- Sustainment.

Of these, only the operational effect of movement, protection, and perhaps sustainment are generally supported well in most representations.

The MDRF approach is to acknowledge that, of the thirteen Combat Interactions, destruction and movement are easily the categories that most nearly define interactions to be "combat." As such, they should always be included. However, restricting outcomes to destruction and movement alone as the root issues should not be the sole criteria when addressing the larger issue of what constitutes winning and losing. Therefore, the MDRF approach seeks to incorporate the full range of Combat Interactions.

Having expanded the number of key interactions from two or three to more than ten, some approach is needed to manage and constrain the increased complexity. This amounts to selecting an organizing principle for Combat Interactions.

MDRF addresses this by focusing on the concept of "tactical deterrence" [25]. Tactical deterrence contrasts the traditional view of combat as mutual attrition with the hypothesis that the purpose of contemporary combat is to influence/compel the opponent (at some critical echelon) to effect a decision desired by own-forces (*e.g.* cease fire, retreat, surrender). This appears particularly apropos for peacekeeping and anti-terrorist activities where success is prevention.

MDRF employs tactical deterrence as follows: Destroying the enemy and avoiding destruction by the enemy is easily the most military of activities. Therefore, perception of vulnerability – both the vulnerability of opposing forces to own forces (our lethality) and the vulnerability of own forces to opposing forces (their lethality) – tends to dominate combat decision-making. **Figure 5** uses as simplified notion of Perceived Battle State to illustrate this approach. Each side will evaluate Perceived Battle State then select own Combat Processes to generate Combat Interaction outcomes that drive the Perceived Battlespace from its present (perhaps unsatisfactory) state to a desired state (usually Tactical Overmatch or Not Engaged). In seeking to drive the OPFOR to a

Tactical Overmatch situation while avoiding unnecessary vulnerability by own forces, the resulting collision of contending Combat Processes will exercise the full range of Combat Interactions.

5.3 Strategy-to-Mission-to-Task Decomposition

Having defined the organizing principles for the Combat Interactions within the weapon systems analysis in step 2, step 3 returns to the top-level and performs a hierarchical Strategy-to-Mission-to-Task decomposition. MDRF recommends the well-known Universal Joint Task List (UJTL) mission-operation-task formalism. For details, see Refs. 26 and 27. In MDRF, the connection between UJTL and the Concise Theory of Combat is that Tasks capture "what" is to be done (*e.g.* movement to contact, suppress enemy air defenses). Within each specific Task, Combat Processes capture the tactics, techniques, and process of "how." For example, if the Task "what" is Movement to Contact, the Combat Process "how" could be Road-March, Move-by-Bounds, or Final-Rush.

5.4 Order-of-Battle Decomposition

Step 4 assigns resources (usually in the form of military forces) to tasks. MDRF employs the Unit Order-of-Battle Data Access Toolset (UOB-DAT) to task-organize standing units into temporary ground forces (*e.g.* integrated combat teams), aviation forces (*e.g.* strike packages), and/or maritime forces (*e.g.* task forces). See Ref. 28 for details. Which Combat Processes are assigned to complete a Task is largely determined by the intrinsic capabilities of the specific forces assigned to the Task relative to the intrinsic Combat Process capabilities of the specific opposing forces in order to drive Perceived Battle State to achieve the desired Combat Interaction outcomes.

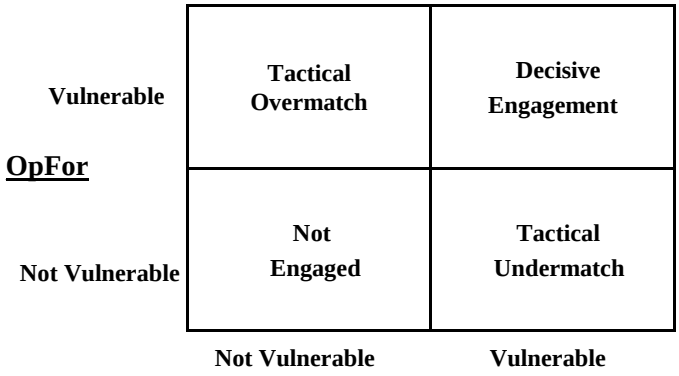

Figure 5. Perceived Battle States.

5.5 Establish Task-based Fault Trees

Entity-based fault trees based on physical component states are widely used in materiel reliability studies. For example, the MUVES ballistic vulnerability assessment suite discussed above employs an entity-based fault tree in the $\mathbf{O_{2,3}}$ mapping between **Level 2]** component state and **Level 3]** residual physical capability. MDRF intends to employ a Task-based fault tree in the $\mathbf{O_{3,4}}$ mapping between **Level 3]** functional capability and **Level 4]** warfighting utility. The UJTL notion of measures (**Level 3]** performance), conditions (*e.g.* physical, civil, political environment), and standard is being employed. Standards are thresholds of **Level 3]** performance (which are the results of Combat Processes executed by Task-Organized forces) which form boundaries between Task success/failure based on the Combat Interaction outcomes for that Task. Work is in progress on an example of this approach and will be reported elsewhere. This step defines the MoPs, the MoEs, and establishes the mapping between them.

5.6 Construct Use-Case Threads

This step integrates the individual Tasks (with associated forces) into a composite, time sequenced whole. MDRF employs a combination of the DMSO Functional Description of the Mission Space (FDMS) procedure and the C4ISR Architecture Framework procedure. See Refs. 29 through 32 for details.

5.7 Compute Measures

Having created the formal framework for the analysis, step 7 then executes the Use-Case Threads and collects all the Combat Interaction outcomes. Depending on the circumstances, this may be computed using models and simulations, may be measured in live experiments, or may be inferred from after action records of actual military operations.

5.8 Determine Combat Process Outcomes

Steps 1 through 6 are a systematic decomposition of the analysis problem. Step 7 establishes the "atomic level" outcomes as the leaf nodes of the decomposition trees. Step 8 is the systematic recomposition that integrates and aggregates the results. The easiest case is when one Task provides a direct input to a subsequent Task. The details of the impact are defined by the interface between the Tasks.

In addition to the direct input via sequence, a unique feature of the MDRF is the indirect roll-up using the Task-based fault trees. This work is ongoing and will be reported separately.

5.9 Express Warfighting

Ultimately, the outcome of a Combat Interaction affects the warfighter through enabling and constraining tasks. At one extreme, this is the essence of the Pyrrhic Victory, where the immediate physical outcome was in Rome's favor but the long term prognosis was disaster if similar victories were endured. At the other extreme is the "Race to Pristina" at the conclusion of the recent Kosovo Campaign. There were no shots exchanged or casualties endured – but there was a clear winner and clear loser in the multi-national political calculus that generated the race.

6. Summary & Conclusions

We have described an analysis framework that:

- has three linked metrics – utility, capability, componentry
- where utility is based on mission-related capabilities
- where capabilities are based on componentry
- where platform componentry is the fundamental metric, and
- the linkages include dependencies on specific military missions/contexts

The platform effectiveness changes with time as:

a. mission requirements change, and/or
b. the component infrastructure degrades/is reconstituted

What can be measured or modeled is:

a. the effect of the military environment (*e.g.* bullets, wear out, resupply) on platform component parts and
b. the performance (*e.g.* move, shoot, communicate) of the platform as a whole in the military environment.

What can be modeled, but not measured, is platform military effectiveness, and must seek the warfighter input to infer:

a. how performance forms the basis for effectiveness and
b. what defines the military environment(s).

This process also implies that you must begin by defining:

1) what constitutes operational effectiveness, then
2) the key supporting capabilities, and then
3) the robustness of the key components which support those capabilities.

This process implies a clear division of labor between the Scientist/ Engineer and the Warfighter/Operator, and who has the appropriate knowledge for each piece of the weapons analysis mosaic.

In the physical analysis of ballistic vulnerability, the **Combined Level 2]** fault-tree is the crux of the system of systems representation. The $\mathbf{O_{1,2}}$ interactions affect **Combined Level 3]** performance through this entity-oriented fault tree.

In developing the Warfighting Context, the Task-based fault tree is the analogous pivot point. Combat Process outcomes change Battle State. Tasks are affected by changes in Battle State through the Measures (under extant Conditions). Individual Tasks are successful when the prescribed Measures values meet the identified Standards. The combined effect is deduced from the Task-based fault tree. Warfighting utility is then expressed in terms of outcomes/capabilities that enable or constrain the Tasks required to complete the Mission within the Scenario constraints.

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