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Towards a Theory of Measures of Effectiveness

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The Theory of MOEs

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Abstract

An explicit theory for "measures of effectiveness" (MOEs as they are commonly referred to) does not exist. As a result several definitions for MOEs have been advanced, that while similar, do not provide the needed insight in to system performance evaluation.

Original studies performed by the Military Operations Research Society's (MORS) Command and Control workshop in the mid- 1980s laid a foundation for a more theoretical approach that was well received within the MORS community. However, little has been done in the last decade to further this work. Most papers in the latter part of the 1990s make no reference to the workshop reports and other published papers that resulted from the workshop.

This paper will present a review of the original work performed by MORS as well as relevant material that has been published in the intervening years. It will extend the original body of work using the systems-of-systems perspective originally developed by Russell Ackoff. A concise systems based definition of MOEs will be derived using this framework. The paper will also present the framework for a consistent mathematical theory for MOEs.

Introduction

The earliest references to MOEs are found in the post WWII report of the Operations Evaluation Group subsequently published as "Methods of Operations Research" [25]. Their description of MOEs is somewhat general and does not really provide a usable definition. They instead developed the concept of "constants" to define system performance. Goode and Machol [9] provide the first actual definition that this author could find. Their definition is simple and straightforward:

"The measure of effectiveness is the criterion by which solutions will be judged – proposed solutions, solutions under test, or solutions in being".

Goode and Machol also developed a set of desired characteristics for MOEs and recognized the possible existence of multiple measures. A 1964 report by the Weapon System Industry Advisory Committee (WSEIAC) also addressed the problem of systems effectiveness [30]. This report gave MOEs a systems flavor in its definition:

"Systems effectiveness can be defined as a measure of the extent to which a system maybe expected to achieve a set of specific mission requirements".

Rudwick further notes that the WSEIAC approach handles the measurement of any system in a hierarchy of systems. He also pointed out that by their definition of system effectiveness, the result is always measured in a probabilistic manner. Ackoff [1-3] also arrived at the same conclusion, i.e., a system of systems with performance results measured probabilistically.

Others have also addressed the issue of MOEs in the intervening years, but there are two efforts that are noteworthy. First is the MORS work that will be described shortly [36-41]. Second is the work of Noel Sproles [32-34] who has written extensively on the operational definition of MOEs. All the aforementioned papers will provide a foundation for a theory of MOEs.

Building on this foundation, the goal of this paper is to present a theoretical paradigm for MOEs that is grounded in the first principles of systems theory. The result will be a consistent approach that provides a basis for developing testable MOEs within a mathematical framework that allows for evaluating the statistical significance of change when performing analysis of alternatives.

The Military Operations Research Society and MOEs

The discussion of MOEs in the literature was not widespread.[1] As a result, prior to the Military Operations Research Society (MORS) series of Command and Control (C2) workshops there was a lack of consensus among analysts and decision-makers over the use of a consistent set of definitions relevant to both C2 systems and the measurement of their performance.[2]

The MORS study charter came from the Deputy Chief of Staff, Plans and Programs, Headquarters, Air Force Systems Command, who challenged Air Force planners to evaluate the effectiveness of C2 systems. He noted that there was a lack of analytic definitions as to what C2 architecture is. He felt that there is a need as well as a requirement for generic tools to evaluate C2 systems and architectures. He also identified the all too common problem that such tools as do exist are usually focused upon the specific aspects that the analyst doing the problem is most familiar with, regardless of their fit to the problem.

The crux of the problem that faced the first workshop participants was twofold. First, how to establish the relationship between a C2 process and the physical entities that are a part of the C2 system. Second was how to evaluate the resulting system. To accomplish this they had to develop the specification of an appropriate model of C2 and the integration of the selected C2 model, measures, methods, and mathematics. This involved developing an approach that accounted for the relationship between the decision to be supported and the analysis itself and the way in which a C2 model may be integrated into a specific problem.

[1] the majority of the known sources are listed in the Reference section.

[2] C2 will be used throughout this paper in a broad generic sense; i.e., the concepts apply to command, control, and communications (C3), command, control, communications, and intelligence (C3I) etc.

MORS Workshops

The initial Command, Control, Communications, and Intelligence (C3I) Measures of Effectiveness workshop took place in early 1984. The workshop focus was on the following issues:

- C3I model
- Transfer functions
- Analysis objectives
- Standard terminology
- Methodology
- Measures of Effectiveness applications
- Decision making and decision makers

The results of this workshop were presented at the 52nd MORS symposium. The interest and obvious need led to a MORS sponsored workshop in January 1985 where a strawman C2 MOE approach was developed and evaluated [36]. The results of the work with the strawman concepts were presented to a special session at the 53rd MORS symposium and were eventually published by MORS in June 1986 [37].

In January 1986, the workshop participants gathered again to test the architecture concept now known as the Modular Command and Control Evaluation Structure (MCES) [39] that had evolved from the earlier work. This workshop focused on four applications as a test of the MCES. The four applications: Navy Battle Force Architectural Study; Identification Friend, Foe, or Neutral Test Bed Architectural Study; Strategic Air Command Operational Testing Study; and Global Scale Warfare C2 Architecture (SuperCINC) Study demonstrated that the MCES approach was effective over a range of diverse problems. The next several years saw the approach gain acceptance within the Department of Defense as well as within the C2 community.

In the fall of 1992, MORS convened another workshop to "examine the context, processes, and methodologies for developing and using C3IEW [28]."[3] The impetus for this workshop was the perception that the rapid growth in computer and communications technologies required that the previous work be updated. The objectives of this workshop were similar to the original workshops; i.e., it was to assess the ability of current methodologies to evaluate the impact of C3IEW on campaign force-level effectiveness. It was to identify any deficiencies with methods and tools and identify resolutions to these deficiencies. Again, like the original workshops, this workshop led to another workshop in the spring of 1993. The purpose of this workshop was to evaluate the results of the first workshop using the example of the unmanned aerial vehicle (UAV) [35]. The outcome of these workshops confirmed the validity of the original work.

A major issue is that the results appear to have been confined to the C2 and MORS community even though several books have published [4], [15], [16], [44] that incorporate the approach.. Since this effort there has been little to no work in this area

[3] Electronic Warfare was added as a new dimension to the C3I process thus C3IEW.

and the body of work has not been cited in any of the eight to ten MOE focused papers that the author has reviewed in the last ten years.

Review of the MORS Approach

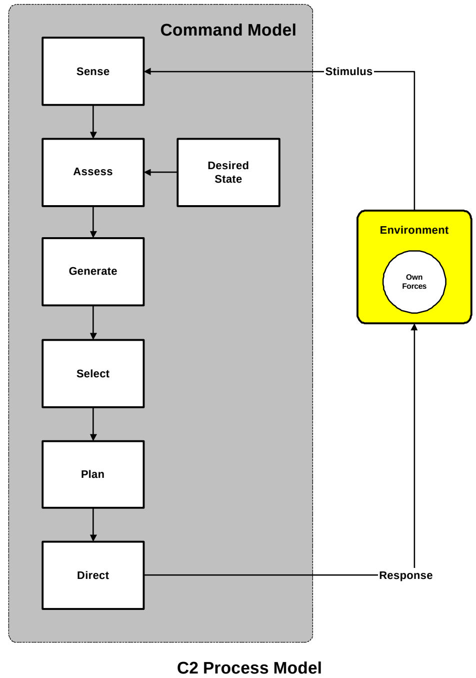
The MORS approach consists of two parts: (1) theory, and (2) an analytic framework (MCES). MCES ties together a number of conceptual points that help the analyst and the decision-maker to better understand the bounds of their analysis.

The Theory

The MORS approach starts with a set of standard terminology and ideas. The goal was to provide a common reference point in order to promote understanding and reduce controversy. The working group developed the following definitions as their starting point:

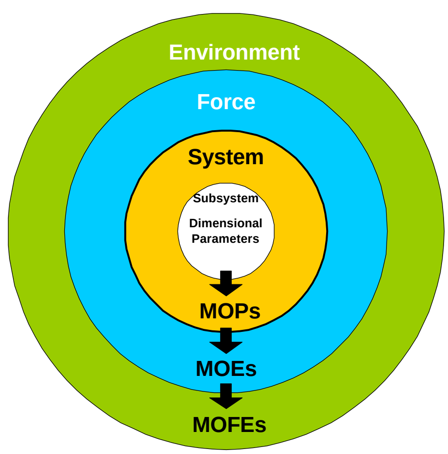
- **C2:** "The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of his mission." This definition was extracted directly from the Joint Chiefs of Staff Publication 1 (JCS Pub 1).
- **C2 system:** Viewed as having three components: physical entities, structure, and a C2 process. Physical entities refer to hardware, software, and people. Structure refers to the relationship between physical entities, procedures, protocols, and concepts of operation and information patterns. It can reflect the effects of doctrine, the scenario, and time and space.
- **C2 Process:** The C2 process reflects the functions carried out by the C2 system - sensing, assessing, generating, selecting alternatives, planning, and directing. Figure 1 represents the C2 process interacting with its environment (This model is based on the work of Lawson [14]).
- **Boundaries:** The boundary of a C2 system is a function of the system under analysis and delineates the system being studied from the environment. The definitions that follow apply in the context of the system boundary including the environment.
- **Dimensional Parameters:** Properties or characteristics in the physical entities whose values determine system behavior and the structure under consideration even when at rest.
- **Measures of Performance (MOP):** Related to inherent parameters (physical and structural) but measure attributes of system behavior.
- **Measures of Effectiveness (MOE):** Measure of how the C2 system performs its functions within an operational environment.
- **Measures of Force Effectiveness (MOFE):** A measure of how the C2 system, and the force of which it is a part, performs its missions.
- **Measures of Merit (MoM):** A term defined by the 1992 workshop. MoMs subsume all the measures that characterize a C2 system. The context in which MoMs are measured affects the way in which they are defined. Depending upon the analytic perspective a MoM could be a MOP or a MOE. It depends upon the question being answered in the analysis. MoMs are generally not multi-purpose; i.e., measures that are used to evaluate a system's life cycle may not be applicable to measuring operational goals (e.g. doctrine development). It is highly unlikely

that a single set of measures can be used in every application, or that each measure selected can be used in every application.



Lawson's C2 Process Model
Figure 1

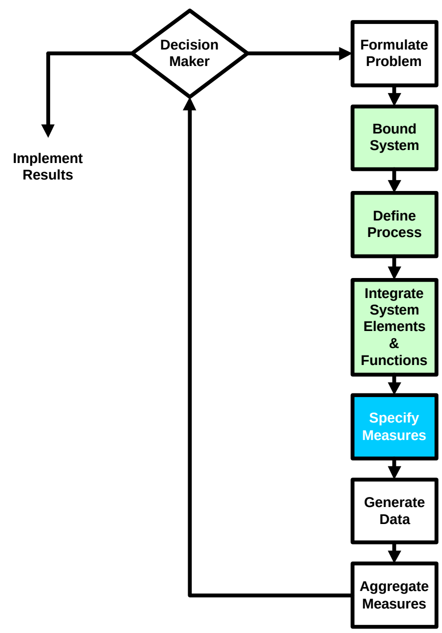
Figure 2 relates the C2 system boundaries to the various levels of measures. Dimensional parameters and MOPs are specified and measured within the C2 system boundary whereas MOEs and MOFEs are specified and measured external to the boundary.



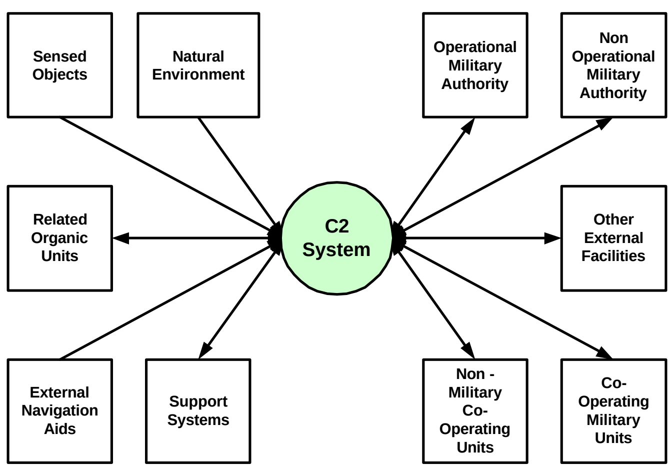
C2 System Boundary Levels
Figure 2

The MCES Process

While the definitions were developed for evaluating C2 systems the definitions apply to all systems and systems of systems as well. The key point is describing the system boundary with the external environment and the processes of functions that are contained within the boundary. Figure 3 shows that the first steps are to bound the system and define and integrate the processes of interest; only then can the measures be specified. In systems engineering this boundary is shown in a context diagram such as that shown in Figure 4.



The MCES Process
Figure3



C2 System Context Diagram
Figure 4

Table 1 is a summary of the characteristics that a MoM[4] should possess as defined by the workshop. This list is similar to the attributes listed by Goode and Machol. They include the requirement that the MoM be efficient in the statistical sense (small variance/reasonable accuracy). However, neither set supports the concept that all measures are expressed as a probability as advanced by Rudwick. This is a crucial issue and will be one of the focal points for the rest of this paper. In the author's opinion, the main problems that most analysts have with development of MoMs is the failure to adhere to the MCES process and the failure to realize that MoMs are related to the outcome of a process. To this extent the MORS work is incomplete.

Developing the Theory

It should be clear that the MORS work represents a good starting point. It is based on the knowledge and experience of many people. Thus, while several definitions for MOEs have been advanced in recent years including those of Sproles and Hockberger [13], this paper will argue that the MORS definitions will serve well. In summary, the points to build on are:

- The importance of system bounding;
- The hierarchal relationship between measures, and;
- The focus on process and resulting interactions with the environment.

All that remains is to place them in a true systems context with their associated mathematical relationship.

Characteristics	Definition
• Mission oriented	• Relates to force/system.
• Discriminatory	• Identifies real difference between alternatives.
• Measurable	• Can be computed or estimated.
• Quantitative	• Can be assigned numbers or ranked.
• Realistic	• Relates realistically to the C2 system and associated uncertainties.
• Objective	• Defined or derived, independent of subjective opinion (it is recognized that some measures cannot be objectively defined).
• Appropriate	• Relates to acceptable standards and analysis objectives.
• Sensitive	• Reflects changes in system variables.
• Inclusive	• Reflects those standards required by the analysis objectives.
• Independent	• Mutually exclusive with respect to other measures.
• Simple	• Easily understood by the user.

Desired Characteristics for Measures of Merit
Table 1

Some Basic Systems Theory

Maier and Rechtin [21] define a system to be:

A set of different elements so connected as to perform a unique function not performed by the elements alone.

[4] Measures of Merit will be used throughout the rest of this paper to be consistent with the MORS definitions.

Ackoff [3] notes that "the function(s) of a system is the production of the outcomes that define its goals(s) and objective(s)." To that end complex man made systems (C2 systems, modern automobiles, etc.) exhibit the following characteristics:

- They are open systems – they interact with their environment (as per the Lawson model).
- They exhibit closed loop behavior – they respond to the environment.
- They operate in a continuous or discrete state but not steady state.
- Systems are hierarchal in nature – examination of the elements or structure provides a more detailed view of its static characteristics.
- Its functional properties are highly differentiated and capture behavior or the dynamic characteristics as it interacts in its environment.

Describing the dynamic behavior and its outcome is the crux of the analyst's problem. Does the set of behaviors provide the expected outcome? By the requirement for the MoM to be quantitative the expected outcome is expressed as an expected value or probability of occurrence. Rudwick notes that to evaluate system effectiveness the system must be placed in its operational environment and operated in accordance with the specified environmental conditions established in the analysis. As mentioned earlier, he states that by this definition, system effectiveness is *always* measured in a probabilistic fashion. Ackoff defines this idea mathematically [2].

$$E = f(c_i, u_i)$$

Where:

- E= a measure of the performance of the object, organism, or organization involved.
- c_i = the set of controlled variables.
- u_i = the set of uncontrolled variables.
- f = the relationship between the preceding variables.

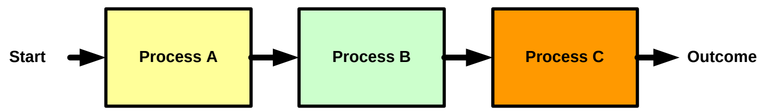
Referring back to the MORS definitions c_i and u_i represent the parameter set of the system and the environment respectively. Ackoff further specifies that $A_i\left(1 \le i \le m\right)$ represents different actions available to a system in a specific environment [3] (a change in the parameter set will change the behavior). P_i is the probability that the system will select these courses of action in that environment. Then:

$$\sum_{i=1}^{m} P_i = 1.0$$

If E_{ij} represents the probability that a course of action A_i will produce an outcome O_j then the efficiency of the system in producing the outcome O_j is:

$$P_o = \sum_{i=1}^{m} P_i E_{ij}$$

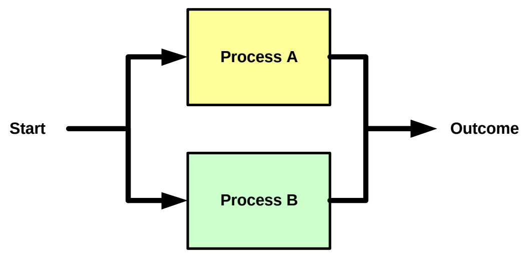
More on Processes
As noted earlier systems will instantiate their behaviors either continuously or discretely or in a combination. As an example radar can search (continuous) and detect (discrete) at the same time. Processes can also occur sequentially or parallel or in combinations thereof. Thus radar will search, detect, and track sequentially but can also search and track in parallel (once the target meets tracking criteria).



Serial Processes
Figure 5

The product of the individual outcomes of A, B, and C gives the overall outcome of these processes.

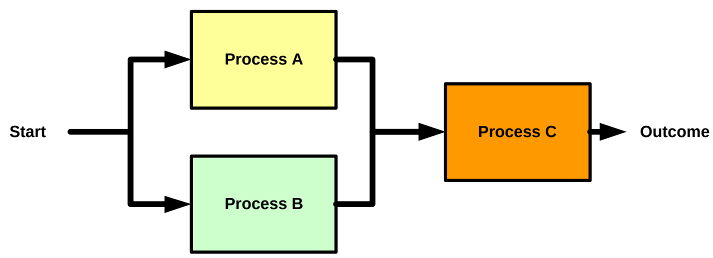
$$P_t = P_A P_B P_C$$



Parallel Processes
Figure 6

For a parallel network the overall outcome is given by

$$P_t = P_A + P_B - P_A P_B$$



Series-Parallel Processes
Figure 7

For a series-parallel network the overall outcome is given by

$$P_t = P_c(P_A + P_B - P_A P_B)$$

Evaluation of more complex processes can be accomplished by applying the mathematics of reliability theory to the network of processes.

What Really Constitutes a MOM?

Rudwick believed that systems effectiveness was a function of three primary components:

- Availability,
- Dependability (Reliability), and
- Capability.

Marshall [23] believed that system effectiveness or probability of performance (P_p)had a fourth component – survivability. He expressed the relationship between these components as follows:

$$p \quad o \quad m$$

Where A is availability, R is reliability, S C is capability and all are

What both have said is, that from a Systems Theory perspective, the dynamics of the system interacting with its environment is a complex process that involves consideration

An Example

Consider the performance of a battlegroup in defending itself against hostile air threats

processes for this system of systems are detection, command and control, and engagement. Using Marshall's approach, the efficiency of the battlegroup in the defense

availability of AAW assets, reliability of AAW assets, Survivability of the AAW assets and the overall engagement capability of the AAW assets: the probability of detecting the

of completing the target weapon interaction successfully.

A detailed breakdown of each term is beyond the scope of this paper. However,

the probability of a successful engagement P is given by:

$$se \quad d \quad c \quad e$$

searching at the same time) so the performance of the poorest unit could drag overall detection performance down.

The Role of Time

Analysts frequently use time as a performance measure- erroneously! Their error is that they lose sight of the fact that the goal is to evaluate the outcome of a process. Because processes can combine serially or in parallel time is the independent variable and the outcome is expressed as an expected value given a time window or the expected value that a process can be completed within a time window.

Summary/Conclusions

The MORS workshops of the 80's and 90's provided a solid foundation for developing a needed mathematical approach to MoMs. This body of work emphasizes that to properly develop MoMs the analyst must focus on bounding the system properly and describing the processes to the appropriate level of abstraction. Understanding that the focus is on process provides for an appropriate mathematical formulation of the process and its outcomes. The outcome of a process is an expected value based upon system parameters for a given environment. In addition, a true system assessment may require the evaluation of several factors

This paper is a work in progress. Future work will include extending the mathematical formulation through application to selected problems in both the military and business domains.

Biography

Mr. Green is a Senior Lecturer at the Naval Postgraduate School. He was the chair of the MORS MOE working group for several years and was involved in the original research upon which this paper is based.

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