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# Interoperability Measurement

Thomas C. Ford

**INTEROPERABILITY MEASUREMENT**

DISSERTATION

Thomas C. Ford, Major, USAF

AFIT/DSE/ENV/08-S01

**DEPARTMENT OF THE AIR FORCE**
**AIR UNIVERSITY**

# AIR FORCE INSTITUTE OF TECHNOLOGY

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**INTEROPERABILITY MEASUREMENT**

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Thomas C. Ford, BS, BA, MSE

Major, USAF

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Thomas C. Ford, BS, BA, MSE

Major, USAF

Approved:

John M. Colombi, PhD (Chairman) — 25 Aug 08 — Date

David R. Jacques, PhD (Member) — 26 AUG 08 — Date

Major Scott R. Graham, PhD (Member) — 26 Aug 08 — Date

Accepted:

MU Thomas — 28 Aug 08

Marlin U. Thomas, PhD — Date
Dean, Graduate School of
Engineering and Management

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who blessed us with all.

Thomas C. Ford

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## Abstract

There is no general method of measuring the interoperability of systems which accommodates all types of systems and interoperations. Additionally, no mathematical method of describing the impact of interoperability on operational effectiveness has been published. Creating a general method of measuring the interoperability of systems is difficult because the number of system types and means of their interoperation is infinitely large. The complexity of modeling interoperations between all system types and the impossibility of cataloging them has precluded the publication of a general method of measuring interoperability. While limited methods of measuring the interoperability of certain types of systems interoperating in specific ways have been published, these methods are compartmentalized, largely incompatible with each other, quickly become outdated as technology changes, and produce imprecise measurements. Because of the difficulty in creating a general interoperability measurement method, other researchers have relied upon a problem decomposition approach, effectively fracturing the problem and driving them further from the solution.

In this research, a holistic, fundamental, and flexible approach towards describing a general method of interoperability measurement was taken. The method applies to both collaborative and confrontational interoperability. It models systems according to their interoperability-related features in the context of an operational process. The system models are as abstract or concrete as desired which supports a final interoperability measurement that is not limited to a small set of levels, and is as precise as desired. A

fundamental result of the method states that a measure of the similarity of systems modeled in this way is a measure of their interoperability. Furthermore, if systems implement a confrontational operational process and are identified and modeled in the context of a measure of operational effectiveness tied to that process, then another fundamental result mathematically relates the change in interoperability of the systems with a change in the measure of operational effectiveness.

As a general method of measuring interoperability it has uncountable uses, however three applications are given to illustrate the method. The first application shows how the method can be used to measure the interoperability of coalition forces in the context of a multi-national operation. The application also demonstrates that many extant interoperability measurement methods are special cases of the more general method given in this research. The second application demonstrates the relationship between interoperability and operational effectiveness in the context of a suppression of enemy air defenses (SEAD) problem. It also illustrates that an interoperability measurement can motivate system upgrades and highlights the concept that friendly systems should be directionally interoperable with adversary systems (i.e., friendly systems should control adversary systems). The final application explains the time-variance of interoperability in the context of a precision strike example and further illustrates the sufficient conditions for operational effectiveness. More applications are proposed in the areas of non-technical interoperability, cross-domain interoperability, and international interoperability. Finally, observing that the method in this dissertation measures direct interoperability of systems, further research is proposed in the area of indirect interoperability, noting that a system may not directly impact adjacent systems, but might strongly, and indirectly, impact distant systems.

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## Definitions

*Architecture* "The structure of components, their relationships, and the principles and guidelines governing their design and evolution over time." (DoD, 2007a)

*Architecture Framework* "Guidance and rules for structuring, classifying, and organizing architectures." (Ibid)

*Blue System* "A U.S. or allied system; a friendly system."

*Capability* "The ability to execute a specified course of action. (A capability may or may not be accompanied by an intention.)" (JP 1, 2007)

*Character* "A feature, trait, attribute, or characteristic."

*Classification* "A taxonomy."

*Collaborative Interoperability* "The interoperability between friendly (blue) systems."

*Confrontational Interoperability* "The interoperability between friendly (blue) and adversary (red) systems."

*Confrontational Operational Process* "An operational process implemented by two or more opposing sets of systems."

*Contextual Interoperability Measurement* "A measure of the interoperability of two systems whose instantiations have been aligned with at least one other system possessed of one or more different characters not possessed by the original two systems."

*Diagnostic Character* "A character which distinguishes one taxon from related taxa."

*Diametric Measure of Operational Effectiveness* "A measure of operational effectiveness written as a pair which relates the effectiveness of the blue systems to the lack of effectiveness of the red systems."

*Directional Interoperation* "An interoperation that occurs from System A to System B, but not vice versa."

*Effect* "A change to a condition, behavior, or degree of freedom." (JP 1, 2007)

*Interoperability* “The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together.” (JP 1-02, 2008)

*Interoperability Character* “Short for *System Interoperability Character*. A character which describes how a system provides and accepts services from another system.”

*Interoperability Character State* “A qualitative or quantitative instance of a system character; a sub-division of a system character.”

*Interoperability Function* “A similarity function which takes a pair of system instantiations as its arguments, has a range of [0,1], rewards for shared characters and optionally penalizes for unshared characters, and gives a greater reward to system pairs whose shared characters’ states have a “better” value.”

*Interoperability Measurement* “A measure of the interoperability of two or more systems, or in other words, a measure of the similarity of two or more systems instantiated with interoperability characters.”

*Maturity Model* “A model which describes the stages through which a process progresses.” (DoD, 1998)

*Measurement* “The assignment of numbers to properties or events in the real world by means of an objective empirical operation, in such a way as to describe them.” (Finkelstein & leaning, 1984)

*Measure of Effectiveness* “A criterion used to assess changes in system behavior, capability, or operational environment that is tied to measuring the attainment of an end state, achievement of an objective, or creation of an effect. Also called MOE.” (JP 1-02, 2008)

*Measure of Operational Effectiveness* “An MOE associated with an operational process which is used to assess changes in the production of a desired operational effect. Also called MoOE.”

*Natural Character* “A character which is not confounded with another character.”

*Numerical Taxonomy* “The grouping by numerical methods of taxonomic units into taxa on the basis of their character states.” (Semple & Steele, 2003)

*Operation* “1. A military action or the carrying out of a strategic, operational, tactical, service, training, or administrative military mission. 2. The process of carrying on combat, including movement, supply, attack, defense, and maneuvers needed to gain the objectives of any battle or campaign." (JP 1-02, 2008)

*Operational Advantage* "The condition in which a set of friendly (blue) systems enjoy directional interoperability over a set of adversary (red) systems."

*Operational Process* "A series of activities and decisions, logically sequenced, which when executed achieve a desired effect."

*Performance Enhanced Instantiation* "A system instantiation with a performance overlay (e.g., cost, efficiency, throughput, rate, etc.)"

*Pure Interoperability Measurement* "A measure of the interoperability of two systems whose instantiations are aligned only with themselves."

*Red System* "An enemy or adversary system."

*Self-Interoperability* "A type of interoperation which originates at a system, exits the system boundary, and then is accepted back through the boundary."

*Similarity Function* "A function used to measure the resemblance of two or more system instantiations. The converse of a distance (dissimilarity function)."

*System* "An entity which is composed of at least two elements and a relation that holds between each of its elements and at least one other element in the set" (Ackoff, 1971)

*System Characterization* "A set of system instantiations which have been aligned with each other."

*System Identification* "The association of a system with the activities and decisions of an operational process."

*System Instantiation* "A sequence of character states which models a system."

*System Similarity* "A measure of the resemblance of two systems made by providing two aligned system instantiations representing those systems as the arguments to a similarity function."

*Taxon* "(plural taxa) A taxonomic grouping."

*Taxonomy* "An orderly grouping of systems into taxa according to their characters."

*Time Variant Interoperability Measurement* “A set of interoperability measurements associated with a set of time periods.”

## Notation

| | |
|---|---|
| $s_i$ | An individual system |
| $S$ | A set of $n$ systems $s_i$ |
| $c_i$ | A system character state |
| $C$ | A set of $n$ system character states $c_i$ |
| $x_i$ | A system character |
| $X$ | A set of $n$ system characters $x_i$ (called the Characterization of $S$) |
| $X_T$ | A set of "transmit" system characters |
| $X_R$ | A set of "receive" system characters |
| $\sigma_i$ | An instantiation of $s_i$ |
| $\sigma_T$ | The "transmit" portion of $\sigma_i$ |
| $\sigma_R$ | The "receive" portion of $\sigma_i$ |
| $\sigma_B$ | A blue system instantiation |
| $\sigma_R$ | A red system instantiation |
| $\Sigma$ | A set of $n$ aligned system instantiations $\sigma_i$ (called the Instantiation of $S$) |
| $\Sigma_B$ | A set of aligned blue system instantiations |
| $\Sigma_R$ | A set of aligned red system instantiations |
| $I$ | An interoperability function |
| $m_{i,j}$ | The directional interoperability measurement from $s_i$ to $s_j$ |
| $M$ | An interoperability measurement |
| $O$ | A diametric measure of operational effectiveness |
| $O_B$ | Blue operational effectiveness |
| $O_R$ | Red operational effectiveness |
| $G$ | An interoperability graph |
| $V(G)$ | The vertex set ($S$) of an interoperability graph |
| $E(G)$ | The edge set of an interoperability graph |
| $Sim$ | A similarity function |

# INTEROPERABILITY MEASUREMENT

## 1. Introduction

*Developing and applying precise measurements in an area as multidimensional and complex as interoperability is difficult. However, measuring, assessing, and reporting interoperability in a visible way is essential to setting the right priorities.*
*—M. Kasunic & W. Anderson*

### 1.1 Overview

In 2004, then Secretary of Defense, Donald Rumsfeld, said "we've put a premium…on interoperability." That same year, the Department of Defense (DoD) hired a Federally Funded Research and Development Center (FFRDC), the Carnegie-Mellon University Software Engineering Institute (CMU-SEI), to research and report on the state of the practice in interoperability measurement. They responded that measuring interoperability is difficult yet essential (see quote at chapter head). (Kasunic & Anderson, 2004:vii) Unfortunately, they also wrote that "despite laudable case-by-case efforts, there is today no method for tracking interoperability on a comprehensive or systematic basis." (Kasunic & Anderson, 2004:ix) In fact, CMU-SEI highlighted one extant interoperability measurement model, published nearly a decade earlier, as the state of the practice and called it "immature." (Ibid) There has been little change to the state of the practice since.

### 1.2 Uniqueness and Substantiality of Research

This research presents an inaugural general method of quantitatively measuring the interoperability of a heterogeneous set of systems. It overcomes the weaknesses of extant methods (Chapter 2) which, 1) limit their scope to specific types of systems and interoperability, 2) generally qualitatively bin systems into a limited number of interoperability levels, resulting in an imprecise measurement, 3) do not provide a means of correlating interoperability to operational effectiveness in context of a confrontational operational process, 4) restrict themselves to interoperability attributes which can become outdated, 5) limit themselves to collaborative interoperability and do not recognize the confrontational interoperability between opposing systems, units, or forces, and 6) do not describe appropriate extensions to the DoD Architecture Framework (DoDAF) which would facilitate the use of existing architecture descriptions in performing interoperability measurement. Noting that "everything in the world can be expressed as a system," (Guan, et. al., 2008) this research uniquely provides a general method of measuring the interoperability of many different types of entities, described as a heterogeneous set of systems (e.g., coalitions, technological systems, organizations, cultures, political philosophies, languages, people, and religions, among others), experiencing a wide variety of types of interoperations (e.g., enterprise, doctrine, force, joint, logistics, operational, semantic, and technical, among others). Indeed, the method improves upon existing stoplight models, maturity models, interoperability attribute models, and frameworks by applying those models' descriptions of system types and interoperability hierarchies, levels, and attributes towards the creation of a foundational theory and general method of interoperability measurement. The method of this research is flexible and allows systems and their interoperations to be defined at any level of abstraction, resulting in interoperability measurements which are not limited to a small set of possible values, but are as precise as desired. The method includes proposed extensions to DoDAF which allow an architecture to be better used in interoperability analysis and, more importantly, interoperability-based operational effectiveness analysis. The method recognizes that interoperability is not an end unto itself, but that it facilitates operational advantage and effectiveness. Finally, the method introduces the important concept of confrontational interoperability, and mathematically correlates the impact of interoperability on operational effectiveness.

A brief background on interoperability is given next, followed by a specific statement of the research problem and associated hypothesis and research goals. The interoperability measurement method is then previewed and limitations of and assumptions pertinent to the method are given. Chapter 1 concludes with an overview of the structure of the dissertation.

## 1.3 Background

Interoperability has been an important and widely discussed topic over the past decade, and continues to be so, especially within the Department of Defense (DoD) (Ford, et. al., 2007b). A search of thirty years of definitions and types of interoperability (Appendices A1 and A2) indicates the recent surge in popularity of the subject (Figure 1). The survey of interoperability types and definitions revealed that interoperability, as a research area, is broad with at least a thousand academic papers written on the topic. The oldest definition found (first published in 1977) is still one of the most popular and is the official definition given in Joint Publication 1-02, DoD Dictionary of Military and Associated Terms, "the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together." (2008) This definition, while not perfect (e.g., it limits the object of an interoperation to a service and does not address the confrontational interoperability of adversarial forces), is adopted in this research because it 1) infers that interoperation occurs between many types of entities (e.g., systems, units, or forces), 2) describes interoperability as a relationship between those entities, 3) implies that interoperation is an exchange, 4) infers that interoperation requires a "provider" and an "acceptor," and 5) explains that interoperation enables effective operation. These important concepts permeate and are foundational to this research.

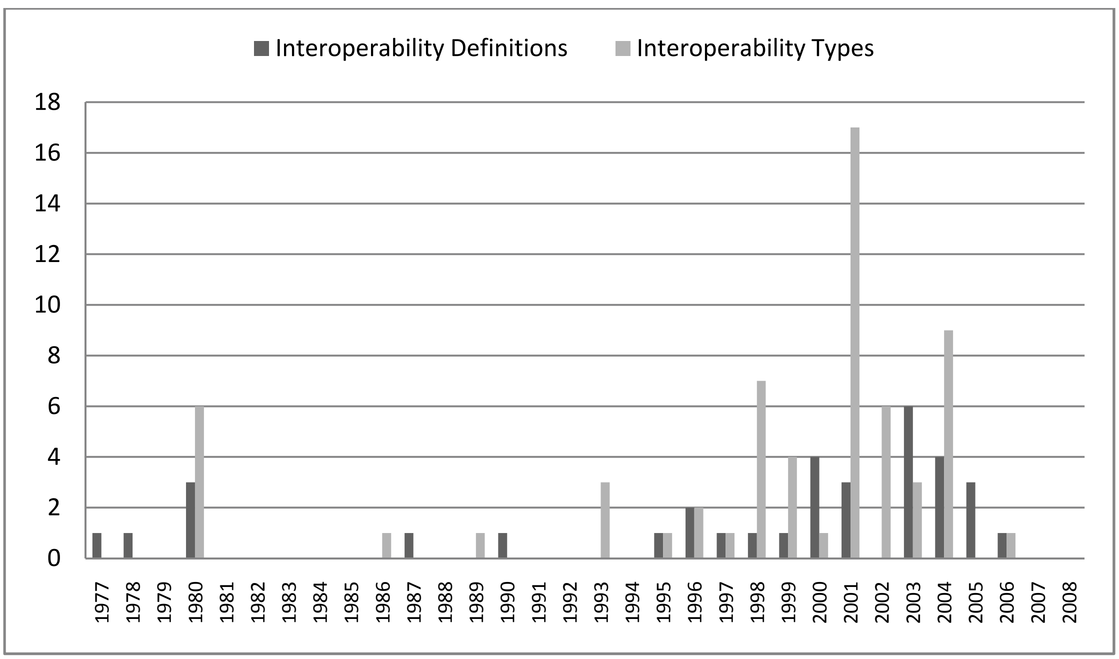



Figure 1. Popularity of interoperability research as indicated by the number of definitions and types introduced over the past thirty years (adapted from Ford, et. al., 2007b)

It is important to understand that interoperability occurs in collaborative and non-collaborative (confrontational) ways. For example, a computer network consists of a set of systems working in a collaborative fashion to provide and accept information and services from each other. Collaborative interoperability is the most commonly understood type of interoperability today. However, a second type of non-collaborative interoperability, called confrontational interoperability, is critical in both military and non-military domains. Confrontational interoperability occurs when sets of opposing systems attempt to control each other (i.e., a jammer's attempt to degrade an enemy communication system's effectiveness or a negotiation team's attempt to swing a deal in their favor). While collaborative interoperability has been previously researched, confrontational interoperability has not, and is introduced in this research. An understanding of this new topic of confrontational interoperability is critical to being able to relate interoperability to operational effectiveness.

Joint Vision 2020 clearly states the importance of interoperability to the DoD: "interoperability is the foundation of effective joint, multinational, and interagency operations." (2006:15) In fact, sixty joint publications cataloged in the Joint Doctrine, Education and Training Electronic Information System (JDEIS) mention interoperability. (2008) The recent Chief of Staff of the US Air Force stated that he takes every opportunity "to highlight the significant advantages of interoperable equipment and systems with…joint and coalition partners," that he looks for "interoperability opportunities with…coalition and allied partners," and he recognizes that "interoperability is cultural, as well as technical." (Moseley, 2007) In light of the importance of interoperability and noting that "management must be able to measure what they wish to change," (Kasunic & Anderson, 2004:16) a comprehensive method for measuring collaborative and confrontational interoperability and associating it with operational effectiveness is needed.

### 1.4 Problem Statement

How can collaborative and confrontational interoperability be measured, and how can the effectiveness of an operational process be improved by first measuring, then changing the interoperability of a heterogeneous set of systems implementing the process?

### 1.5 Hypothesis and Research Objectives

It is hypothesized that interoperability of a heterogeneous set of systems implementing an operational process can be measured and that there is a relationship between that interoperability measurement and measures of effectiveness associated with the process. To confirm the hypothesis, the following research objectives are pursued.

1) How are operational processes modeled and what are appropriate measures of operational effectiveness for a process?
2) How are systems implementing an operational process identified, modeled, and classified? Specifically, what characteristics, features, attributes, or traits of a system are important if the interoperability of systems is to be measured? What represents a common framework of system interoperability characteristics?
3) How can the interoperability of systems be measured? What is an acceptable measurement according to accepted metrological standards?

4) What is the relationship between operational effectiveness and interoperability?
5) What is the role of architecture in interoperability measurement? Can a Department of Defense Architecture Framework (DoDAF) architecture be used and/or extended to source and store information required for interoperability measurement?
6) Demonstrate the interoperability measurement method by application.

### 1.6 Method Preview

Systems representing both friendly (blue) and adversary (red) forces implement the activities and decisions of an operational process and can be modeled as a sequence of states of system characteristics. If strictly interoperability-related characteristics are used to model systems, then a fundamental result is obtained—that a measure of the similarity of a pair of system models is a measure of their associated systems' interoperability. This constitutes a general method of measuring the interoperability of systems implementing both collaborative and confrontational operational processes.

The research is taken one step further however, and it is shown that given a measure of operational effectiveness for a confrontational operational process, another fundamental result is obtained which states that if all systems and system interoperability features pertinent to the confrontational operational process are completely modeled, then friendly (blue) systems have operational advantage over adversary (red) systems if the blue systems are more directionally interoperable with red systems than vice versa. In other words, blue is able to control red (and prevent red from reciprocating) if blue is more directionally interoperable with red than red is with blue. This important result allows an interoperability measurement to be related to operational effectiveness.

### 1.7 Assumptions/Limitations

The interoperability measurement method presented in Chapter 3 is applicable to both military and non-military scenarios. However, in this research, it is purposefully focused on military applications (Chapter 4). Those wishing to measure the collaborative (non-confrontational) interoperability of non-military systems or use the method in blue/blue situations are encouraged to rely heavily on the Performance Enhanced Instantiation section (3.4.5) vice the Interoperability Impact on Operational Effectiveness section (3.6) and to reference the discussions on indirect interoperability and blue-to-blue impact on operational effectiveness presented in the Future Research section (5.3) of Chapter 5. Also, as the method is model-based, any resultant interoperability measurement or operational effectiveness assessment should be accepted at the same level of accuracy and precision as the model which generated it. Indeed, an imprecisely built model of a set of systems and their interoperations can result not only in an imprecise interoperability measurement, but possibly inaccurate analysis. The accuracy of the application of the Interoperability Impact on Operational Effectiveness axiom especially depends upon the accuracy and precision of the initial system models.

### 1.8 Dissertation Overview

The next chapter contains a review of seminal and recent publications underpinning all aspects of the interoperability measurement method presented in

Chapter 3.  Chapter 4 uses the method in several applications, demonstrating that 1) extant maturity model methods of measuring interoperability, such as the Organizational Interoperability Maturity Model, can be derived from the more general method of this dissertation, 2) many types of interoperability can be measured, such as coalition and confrontational interoperability, 3) the Interoperability Impact on Operational Effectiveness axiom provides a sufficient condition for relating interoperability to operational advantage or effectiveness, and 4) interoperability is often time variant. Chapter 5 summarizes and makes recommendations for application of the dissertation method and proposes future research based upon the dissertation findings.  Augmenting the body of the dissertation are multiple appendices which provide additional original research results and analysis which have not been included in the body of the dissertation in order to optimize flow and readability of the document.

# 2. Literature Review and Analysis

*The quest for interoperability is not new,*
*but it has never been so important.—D. Alberts & R. Hayes*

## 2.1 Overview

Current approaches to interoperability measurement, numerical (mathematical) taxonomy, and system classification are the starting point and the basis for development of the interoperability measurement method in Chapter 3. Important publications, both historical as well as recent, in these areas and others are surveyed and analyzed for their significant contributions. A summary of work in the supporting topic areas of process modeling, operational effectiveness measurement, and architecture is also presented. An analysis of all these publications is given which highlights key concepts pertinent to interoperability measurement and its relation of interoperability to operational effectiveness. Current gaps in research are highlighted and discussed.

## 2.2 Interoperability Measurement

Few papers have been published specifically on interoperability measurement. Allowing for a very broad definition of the term "interoperability measurement," approximately a dozen papers have been written on the topic—most published within the decade. All limit themselves to discussions of collaborative interoperability with none addressing confrontational interoperability. Those proposing a new interoperability measurement method or an extension/improvement to an existing method include (LaVean, 1980; Mensh, et. al., 1989; Amanowicz & Gajewski, 1996; DoD, 1998; Leite, 1998; Clark & Jones, 1999; Hamilton, et. al., 2002; Alberts & Hayes, 2003; Fewell &

Clark, 2003; NATO, 2003; Tolk, 2003; Tolk & Muguira, 2003; Stewart, et. al., 2004, 2005; Kingston, et. al., 2005; Schade, 2005; Ford, et. al., 2007a, 2008b). Other papers offer analyses of existing methods (Sutton, 1999; Brownsword, et. al., 2004; Kasunic & Anderson, 2004; Morris, et. al., 2004; Ford, et. al., 2007b). Each published method can be classified as maturity- (leveling) or non-maturity model-based and generally is applicable to only one system and interoperability type. Ford, et. al. provide a detailed survey of the aforementioned interoperability methods (Figure 2) in a separate paper (2007b) which is excerpted and augmented with more detail in Appendices A3 and A4.

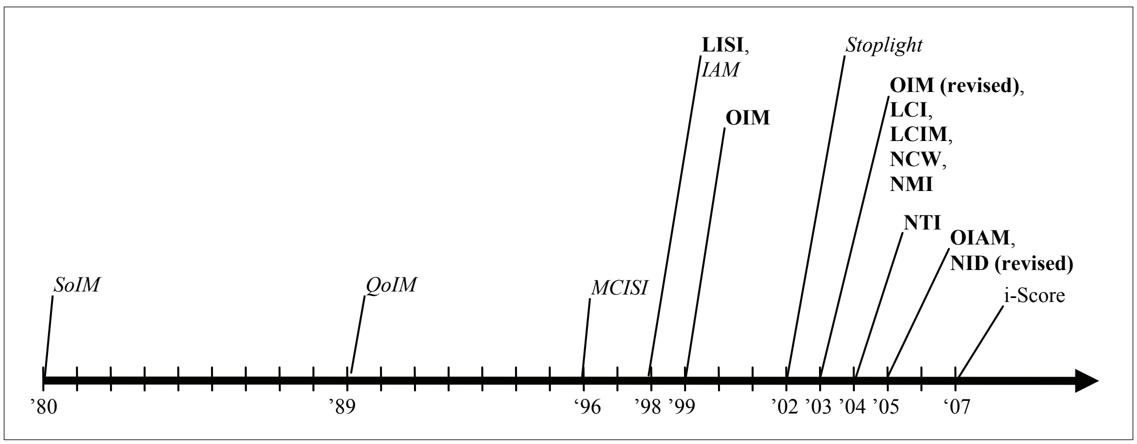



Figure 2. Chronology of published interoperability measurement methods (non-maturity model-based methods in *italics*, maturity-based methods in **boldface**)

### 2.2.1 Maturity Model and Other Leveling Methods

The US Air Force developed the maturity model concept through a grant to the Carnegie Mellon Software Engineering Institute (CMU-SEI) in 1987. (Humphrey & Sweet, 1987) Although the maturity model concept, which describes the stages through which a process progresses (DoD, 1998:2-1), was originally designed as a management tool to assess contractor software engineering ability, it was adopted in 1998 by the MITRE Corporation as the basis of the first maturity model-based interoperability measurement method called Levels of Information System Interoperability (LISI) (Figure 3). (Ibid) This method was eventually formalized and mandated in CJCSI 6212.01B *Interoperability and Supportability of Information Technology and National Security Systems* (2000) but later deleted as a requirement in the 2006 issue of the same document. In the LISI model, maturity was represented by thresholds of interoperability capability which defined measurable levels of interoperability. (DoD, 1998) From 1998 to 2006, LISI was the template for numerous maturity model and maturity model-like (leveling) interoperability measurement models designed to measure both information and non-information system interoperability such as the Organizational Interoperability Model for C2 (OIM) (Clark & Jones, 1999; Clark & Moon, 2001; Fewell & Clark, 2003), the Network Centric Warfare Maturity Model (NCW) (Alberts & Hayes, 2003), the Levels of Conceptual Interoperability Model (LCIM) (Tolk & Muguira, 2003), Layers of Coalition Interoperability (LCI) (Tolk, 2003), NATO C3 Technical Architecture Reference Model for Interoperability (NMI) (NATO, 2003), the Non-Technical Interoperability Framework (NTI) (Stewart, et. al., 2004), the Organizational Interoperability Agility Model (OIAM) (Kingston et. al., 2005), and a modification of the NATO Interoperability Directive (NID-revised) (Schade, 2005). As can be inferred from the titles of these models, none are generalized models of interoperability, but each is designed to address a specific type of system and interoperability.

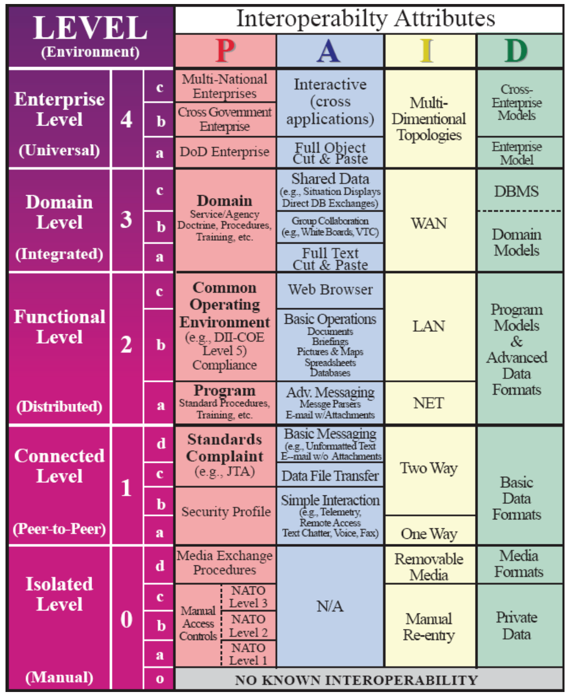



Figure 3. LISI interoperability maturity model (DoD, 1998)

The maturity model (leveling) interoperability measurement approach defines a basic set of interoperability maturity levels (usually five), listed as rows in the model, defined by a set of attributes (usually three or four, but sometimes only one) listed as columns in the model (Figure 3). (DoD, 1998) Thus, the range of interoperability measurements is generally limited to an integer from zero to the number of levels (usually five). This limited measurement range is one of the weaknesses of the maturity model interoperability measurement approach as there is generally not enough fidelity in the measurement to support design, reliability, maintainability, interoperability, or affordability analyses of the systems under measurement. Indeed, two systems sharing the same LISI defined interoperability level may not have any real ability to interoperate. (CMU, 2008) For example, two systems both classified as level 2c may still not be able to share information because the level calls for the ability to create documents, briefings, pictures, maps, spreadsheets, and databases, yet does not specify the application to generate these files, nor does it specify the format the files are to be saved in. Interestingly, the strength of the maturity model is not in providing an interoperability measurement, but in its ability to facilitate a measurement; in other words, to portray a qualitative framework for describing the types of attributes impacting interoperability for different types of systems and interoperability. For example, the LISI model describes four top-level attributes (Policy & Procedure, Application, Infrastructure, Data) and at least five sub-attributes for each. (DoD, 1998) Published maturity model (leveling) methods apply strictly to collaborative interoperability. As will be shown in Chapter 4, the maturity model and other leveling methods are special cases of the more general interoperability measurement method developed in Chapter 3.

### 2.2.2 Non-Leveling Methods

Non-maturity model-based interoperability measurement methods are a much more diverse group and, as a whole, generally pre-date the maturity model-based methods. Like the maturity model methods, they are not generalized methods of measuring interoperability, but specialized to a particular type of system or interoperability. The earliest known model, the Spectrum of Interoperability Model (SoIM), was designed as a program management tool and defined seven levels of interoperability for technical systems. (LaVean, 1980) Nearly a decade later, Mensh, et. al., published their mission-based Quantification of Interoperability Methodology (QoIM) which assigned a measure of effectiveness (MOE) logic equation to each of seven interoperability-related components. (1989) Their noteworthy contributions are 1) associating interoperability measurement with a mission and 2) relating interoperability to measures of effectiveness via a discrete event simulation. Seven years later, Amanowicz & Gajewski made the important observation that the distance between systems described in $n$ dimensional space, according to their features, was a measure of interoperability. (1996) They drew heavily from Florek, et. al., (1951) who, hailing from Wroclaw, Poland, developed a parallel to numerical taxonomy called Wroclaw Taxonomy which relied upon both the Czekanowski coefficient (Czekanowski, 1913) and graphical techniques such as dendrograms. (Sneath & Sokal, 1973) Concurrent with the publication of LISI was the Interoperability Assessment Methodology (IAM), which provided an eclectic mix of interoperability attributes and assorted equations applied by a flowcharted interoperability assessment process. (Leite, 1998) Hamilton, et. al., criticized LISI as being too complex and instead offered an overly-simplified stoplight model (2002) which unfortunately gives no specific basis for assigning colors to systems, and does not provide for system-to-system comparison. The Interoperability Score (i-Score) (Ford, et. al., 2007a; 2008b) recognized that 1) interoperability must be measured in the context of the operational mission, 2) an operation is implemented by systems of many types, and the interoperability measurement must account for them all, 3) perfect interoperability is not always desirable or possible, and 4) it is not the number of interoperations that is important, but the quality of the interoperations.

### 2.2.3 Extant Method Contributions

Each method surveyed in sections 2.2.1 and 2.2.2 contributed towards the general theory of interoperability measurement described in Chapter 3. Table 1 lists their main contributions (details in Appendix A3) and section 2.8 highlights remaining gaps in knowledge which are addressed in this dissertation.

Table 1 Main contributions of extant interoperability measurement methods

| Method | Main Contribution |
|---|---|
| **SoIM** | Interoperability can be measured in levels |
| **QoIM** | Interoperability can be correlated to measures of effectiveness via simulation |
| **MCISI** | The distance between systems modeled as points in space indicates their interoperability |
| **LISI** | Systems possess interoperability attributes |
| **IAM** | Same as LISI |
| **OIM** | Organizations interoperate, but have different interoperability attributes than technical systems |
| **Stoplight** | Operations and acquisitions both have interoperability requirements |
| **LCI** | Operational interoperability is an extension of technical interoperability |
| **LCIM** | Conceptual interoperability bridges system interoperability |
| **NMI** | Same as LISI |
| **NCW** | Interoperability occurs in the physical, information, cognitive, and social domains; lack of interoperability impedes mission accomplishment |
| **SoSI** | System-of-system research is founded upon operational, conceptual, and programmatic interoperability |
| **NTI** | Social, personnel, and process interoperability are valid types of non-technical interoperability |
| **OIAM** | There are levels of ability of organizations to be agile in their interoperations |
| **NID** | Levels of interoperability can be described in linguistic terms |
| **i-Score** | Interoperability measurements are operational process-specific and have a maximum value |

## 2.3 Numerical Taxonomy

The science and methods of numerical taxonomy were introduced to the world by Sokal and Sneath in 1963 in *Principles of Numerical Taxonomy*. Their later text *Numerical Taxonomy* remains the de-facto handbook thirty years after its original publication date. (Sneath & Sokal, 1973) Sneath & Sokal have defined numerical taxonomy as "the grouping by numerical methods of taxonomic units into taxa on the basis of their character states." (1973:4) While numerical taxonomy has largely been applied to biological, botanical, and genetic research, it has also been used with great success in the fields of ecology, medicine, the social sciences, the earth sciences, and the arts and humanities. (Dunn & Everitt, 2004) It has only recently been applied to systems. (Ford, et. al., 2008a) The classification of life on earth (Maddison, et. al., 2007) may be the most visible result of numerical taxonomy and other classification techniques. The methods and applications of numerical taxonomy have been documented in over one-thousand articles and books. Numerical taxonomy defines a science and method used to classify taxonomic units (objects) according to character states. (Sneath & Sokal, 1973) As such, the science of numerical taxonomy includes foundational principles; a definition of pertinent terms such as taxa, character, state, and cluster; a description of types of characters and states; methods of choosing characters; methods of estimating taxonomic resemblance; and methods of identifying taxa and clustering taxon into those taxa. (Ibid; Dunn & Everitt, 2004) If a system is also considered a taxonomic unit which can be described according to its character states, then the methods of numerical taxonomy can appropriately be applied to systems just as they are applied to the classification of animals, bacteria, plants, language groups, minerals, and cultures.

## 2.4 System Classification

The human mind classifies everything according to a variety of factors including morphological, emotional, and functional among others. Expectedly, all branches of study classify. For example, historians demarcate events into time periods, poets and authors attribute a particular literary work to a genre, and artists associate a work with a style. In some disciplines, however, the classification is foundationally important as the basic conceptual and mathematical model of that discipline. For example, the criticality of the biologists' empirically derived classification of organisms (Linnaeus, 1735) and the chemists' quantitative classification of the elements (Mendeleev, 1869) are indisputable to all biological and chemical studies and analyses. The uses of classifications are as numerous as the number of types that exist and include naming, theory promotion, lineage determination, relationship demonstration, and discovery of an object's nature.

Several systems engineers have noted the necessity and usefulness of a system classification. Maier and Magee & de Weck state that the most important use of a classification lies in the realm of system design and analysis. (1999; 2004) Shenhar & Bonen showed by example that a system classification is necessary to determine the proper engineering and management style for system development. (1997) And Maier pointed out that misclassified systems have problems not only in design and development, but also in use. (1999) As Mendeleev's classification predicted new elements (e.g., Germanium) which were later discovered (Mendeleev, 1869), a classification of systems can predict desirable future design directions or new uses of systems which, rather than being discovered, are created by the engineer or implemented by the system operator. Ford, et. al., presented a mathematically rigorous method of classifying systems and postulated that if the systems were classified according to their interoperability characteristics, that a system interoperability measurement could be made from the classification. A table summarizing generic system classifications (taxonomies) published in the system science and systems engineering fields is given in Table 2 with more detail provided in Appendix A5.

Table 2 Historical summary of system taxonomies (adapted from Ford, et. al., 2008a)

| Year | Originator | Basis of Taxonomy | Purpose of Taxonomy |
|---|---|---|---|
| 1955 | Von Bertalanffy | open/closed | Launch General Systems Theory (GST) |
| 1956 | Boulding | complexity | An approach to GST |
| 1957 | Goode & Machol | system inputs | Find solution to problems |
| 1962 | Hall | none given | Partition subsystems & enhance meaning of "system" |
| 1985 | Boulding | world-corresponding | World modeling |
| 1968 | Jordan | organizing principles | Furtherance of systems thinking |
| 1971 | Ackoff | system concepts | Create system concept framework |
| 1981 | Checkland | origin of system | Group by origin |
| 1990 | Wilson | none given | Refine definition of "system" |
| 1995, 1997 | Shenhar & Bonen | technological uncertainty & scope | Allocate appropriate SE method to the system |
| 1997 | Martin | product type | Provide SE checklist |
| 1999 | Maier** | Operational & managerial independence of components | System-of-system architecting |
| 2005 | Gideon et al.** | acquisition type, operational type, domain type | Aid in system-of-system understanding |
| 2005 | Kovacic | complexity | Reduce set of systems into meaningful clusters |
| 2006 | Blanchard & Fabrycky | similarities & differences | Provide insight into wide range of systems |
| 2007 | Valdma | information classes | Study of non-deterministic phenomena |
| 2008 | Ford, et. al. | similarity of system characters | Support system design |

System classification is important to interoperability measurement for the following reasons; 1) generic classifications of systems (Table 2) assist in ensuring that all systems implementing an operational process are identified; 2) system classifications highlight characteristics of systems, including interoperability-related characteristics; 3) quantitative classifications of systems describe numerically the similarity between systems; and 4) numerical taxonometric-based system classification provides a method for orderly characterizing systems.

## 2.5 Process Modeling

Numerous process modeling methods and formats have been published over the past several decades. A detailed survey was published by Knutilla, et. al. in 1998 which identified common attributes of all process modeling methods and formats, however several important candidate operational process models and formats were not included—the Process Specification Language (PSL) (NIST, 2007), the flow chart (IBM, 1969), the SysML activity diagram (OMG, 2007), and the DoD Architecture Framework (DoDAF) Activity & System Diagrams (OV-5, OV-6a, b, c, SV-5b) (DoD 2007a, b, c). A complete list is given in Appendix A6. A process modeling method or format used to represent an operational process in support of an interoperability measurement must 1) identify and describe the operational tasks (activities and decisions), 2) describe the order and decision logic associated with the task flow, and 3) identify and associate systems to tasks. Mapping process modeling attributes from Knutilla, et. al. to these requirements results in the following.

- Req. #1: Identify and describe the tasks
    - Simple Task Representation and Characteristics
    - Complex Task Representation and Parameters
- Req. #2: Describe the order & decision logic associated with the task flow
    - Simple Sequences
    - Simple Precedence

    - Alternative Task
    - Complex Sequences
    - Concurrent Tasks
    - Conditional Tasks
    - Iterative Loops
    - Parallel Tasks
    - Serial Tasks
    - Complex Precedence
    - Synchronization of Multiple, Parallel Task Sequences
- Req. #3: Identify & associate systems to tasks
    - Resource
    - Resource Requirements for a Task
    - Simple Resource Capability/Characteristics
    - Resource Allocation/Deallocation for One or Many Tasks

The following process modeling methods possess most of the aforementioned attributes and are considered as candidate operational process model formats: ACT Formalism, I-N-OVA Constraint Model, O-Plan Task Formalism, Virtual Process Modeling Language (VPML), Process Specification Language (PSL), and SysML. Although other methods could have been chosen, for this dissertation, the SysML Activity Diagram is the operational process modeling format of choice because 1) it is an emerging systems engineering tool, 2) it is derived from and similar to the ubiquitous

Unified Modeling Language (UML) diagrams, and 3) several popular software packages available at the Air Force Institute of Technology support it.

### 2.6 Operational Effectiveness Measurement

There has been much published on measures of effectiveness, to include a recent doctoral dissertation (Bullock, 2006), master's theses (James, 1996; Bell, 2005), research reports (Doyle, et. al., 1997; Gaedecke, 2006), technical reports (including a survey paper) (Nelson, et. al., 1996; Campbell, 2004), refereed journal articles (Sproles, 2000; Sproles, 2001; Murray, 2001; Sproles, 2002; Finkelstein & Morawski, 2003; Finkelstein, 2003; Bullock & Deckro, 2006), conference papers (Sarle, 1995; Green, 2001; Smith & Clark, 2004), and workshop reports (Sweet, et. al., 1985; Green & Johnson, 2002). Also published have been many textbooks (of which only two are referenced here) (Keeney, 1992; Geisler, 2000) and several Department of Defense documents (Bornman, 1993; Stenbit, et. al., 2002a; USJFCOM, 2005; DAU, 2006; DAU, 2006a; JP 3-0, 2006; JP 5-0, 2006; JP 1, 2007). Measures have many names, including metrics, measures of merit, figures of merit, measures of effectiveness, and measures of performance among others. (Stenbit, et. al., 2002a) Many researchers have acknowledged confusion with regards to terminology. (Bell, 2005; Bullock, 2006; Green & Johnson, 2002; Green, 2001; Stenbit, et. al., 2002; Nelson, et. al., 1996; Smith & Clark, 2004; Sproles, 2000; Sproles, 2001) The term measure of operational effectiveness (MoOE) is used in this dissertation and is appropriately chosen because it 1) reflects the importance of capturing the effectiveness of an operation to the end of describing how changes in interoperability affect operational effectiveness; 2) synchronizes with Department of Defense publications which define an

MOE as a measure of an effect (JP 3-0, 2006; JP 5-0, 2006); and 3) fits properly within the measurement hierarchy (Stenbit, et. al., 2002) which has been widely accepted by MOE researchers. Appendix A6 includes additional analysis on the hierarchy of measures, operational effectiveness assessment in joint operations, and MOE characteristics, types, and domains.

## 2.7 Architecture

An architecture is a depiction (written or drawn) of "the structure of components, their relationships, and the principles and guidelines governing their design and evolution over time." (DoD, 2007a) Curts & Campbell stated, "without a consolidated, coordinated, and organized architecture there is little chance of ever attaining that elusive goal of total interoperability." (1999:1) The architecture description is a possible source and repository for that which is required to make an interoperability measurement as well as for decisions based upon the measurement. Many frameworks exist which provide guidelines for creating such an architecture description. The first of these was the Zachman Framework (Zachman, 1987) followed by numerous others including the Federal Enterprise Architecture Framework (FEAF) (Federal CIO, 1999), the Treasury Enterprise Architecture Framework (TEAF) (Department of the Treasury, 2000), the Open Group Architecture Framework (TOGAF) (The Open Group, 2003), and the latest version of the Department of Defense Architecture Framework (DoDAF) (DoD, 2007a, b, c). As can be inferred from some of their titles (the Zachman framework and TOGAF excepted), each of these frameworks was developed for a specific government agency or application. DoDAF's relationship to interoperability is specifically addressed in this research.

Volume II, version 1.5 of DoDAF mentions many uses of DoDAF architecture descriptions—one of which is system interoperability analysis. (DoD, 2007b:2-5, fig 2-2) Specifically, the architecture products listed in Table 3 are named as being highly, partially, or non-applicable to system interoperability uses. While some of the elements required for system interoperability measurement are stored cleanly within the DoDAF products in the table, section 3.7 shows that some are absent, or stored but not easily extracted. For example, the interoperability measurement method of Chapter 3 accommodates a broad definition of the word "system" whereas DoDAF defines a strong separation between operational nodes and organizations and system nodes and systems. This hampers its ability to act cleanly as a source/repository for interoperability measurement key elements.

Table 3 DoDAF claimed product applicability to system interoperability (DoD, 2007b)

| Level | DoDAF Product |
|---|---|
| **Highly applicable** | AV-1, 2<br>OV-1, 2, 3, 5, 6<br>SV-1, 4, 6, 8<br>TV-1 |
| **Partially applicable** | OV-4, 7<br>SV-2, 7, 11<br>TV-2 |
| **Not applicable** | SV-3, 5, 9, 10 |

## 2.8 Gaps in Current Research

The following selected key concepts, which are critical to a unified method of interoperability measurement, have not been addressed by other researchers and represent gaps in knowledge. All are addressed in Chapter 3. The list is not comprehensive, but is representative in showing the magnitude of the current gap in interoperability measurement understanding.

What entities should have their interoperability measured?

How are systems modeled in support of an interoperability measurement?

How does a measure of system similarity relate to interoperability?

Should the similarity measure be allowed to be a distance measure?

What does a complete framework of system interoperability attributes contain?

What method can be used to identify interoperability attributes?

How can the interoperability of two heterogeneous systems be measured?

How are multiple interoperability types accommodated in the measurement?

Can one measurement accommodate different systems and interoperability types?

Can the interoperability of confrontational (i.e., opposing systems) be measured?

What is the difference between collaborative and confrontational interoperability?

How do interoperability and operational effectiveness relate?

Is an interoperability measurement specific to an operational process?

Where should interoperability data be stored and obtained?

How interoperable must systems be?

How can an interoperability measurement be used?

## 2.9 Conclusion

Analysis of the aforementioned publications indicates that the following concepts are important for interoperability measurement: 1) interoperability of sets of systems (vice single systems) should be measured; 2) the set of systems should be determined by an operational process; 3) a framework of interoperability attributes should be used to help identify system interoperability characters; 4) systems should be modeled as a set of system interoperability character states; 5) system character states should be identified numerically or coded numerically; 6) a similarity function gives the resemblance between systems as pertaining to their system character states; 7) the similarity function is the interoperability measurement if the systems have been appropriately modeled; 8) interoperability is related to measures of operational effectiveness associated with the operational process; 9) the interoperability of collaborative and confrontational systems can be measured; 10) an interoperability architecture can be used to supply and store the data supporting an interoperability measurement.

# 3. Method

*Interoperability will never be an analytically useful field of study until it is defined in a quantitative way.—E. Presson*

## 3.1 Overview

This chapter describes a general interoperability measurement method (Figure 4) which can be summarized as follows. Given a purpose for making an interoperability measurement and an associated operational process, a set of systems implementing the activities and decisions of that process can be identified. Each system in that set can be modeled quantitatively as a sequence of states of descriptive features of the system. These system models, called system instantiations, can be aligned with each other and their similarity measured. A fundamental concept of the interoperability measurement method is that if the set of systems is instantiated strictly according to interoperability features, then a measure of the similarity of a pair of system instantiations is a measure of the associated pair of systems' interoperability. Furthermore, another fundamental concept states that if the systems are instantiated with interoperability features pertinent to a measure of operational effectiveness associated with a confrontational operational process, then the interoperability measurement can be related mathematically to the measure of operational effectiveness. Finally, the method can be integrated with the Department of Defense Architecture Framework which is suitable for storing key interoperability measurement elements. Succeeding sections address the method in detail.

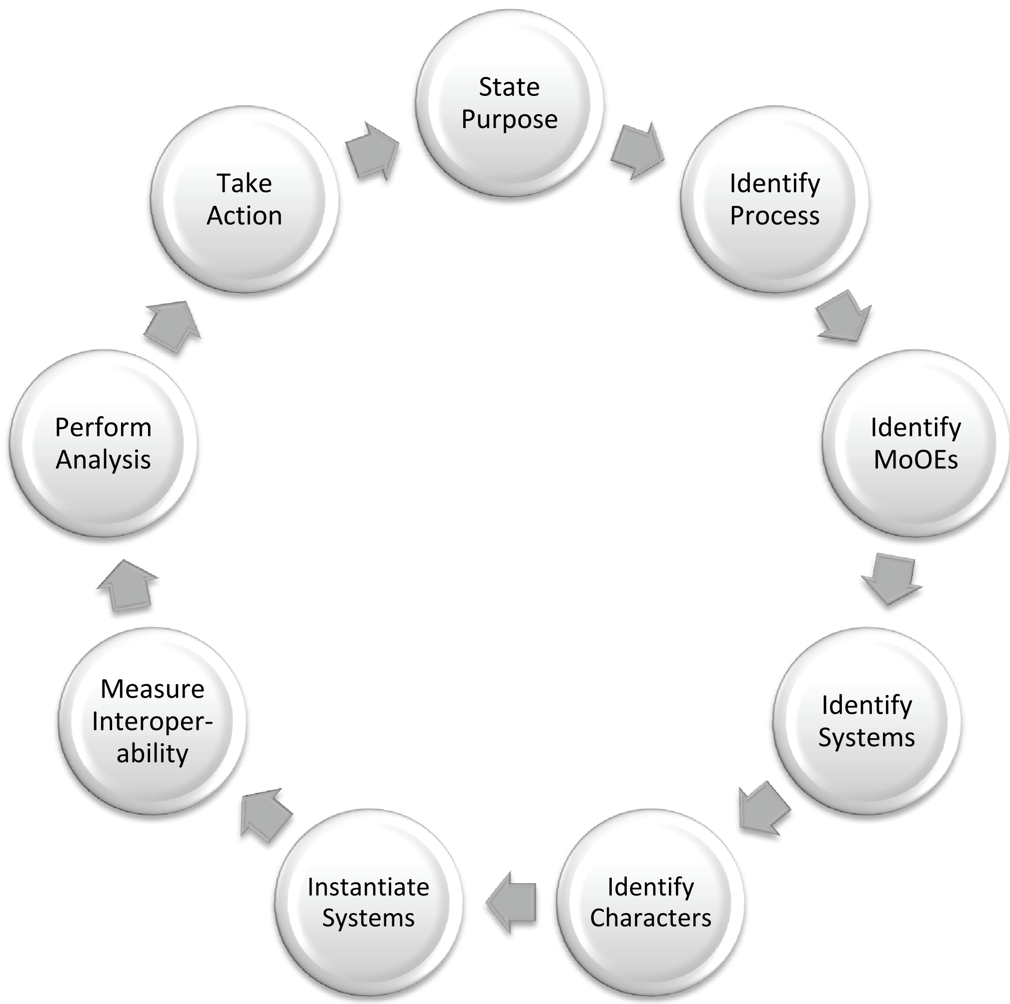



Figure 4. Interoperability measurement method

## 3.2 Purpose of Interoperability Measurement

The number of interoperability types is large (Appendix A2) and the number of reasons to measure interoperability is even larger. Some reasons important to the Department of Defense, extracted from selected joint publications and the Department of Defense System Engineering Plan Preparation Guide (DoD, 2008), are given in Table 4. Before an interoperability analysis is undertaken, the purpose of the analysis must be stated. Identification of this purpose is critical in keeping the analysis focused and properly scoped.

Table 4 Some DoD reasons for measuring interoperability

| MULTINATIONAL OPERATIONS REASONS | Collaborative or Confrontational Interoperability |
|---|---|
| Determine level of integration and synchronization of coalition forces (JP 3-16) | Collaborative |
| Measure effectiveness of coalition equipment (JP 3-16) | Confrontational |
| Troubleshoot coalition logistics problems (JP 3-16) | Collaborative |
| Determine mission impact of lack of common tactics, techniques, and procedures (JP 3-16) | Collaborative |
| Measure mission impact of language and cultural difference among coalition forces (JP 3-16) | Collaborative |
| Measure results of multinational planning and preparation on mission success (JP3-16) | Collaborative |
| Predict impact of liaison officers on coalition force mission success (JP 6-0) | Collaborative |
| Provide metrics to 5-nation Combined Communications Electronics Board in support of their pursuit of communications-electronics interoperability (JP 6-0) | Collaborative |
| Provide COCOM with interoperability reqs. for theater security cooperation plan (JP 6-0) | Both |
| Determine impact of interface (translation) used to ensure interoperability of incompatible communications systems (JP 6-0) | Both |
| Determine predicted advantage over the enemy | Confrontational |
| Identify areas for improvement in coalition operations | Both |
| **JOINT OPERATIONS REASONS** | |
| Determine impact of communications interoperability on personnel recovery (JP 3-50) | Collaborative |
| Determine impact of joint service training on mission success | Collaborative |
| Specifying joint force interoperability requirements | Both |
| Measure success of joint force exercises | Confrontational |
| Determine impact of insertion of new communications technology (JP 6-0) | Both |
| Assessing shortfalls/deficiencies of communications on operational effectiveness (JP 6-0) | Both |
| Determine ability to cooperate with OGAs and NGAs (JP 6-0) | Collaborative |
| Facilitate CIO responsibility to enforce interoperability (JP 6-0) | Collaborative |
| Support COCOMs in verifying operational interoperability procedures (JP 6-0) | Both |

| | |
|---|---|
| Measure interoperability of the joint communications system (JP 6-0) | Collaborative |
| Determine ISR product distribution bottlenecks (JP 6-0) | Collaborative |
| Measure system-to-system compatibility (JP 6-0) | Both |
| Validate key interoperability solutions prior to mission execution (JP 6-0) | Both |
| Correlate interoperability with the speed of commander decisionmaking (JP 3-27) | Both |
| Predict advantage over the enemy in future conflicts | Confrontational |
| **SYSTEMS ENGINEERING REASONS** | |
| Determine compliance with program certification requirements (SEPPG) | Both |
| Specify program requirements in terms of interoperability measurements (SEPPG) | Both |
| Characterize system design requirements in the System Engineering Plan (SEPPG) | Both |
| Determine level of interoperability within and without the System-of-System (SEPPG) | Both |
| Determine impact of system configuration changes (SEPPG) | Both |
| State interoperability key performance parameter requirements (SEPPG) | Both |
| Ensure systems in development will be interoperable with fielded systems (SEPPG) | Collaborative |
| Facilitate interoperability testing (JP 6-0) | Both |
| **HOMELAND DEFENSE REASONS** | |
| Measure and predict future interagency interoperability (JP 3-27) | Collaborative |
| Establish requirements for interagency emergency response communications (JP 3-27) | Collaborative |
| Measure ability of government agencies to share information during crisis (JP 3-27) | Collaborative |
| Measure operational connection between agencies in a dynamic environment (JP 3-27) | Collaborative |
| Determine possibility of information overload as multiple first responders use common equipment and procedures | Collaborative |
| Determine usefulness of inserting commercial communication standards into DoD acquisition requirements (JP 3-27) | Collaborative |
| **HEALTH SERVICE REASONS** | |
| Justify standardization of medical capabilities and material with other nations (JP 4-02) | Collaborative |
| Methodically measure compliance with OPLAN (JP 4-02) | Collaborative |
| Discover medical training, logistics, doctrine, and other concerns (JP 4-02) | Collaborative |

| | |
|---|---|
| Determine communication interoperability concerns between MEDEVAC platforms and medical regulating authority (JP 4-02) | Collaborative |
| **OTHER REASONS** | |
| Determine level of net-centricity of networked systems | Collaborative |
| Quantify Joint Interoperability Test Command operational interoperability test requirements (JP 6-0) | Both |

### 3.3 Operational Process

After determining the purpose for an interoperability measurement analysis, the subjects of the interoperability measurements must be determined and a method for identifying them must be given. In this dissertation, the operational process is used to identify a set of systems, both friendly (blue) and adversarial (red), whose interoperability is to be measured and to identify the measure of operational effectiveness to which the interoperability measurement will be correlated. The operational process is defined as a set of tasks, logically sequenced, which when executed achieve a desired effect. Operational processes can be collaborative, which are operational processes implemented by a set of friendly systems working together to achieve a shared goal, or confrontational, which are operational processes implemented by two sets of systems acting in opposition to each other (i.e., when one set of systems experiences a level of success in implementing the operational process, the other experiences a corresponding level of failure).

#### 3.3.1 Modeling Methods

While many practical operational processes are simplistic in structure, it is possible to define a process in which all, some, or none of the tasks occur concurrently and in which timing and logic are associated with the elements of the process. For example, the finish of one task may drive the start of another, or the decision of which task to execute next might depend upon certain prerequisites (including timing) being met. Not surprisingly, many methods and formats of task, activity, process, and thread modeling have been devised over the years. These methods and formats are graphical, mathematical, and linguistic in nature and all have different fortes. Of three dozen candidate modeling methods and formats (Appendix A6), the SysML activity diagram is appropriate for operational process modeling and is the method of choice for this dissertation because it 1) captures the operational activities and decisions in a process, 2) describes what is transferred between activities and decisions, 3) describes the decision logic and timing (swim-lane variant) of the process, 4) accommodates the association of systems to activities and decisions as an object attribute, and 5) is supported by a growing number of software packages. An example SysML activity diagram with six activities and one decision is given in Figure 5.

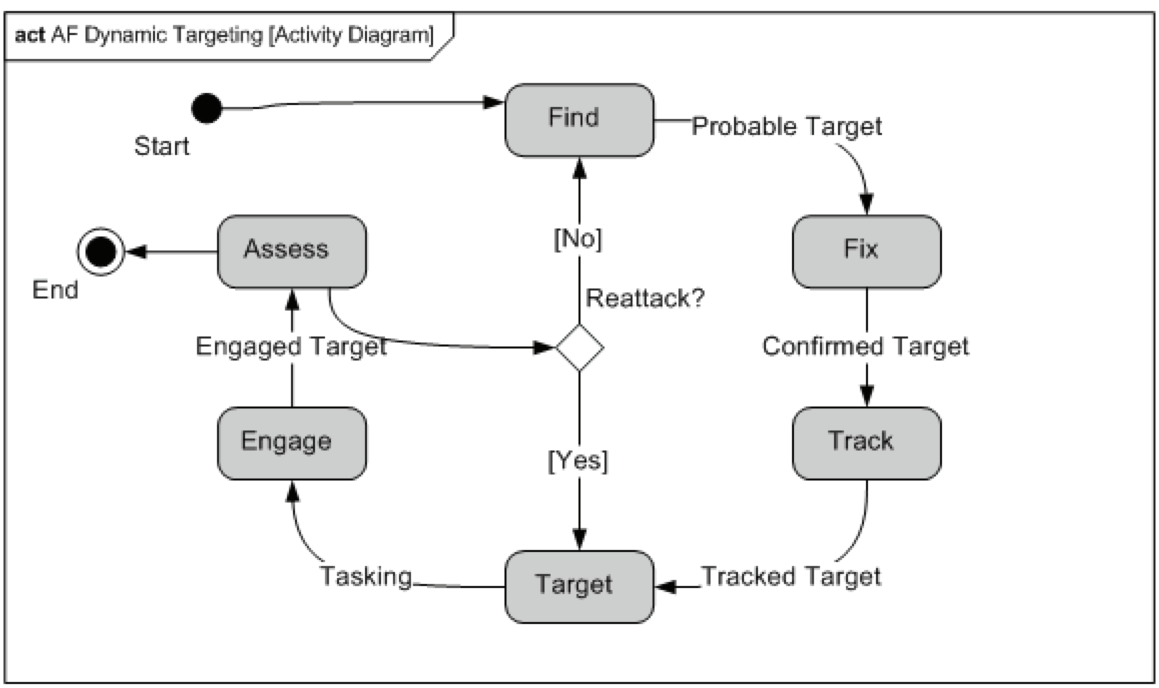



Figure 5. Sample SysML activity diagram used to model an operational process

### 3.3.2 Measures of Operational Effectiveness

An interoperability measurement can be correlated to operational effectiveness for both collaborative and confrontational operational processes. For a collaborative operational process, this correlation must be done via discrete event or other type of simulation and is outside the scope of this research. An early attempt at doing this was made in 1989 by Mensh, et. al. in which the interoperability of Battle Force Command, Control, and Communications systems was measured and correlated to measures of effectiveness and measures of performance written as binary logic equations. For a confrontational operational process however, this research provides sufficient conditions which allow the interoperability measurement to be related to a measure of operational effectiveness (MoOE) for the operational process. The MoOE should be written at a level of abstraction equivalent to that of the operational process and can be a natural, constructed, or proxy measure originating from the physical, information, or cognitive domain (Appendix A7). Ideally the MoOE is relevant, measurable, responsive (sensitive), resourced, understandable, discriminatory, quantitative, realistic, objective, appropriate, inclusive, independent, valid, and reliable. Additionally, in order to apply the Interoperability Impact on Operational Effectiveness axiom (section 3.6) the MoOE must be written diametrically. In other words, the MoOE must be written as a pair $O = \{O_B, O_R\}$ which relates the effectiveness of the set of friendly (blue) systems to the lack of effectiveness of the set of adversary (red) systems. For example, $O_B + O_R = 1$ describes the relationship between the diametric MoOE $O = \{O_B, O_R\}$ where $O_B$ is the percent of red force targets destroyed and $O_R$ is the percent of red force targets protected. While many MOEs contained in the Universal Joint Task List (UJTL) (CJCSM 3500.04D, 2006) cannot be written as diametric MoOEs, such as OP 2.2.1, M31, "Minutes to determine raid size.", many others can. For example, numerous percentage MOEs in the UJTL such as SN 3.4, M7 "percent of cruise missiles destroyed before impact," ST 1.3.5, M5 "percent of enemy forces drawn away from main thrust after demonstration," or OP 1.2.4.7, M13 "percent of friendly personnel recovered uninjured" can be all be written diametrically. Similarly, MOEs in the UJTL which represent a count such as SN 3.4.1, M11 "number of safe passage aircraft engaged," can be normalized and converted to a percentage (e.g., "percent of safe passage aircraft engaged") and then written diametrically. In general, UJTL MOEs which can be converted to a percentage and which correlate friendly force action to enemy force reaction (or vice versa) are candidate diametric MoOEs.

### 3.4 Systems

Among others, the interoperability of processes, enterprises, organizations, coalitions, concepts, functions, objects, products, models, cultures, doctrines, forces, cities, public services, and applications can be measured, however, systems are chosen as the object of the interoperability measurement in this research. The word "system" is used in a variety of fields of study, but its definition is fairly standardized across those disciplines. For example, the military scientist defines system as "a functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements; that group of elements forming a unified whole." (JP 1-02, 2008:534) The system engineer defines it as "a combination of interacting elements organized to achieve one or more stated purposes." (Haskins, 2007:1.5) The management scientist defines it as "an entity which is comprised of at least two elements and a relation that holds between each of its elements and at least one other element in the set" (Ackoff, 1971:662). And finally, the physician defines it as "a consistent and complex whole made up of correlated and semi-independent parts; a complex of functionally related anatomic structures." (Pugh, 2000:1775) There are three common themes to these definitions: 1) systems are comprised of a set of elements, 2) those elements interact, and 3) the interacting set of elements forms a whole and act in concert to achieve the system's purpose. Therefore, in this research a system is defined as "an entity comprised of related interacting elements, which act together to achieve a purpose." This definition is broad enough to include a wide variety of systems including, but not limited to, technical, biological, environmental, organizational, conceptual, physical, and philosophical, among others. Because the definition of system used in this research is broad, the system interoperability measurement method presented is applicable to an equally broad set of entities.

Other interoperability researchers also promote measuring the interoperability of systems. Nine of the fourteen interoperability measurement method papers surveyed (section 2.2), directly advocated the measurement of system interoperability. (LaVean, 1980; Mensh, et. al., 1989; Amanowicz & Gajewski; 1996; DoD 1998; Leite, 1989; Hamilton, et. al., 2002; NATO, 2003; Stewart, et. al, 2004; Ford, et. al., 2007a; 2008b) The other five recommended measuring the interoperability of an entity that could be modeled as a system or as a system enabler. (Clark & Jones, 1999; Tolk & Muguira, 2003; Tolk, 2003; Stewart, et. al., 2004; Kingston, et. al., 2005;). Although six of the fourteen methods surveyed proposed measuring the interoperability of singleton systems (Leite, 1989; Clark & Jones, 1999; Hamilton, et. al., 2002; Tolk & Muguira, 2003; Tolk, 2003; Kingston, et. al., 2005), measuring the interoperability of a single system is antithetical to the connotation of the word interoperability and to the definition of the word as used in this research. Measuring the interoperability of a set of two or more systems is a better choice. But as the set of all systems is infinite, a means of limiting the size of the set is needed.

### 3.4.1 Constraining the Set of Systems with an Operational Process

Although many methods exist for determining which systems should have their interoperability measured, using the operational process to determine the set of systems is appropriate for at least three reasons. First, systems perform different interoperations in different scenarios (i.e., they are used differently); second, effectiveness is often measured at the operational process level (i.e., measures of effectiveness); and third, operational processes can be written at any level of abstraction which enables system definition at the same level of abstraction. When using an operational process to constrain the set of systems, all systems are identified which implement the operational process. The set of systems is often diverse and can be small or large.

### 3.4.2 System Identification

There are a variety of methods which can be used, within the constraints of an operational process, to identify the set of systems $S=\{s_1,s_2,\ldots,s_n\}$ whose interoperability is to be measured. These methods include architectural methods such as Activity Based Modeling (Ring, et. al., 2004) and DoD Architecture Framework-associated structured analysis modeling (DoD, 2007a, b, c), engineering methods such as IDEF0 and IDEF3, project methods such as the Microsoft Project method (2007), process methods such as SySML activity/decision to resource (system) association (OMG, 2007), as well as others. While seemingly simplistic, it is easy to neglect certain types of systems (e.g., weather systems) which may not be routinely considered as such, but which might be important in the final interoperability analysis. For this reason, any system identification method chosen can be complemented by the use of a generic system taxonomy. These comprehensive taxonomies, while simplistic and general in nature, are reminders of the wide variety of systems that exist. Researchers in the fields of system science and systems engineering have published taxonomies of systems for at least fifty years. A survey of these taxonomies is given in appendix A5.

### 3.4.3 System Characterization

Once the set of systems $S$ has been identified, those systems must be modeled. Applying numerical taxonomic concepts, a system can be modeled using a set of characters $X = \{x_1, x_2, \ldots, x_n\}$ which represent traits, attributes, or characteristics which describe the important features of the system. These system characters can be morphological (e.g., size, shape, color, structure, type and method of construction, material composition, or number of components), physiological (e.g., system functions or behaviors), interfacial (e.g., type and number of system or element interfaces), ecological (e.g., system context, environment, or type of fuel consumed), and distributional (e.g., geographic location or domain) among others. Ideally, the set of characters chosen should be natural (i.e., a character not confounded with another) and diagnostic (i.e., a character which distinguishes one system, or system type, from another). Additionally, the types of characters chosen should be related to the type of interoperability measurement that is to be undertaken. For example, interoperability measurement of devices on a network demands that functional characters be emphasized, whereas a spatial interoperability analysis requires that certain morphological characters should be used.

Extending a definition from the phylogeneticists (Semple & Steel, 2003), characters are functions which map systems in $S$ to the states $C$ of their characters $X$ where the set of valid character states for a set of characters is $C = \{c_1, c_2 \ldots, c_n\}$ (see definition below). Character states are either qualitative (discrete) or quantitative (discrete or continuous), or a mixture of both (Sneath & Sokal, 1973). Generally, the set of character states is restricted to the binary numbers (absence/presence states) or the positive real numbers, although other states are certainly possible.

*DEFINITION (System Characterization): Given a set of systems $S$, then $X : S \to C$ is a function which maps systems to a set of character states $C$ and $X$ is called the characterization of $S$.*

#### 3.4.3.1 Interoperability Characters

As mentioned previously, there are numerous types of system characters that can be used to describe a system. However, in order to form a basis for an interoperability measurement, only a special type of system characters should be used to model a system;

these are called system interoperability characters, or interoperability characters for short. This is a foundational concept in interoperability measurement. In their essence, interoperability characters describe what systems do to each other. For example, opposing forces *attack* each other, two computers *communicate* with each other, and two businesses *trade* with each other. In these three examples, the words *attack*, *communicate*, and *trade* all imply a type of interoperation.

It is not possible to list all interoperability characters, however it is important to note that generally any type of character is an interoperability character in specific circumstances. For example, although physiological and interfacial characters are clearly interoperability characters, the morphological character *shape* becomes an interoperability character when the docking interoperation of the space shuttle and the international space station is measured. Similarly, the distributional character of *domain* is an interoperability character when considering the environment in which systems are used. For example, a Navy destroyer is interoperable with the ocean but not the land, yet the Marine Corps' Expeditionary Fighting Vehicle (EFV) is interoperable with both.

An interoperability character represents a pair of actions, such as "provide" and "accept," which constitute an interoperation. These pairs describe how systems provide and accept matter, energy, or information from each other. A selection of interoperability characters associated with pairs of actions and type of intended interoperability measurement is given in Table 5. While not exhaustive, it gives a sample of the many types of interoperability actions performed by systems. An example framework of some interoperability characters arranged by system type is given in Table 34 in Appendix A8.

Table 5 A selection of interoperability pairs and associated characters

| Interoperability Pairs | Interoperability Type | Character |
|---|---|---|
| Provide ⇔ Accept | General | *Interoperate* |
| Transmit ⇔ Receive | Communication | *Communicate* |
| Attack ⇔ Attacked | Confrontational | *Attack* |
| Impact ⇔ Impacted | Confrontational | *Impact* |
| Detect ⇔ Detected | Technological | *Detect* |
| Publish ⇔ Subscribe | Net-Centric | *Service* |
| Occupy ⇔ Accommodate | Spatial | *Accommodate* |
| Serve ⇔ Be Served | Human | *Service* |
| Give ⇔ Take | Human | *Share* |
| Buy ⇔ Sell | Business | *Trade* |
| Pay ⇔ Get Paid | Financial | *Transact* |
| Output ⇔ Input | Traditional System | *OutputInput* |
| Lead ⇔ Follow | Organizational | *Dance* |
| Order ⇔ Obey | Human, Organizational | *Command* |
| Produce ⇔ Consume | Business, Human | *Economy* |
| Transport ⇔ Transported by | Business | *Transport* |

#### 3.4.3.2 Interoperability Character Identification

Interoperability characters can be extracted in a methodical fashion from sentences which describe what systems do. These sentences may originate in requirements, architecture, and a host of other acquisition, capabilities, and operations documents. A guide for relating the parts of speech commonly found in sentences to system interoperability measurement is given in Table 6. Note that the table does not give definite relationships. For example, the table does not insist that all nouns must be systems, as some nouns are simply objects of verbs.

Table 6 Guide for relating parts of speech to interoperability modeling

| **Part of Speech** | **Relationship** |
|---|---|
| Noun | System or refinement of an interoperability character |
| Verb | Interoperability character |
| Pronoun | System |
| Adverb | Refinement of an interoperability character |
| Adjective | Refinement of a system |
| Preposition | Refinement of an interoperability character |
| Conjunction | Not applicable |
| Interjection | Not applicable |
| Article | Not applicable |

To illustrate, the following sentence is given. "The long train expeditiously transports raw material down the tracks to the factory." Two of the four nouns (train, factory) in the sentence can be considered as systems. The two adjectives refine the names of the systems (long train, raw material), or imply the existence of other systems (e.g., short trains or refined material). The single verb (transports) in the sentence implies interoperation between system pairs and is an interoperability character. The adverb (expeditiously) refines the interoperability character (transports) implying that there may be different types, or levels, of hauling (e.g., sluggishly transports). And the remaining two nouns (material, tracks) also refine the interoperability character by describing what is transported and by which method it is transported. Similarly, the prepositional phrase ("down the tracks") also refines the interoperability character (transports). The last prepositional phrase ("to the factory") hints at the fact that the train and the factory interoperate (e.g., by providing and accepting raw material). From this analysis, it can be seen that a hierarchical description of interoperability characters can be made. If the interoperability pair (transports $\Leftrightarrow$ transported by) is represented by the character $Transport$, then refining interoperability characters can be $Transport.Material$,

$Transport.Material.onTracks$, and $Transport.Material.onTracks.Expeditiously$. If the character states are assumed to be binary then the beginnings of a system interoperability model can be given in (1). If a new system is added to the model, for example, a *truck*, then it can be seen that the *truck* can also *Transport* raw material, but on the road rather than on the tracks (i.e., $Transport.Material.onRoad$).

$$
\begin{aligned}
&S = \{train, material, tracks, factory\} \\
&X = \left\{\begin{array}{l} Transport, \\ Transport.Material, \\ Transport.Material.onTracks, \\ Transport.Material.onTracks.Expeditiously \end{array}\right\} \\
&C = \{0,1\}
\end{aligned}
\tag{1}
$$

#### 3.4.3.3 Interoperability Character Directionality

Interoperability characters are inherently directional. As previously mentioned, interoperability involves a pair of systems doing something to each other. For example, given two systems $s_1$ and $s_2$, assume that $s_1$ attacks $s_2$. From both systems' perspectives, $s_1$ is initiating the attack (i.e., transmitting) while $s_2$ is absorbing the attack (i.e., receiving). Thus the interoperation (e.g., $X = \{Attack\}$) between $s_1$ and $s_2$ is directional from $s_1$ to $s_2$, but not vice versa. The directionality of system interoperation can modeled four different ways (Figure 6).

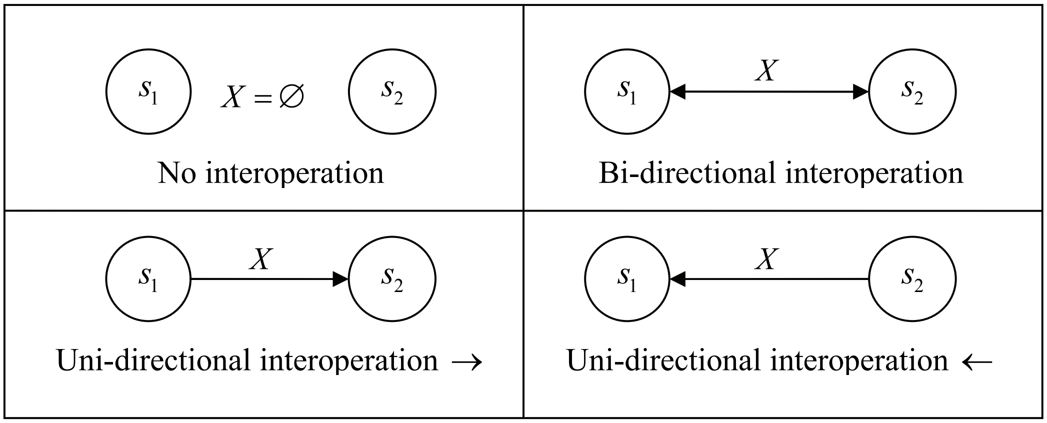



Figure 6. Directional interoperability possibilities

Thus, when an interoperation occurs between two systems, the direction of the interoperation must be captured. This directionality can be annotated by a (T) for transmit or a (R) for receive appended to each interoperability character code. For example, $X = \{Attack(T), Attack(R)\}$ is the complete characterization for the example in the previous paragraph. Generalizing, $X = \{X_T, X_R\}$. Although the size of $X$ doubles in order to accommodate the directionality of interoperability characters, it is important to keep track of one-way interoperations between systems. Both collaborative and confrontational interoperations can be directional. If every interoperability character in $X$ is bi-directional, then the (T) and (R) suffixes are not needed.

### 3.4.4 System Instantiation

Once systems, their interoperability characters, and the states of those characters have been identified, then a specific system can be modeled, or instantiated, as a sequence (Bullock, 2006; Amanowicz & Gajewski, 1996) of states of system characters.

*DEFINITION (System Instantiation): Given a specific $s \in S$ and a set $x \subseteq X$ of system characters descriptive of $s$, then $\sigma = x(s)$ is a sequence of system character states, called the instantiation of $s$, which models $s$.*

Once all $s \in S$ have been instantiated, the system instantiations must be aligned with each other in order to support meaningful system comparisons and other mathematical operations. Unless otherwise stated, hereafter the term system instantiation implies an aligned system instantiation.

*DEFINITION (Instantiation Alignment): Given a set $x' \subseteq X$ of system characters descriptive of $s'$ and a set $x'' \subseteq X$ of system characters descriptive of $s''$, and $X = \{x' \cup x''\}$, then two system instantiations $\sigma'$ and $\sigma''$ are aligned if $\sigma' = X(s')$ and $\sigma'' = X(s'')$. The aligned instantiation of $S$ is given by $\Sigma = X(S)$.*

In order to illustrate these concepts, an example is given. Let $S = \{s_1, s_2, s_3\}$ be a set of systems of interest, let $X = \{x_1, x_2, x_3, x_4\}$ be a set of bi-directional interoperability characters used to characterize $S$, and let all character states be absence/presence states (i.e., $C = \{0,1\}$ ). Define individual, unaligned, system instantiations as in (2), then an aligned instantiation of $S$ is given by (3).

$$
\begin{aligned}
\sigma_1 &= \{x_1(s_1), x_2(s_1), x_3(s_1), x_4(s_1)\} = \{1,1,0,1\} \\
\sigma_2 &= \{x_1(s_2)\} = \{1\} \\
\sigma_3 &= \{x_2(s_3), x_4(s_3)\} = \{1,0\}
\end{aligned} \tag{2}
$$

$$
\Sigma = X(S) = \{\{1,1,0,1\},\{1,0,0,0\},\{0,1,0,0\}\} = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3}
$$

### 3.4.5 Performance Enhanced Instantiation

A system instantiation $\Sigma$ in which interoperability characters are assigned binary character states is an underlying interoperability model upon which a performance-enhanced instantiation is based. The performance-enhanced instantiation can be used to facilitate data rate, cost, efficiency, or throughput analysis, among others. For example, given a set of systems (4) and a set of bi-directional interoperability characters (5) with character states (6), then $S$ can be instantiated as (7) if it is assumed that the $Laptop$ has USB, Wi-Fi, and Serial communication capability and that the $PDA$ possesses the same plus GSM, IR, and Bluetooth functionality.

$$
S = \{Laptop, PDA\} \tag{4}
$$

$$
X = \{Comm.USB, Comm.WiFi, Comm.Serial, Comm.GSM, Comm.Bluetooth\} \tag{5}
$$

$$
C = \{0,1\} \tag{6}
$$

$$
\Sigma = \left[ \begin{array}{c|cccccc} & USB & WiFi & Serial & GSM & IR & Bluetooth \\ \hline Laptop & 1 & 1 & 1 & 0 & 0 & 0 \\ PDA & 1 & 1 & 1 & 1 & 1 & 1 \end{array} \right] \tag{7}
$$

If a data rate focused interoperability analysis is desired, a performance-enhanced system instantiation $\Sigma_P$ can be defined (8) which models, for example, the peak data rates (in Mbits/sec) for each type of interoperation characterized by $X$.

$$\Sigma_P = \left[\begin{array}{c|cccccc} & USB & WiFi & Serial & IR & GSM & Bluetooth \\ \hline Laptop & 480 & 54 & 0.02 & 0 & 0 & 0 \\ PDA & 480 & 11 & 0.250 & 0.271 & 1.152 & 2 \end{array}\right] \quad (8)$$

This performance-enhanced system instantiation assumes that the *Laptop* and *PDA* adhere to the standards given in Table 7.

Table 7 System implementation standards

| | *Laptop* | *PDA* |
|---|---|---|
| *Comm.USB* | USB 2.0 | USB 2.0 |
| *Comm.WiFi* | 802.11g | 802.11b |
| *Comm.Serial* | RS-232 (strict) | RS-232 (relaxed) |
| *Comm.GSM* | N/A | GSM |
| *Comm.IR* | N/A | MIR IrDA |
| *Comm.Bluetooth* | N/A | Bluetooth 2.0 |

### 3.5 Interoperability Measurement

Metrology, or the science of measurement, defines measurement as "the objective representation of our empirical knowledge of the world by numbers," or in other words, "the assignment of numbers to properties or events in the real world by means of an objective empirical operation, in such a way as to describe them." (Finkelstein & Leaning, 1984:25-26) If interoperability is considered as a property of a set of systems, then an operation, called a system interoperability measurement, can be defined which objectively and empirically assigns a number to systems interoperability. This operation, its derivation, and its varieties are defined in succeeding sections.

### 3.5.1 System Similarity

Similarity measures have been well-studied. (Guan, et. al., 2008) In its essence, similarity reflects the degree of resemblance of two or more objects. In this research, the similarity of systems is measured by using a function which takes aligned system instantiations as its arguments, which rewards for shared interoperability characters, and which (optionally) penalizes for unshared interoperability characters.

*DEFINITION (System Similarity): Given aligned sequences* $\sigma', \sigma''$ *instantiating two systems* $s', s''$*, then the similarity between* $s', s''$ *is given by* $Sim(\sigma', \sigma'')$ *where* $Sim(\sigma', \sigma'')$ *is a similarity function.*

There are numerous types of candidate similarity functions to choose from. Sneath & Sokal categorized similarity functions as distance, association, correlation, and probabilistic measures. (1973) Guan, et. al., offered a new classification, describing similarity measures as geometric, feature contrast, alignment-based, and transformational measures. (2008) Each type is briefly addressed below, followed by definitions of two similarity functions especially appropriate for interoperability measurement.

Distance (geometric) functions measure how far apart objects reside in character space. In other words, the geometric function is a measure of dissimilarity vice similarity which is a measure of how close objects reside to each other in character space. (Sneath & Sokal, 1973) A geometric dissimilarity function can be converted to a similarity function by first normalizing the function by maximum character state value $c_{\max}$ and by number of characters $n$ so that its range is $[0,1]$, then subtracting it from 1. Thus, perfect similarity implies $Sim(\sigma',\sigma'')=1$ and no similarity implies $Sim(\sigma',\sigma'')=0$. For example, given the Minkowski distance function (9), the corresponding Minkowski similarity function can be written as (10). $Sim_{\text{Real}}$, as defined later in this section, can be classified as a weighted geometric similarity measure, and is used to measure the similarity of systems instantiated with positive real-valued character states.

$$Minkowski\ Distance = MD = d_r\left(\sigma',\sigma''\right) = \left(\sum_{i=1}^{n}\left|\sigma'(i)-\sigma''(i)\right|^r\right)^{1/r} \tag{9}$$

$$Minkowski\ Similarity = MS = 1-\left(\frac{1}{\sqrt[r]{n}}\right)\left(\sum_{i=1}^{n}\left(\frac{\sigma'(i)-\sigma''(i)}{c_{\max}}\right)^r\right)^{1/r} \tag{10}$$

Association similarity measures are related to distance/geometric similarity measures but are more appropriately described as feature, or character, contrast measures. They are especially appropriate for measuring the similarity of objects described in character space with absence/presence character states. (Batagelj & Bren, 1995; Sneath & Sokal, 1973; Baulieu, 1989) The general form of a character contrast measure is given in (11) where $\theta,\alpha,\beta$ are weights, $f$ is a function, $\sigma'\cap\sigma''$ represents the features that $\sigma',\sigma''$ have in common, $\sigma'-\sigma''$ represents the features that $\sigma'$ possesses that $\sigma''$ does not, and $\sigma''-\sigma'$ represents the opposite. (Guan, et. al., 2008) $Sim_{Bin}$, as defined later in this section, can be considered a character contrast similarity measure and is used to measure the resemblance of systems instantiated with binary (absence/presence) character states. Other examples of character contrast measures include the Jaccard coefficient, the Czekanowski metric, and the Simple Matching coefficient, among many others; Batagelj & Bren compare over twenty character contrast measures (1995).

$$Sim(\sigma',\sigma'') = \theta f(\sigma' \cap \sigma'') - \alpha f(\sigma' - \sigma'') - \beta f(\sigma'' - \sigma') \tag{11}$$

Correlation coefficients associate the similarity of objects modeled in character space with a function of the angle between the object vectors. (Sneath & Sokal, 1973) An example of a correlation coefficient is the cosine function. Probabilistic similarity measures account for the distribution of character states for a particular character (Ibid) and alignment-based similarity measures give greater weight to common features of objects which are related or belong to the same sub-object. (Guan, et. al., 2008) Finally, transformational similarity measures associate similarity with the number of operations required to transform one object so as to become identical to another. (Hahn, et. al., 2003)

An interoperability function is a similarity function which meets certain criteria given in the definition below.

*DEFINITION (Interoperability Function): An interoperability function $I$ is a similarity function which 1) takes a pair of system instantiations as its arguments, 2) has a range of $[0,1]$, 3) rewards for shared characters and optionally penalizes for unshared characters, and 4) gives a greater reward to system pairs whose shared characters' states have a "better" value.*

Although many interoperability functions might be appropriate for interoperability measurement, two fundamental interoperability functions previously alluded to, $Sim_{Bin}$ and $Sim_{\mathrm{Re}al}$, are defined below. $Sim_{Bin}$ is a character contrast similarity function used to measure the similarity of system instantiations with binary-valued (absence/presence) character states. It can be modified in many ways which could be useful for certain applications. For example, $Sim_{Bin}$ does not penalize for unshared interoperability characters, although a penalty term could be easily added. A penalty might be desired when the lack of a certain interoperability character is a severe detriment to the effectiveness of the operational process. $Sim_{Bin}$ adheres to the standard character contrast measure form given in (11) with $\theta = 1/n$, $\alpha = \beta = 0$, and $f = (\sigma' \wedge \sigma'')$.

*DEFINITION ($Sim_{Bin}$): Given a pair of systems $s', s''$ instantiated with*

> *$\sigma', \sigma'' \in \{0,1\}^n$, then $I = Sim_{Bin} = (1/n)\sum_{i=1}^{n}\left(\sigma'(i) \wedge \sigma''(i)\right)$ is an interoperability function which gives a normalized measure of the similarity of systems instantiated with binary-valued character states where $\wedge$ is the boolean AND operator.*

$Sim_{\mathrm{Re}al}$, is a normalized geometric measure appropriate for measuring the similarity of system instantiations with real-valued character states. It assumes that the range of all characters' states are the same $[0, c_{\max}]$, either inherently or by mapping. The core of $Sim_{\mathrm{Re}al}$ is the Minkowski similarity function (10) modified to reward strictly for shared characters by inserting the $b_i$ parameter defined in (13). The modified Minkowski similarity function is given in (12).

$$Modified\ Minkowski\ Similarity = MMS = \left[1 - \left(\frac{1}{\sqrt[r]{n}}\right)\left(\sum_{i=1}^{n} b_i \left(\frac{\sigma'(i) - \sigma''(i)}{c_{\max}}\right)^r\right)^{1/r}\right] \quad (12)$$

$$b_i = \begin{cases} 0 & \sigma'(i) = 0 \ or \ \sigma''(i) = 0 \\ 1 & else \end{cases} \quad (13)$$

Although it would be desirable to just use the Modified Minkowski Similarity function as $Sim_{\mathrm{Re}al}$, this is not possible because it violates the fourth criteria of an interoperability function by not giving a greater reward to system pairs whose shared characters' states have a better value. For example, consider four system instantiations $\sigma_1 = [1]$, $\sigma_2 = [2]$, $\sigma_3 = [3]$, $\sigma_4 = [4]$ and assume $r = 2$ and $c_{\max} = 4$. Each system instantiation possesses one (the same) interoperability character, i.e., $n = 1$, but each exhibits a different state of that character. As expected, $MMS(\sigma_1, \sigma_2) = 0.75$, but $MMS(\sigma_3, \sigma_4) = 0.75$ as well. In other words, $\sigma_1$ resembles $\sigma_2$ just as much as $\sigma_3$ resembles $\sigma_4$, but intuitively, the similarity of $\sigma_3, \sigma_4$ should be higher because those two systems possess larger character state values than $\sigma_1, \sigma_2$. Hence, a weighting must be applied to the similarity measurement to correct this deficiency. Although numerous weighting schemes could be chosen, the average character state value (14) provides a simple, yet appropriate, weighting scheme and is chosen to finalize the definition of $Sim_{\mathrm{Re}al}$. $Sim_{\mathrm{Re}al}$ has the capability of yielding very precise similarity measures of system instantiations limited only by the number of characters and the precision of those characters' states.

$$Average\ Character\ State\ Value = w = \frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}} \tag{14}$$

*DEFINITION (* $Sim_{Real}$ *): Given a pair of systems* $s', s''$ *instantiated as*

> $\sigma', \sigma'' \in \mathbb{R}^n \cap [0, c_{\max}]$ *, then* $I = Sim_{Real} = w \cdot MMS$*, written out completely in* (15)*, is an interoperability function which gives a weighted, normalized measure of the similarity of systems instantiated with real-valued character states where* $w$ *is the average character state value of a pair of system instantiations,* $MMS$ *is the Modified Minkowski Similarity function,* $n$ *is the number of characters used to instantiate* $\sigma', \sigma''$*,* $c_{\max}$ *is the maximum character state value, and* $r$ *is the Minkowski parameter (usually set to* $r = 2$*).*

$$I = Sim_{\mathrm{Re}al} = \left[ \frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}} \right] \left[ 1 - \left( \frac{1}{\sqrt[r]{n}} \right) \left( \sum_{i=1}^{n} b_i \left( \frac{\sigma'(i) - \sigma''(i)}{c_{\max}} \right)^r \right)^{1/r} \right] \tag{15}$$

### 3.5.2 System Interoperability

Applying the concept of similarity to interoperability measurement, a foundational axiomatic relationship between similarity of systems and interoperability of systems can be stated.

*AXIOM (System Similarity and Interoperability): If a pair of systems is instantiated only with system interoperability characters, then the measure of their similarity is also a measure of their interoperability.*

The System Similarity and Interoperability axiom can be used to formally define interoperability measurement.

*DEFINITION (Interoperability Measurement): Given two systems $s', s'' \in S$ instantiated with bi-directional characters as $\sigma', \sigma''$ and an interoperability function $I$, then $m = I(\sigma', \sigma'')$ is a measure of the interoperability of $s'$ and $s''$ where $m = 0 \rightarrow \sigma', \sigma''$ are non-interoperable and $m = 1 \rightarrow \sigma', \sigma''$ are perfectly interoperable. $M = \left[ m_{ij} \right], i, j \leq |S|$ is a matrix of interoperability measurements for all system pairs in $S$.*

If the interoperability characters used to instantiate systems are directional in nature (i.e., a system can provide an interoperation, but not accept it), then directional interoperability measurements (see next definition) must be made.

*DEFINITION (Directional Interoperability Measurement): If two systems $\sigma' = \{\sigma'_T, \sigma'_R\}, \sigma'' = \{\sigma''_T, \sigma''_R\}$ are instantiated with directional interoperability characters $X = \{X_T, X_R\}$, then $m = I(\sigma'_T, \sigma''_R)$ is a measure of the directional interoperability of $\sigma'$ to $\sigma''$.*

### 3.5.3 Interoperability Measurement Modes

#### 3.5.3.1 Directional

All interoperations are either bi-directional or uni-directional. Bi-directional interoperation implies $m_{\sigma', \sigma''} = I(\sigma', \sigma'') = m_{\sigma'', \sigma'} = I(\sigma'', \sigma')$ whereas uni-directional interoperation implies that $m_{\sigma',\sigma''} \neq m_{\sigma'',\sigma'}$ (e.g., $\sigma'$ is a transmit only system and $\sigma''$ is a receive only system).

#### 3.5.3.2 Self

Self interoperability is defined as $m = I(\sigma, \sigma)$ and is usually assumed to be zero. Self interoperability implies an interoperation originating at the system, exiting the system boundary and then accepted back through the boundary. An example of this is a network loopback "ping" in which a computer attempts to detect its own IP address on the local network.

#### 3.5.3.3 Pure

Pure interoperability is a measure of the interoperability of two systems whose instantiations are aligned only with each other, hence their interoperability measure is pure, or unencumbered by other systems' interoperability characters. In other words, $|S| = 2$. Pure interoperability is measured for performance or cost analysis reasons, among others. The following example illustrates the concept.

Given $S = \{s_1, s_2\}$, $X = \{x_1, x_2, x_3\}$ (all bi-directional), $C \in \{\mathbb{R} \cap [0,9]\}$, $S$ instantiated as $\Sigma = \{\sigma_1, \sigma_2\} = \{\{1,2,3\},\{4,5,6\}\}$, and $I = Sim_{\mathrm{Re}al}$ (with Minkowski parameter set to $r = 2$), an interoperability matrix is obtained (16) which shows that the interoperability of $\sigma_1, \sigma_2$ is relatively low. This was to be expected as the values of both system instantiation's character states are all well below $c_{\max} = 9$. No self-interoperability was assumed, so the diagonal of $M$ was assigned a value of 0.

$$M = \begin{bmatrix} 0 & 0.259 \\ 0.259 & 0 \end{bmatrix} \tag{16}$$

If a third system is added to $S$, bringing with it additional interoperability characters, then expectedly, a third instantiation is added to $\Sigma$ and the size of $M$ increases, but the value of $I(\sigma_1, \sigma_2)$ can change as well because the context, or basis, of the interoperability measurement has changed. This phenomenon is called contextual interoperability and is addressed next.

#### 3.5.3.4 Contextual

Contextual interoperability is a measure of the interoperability of two systems whose instantiations have been aligned with at least one other system possessed of one or more different characters not used to characterize the initial two systems. In other words, it is the measure of the interoperability of two systems in the context of a larger set of systems. By increasing the size of $S$, the number of characters in $X$ generally increases (although not necessarily so), thus providing a basis for a more precise interoperability measurement. This is analogous to making a length measurement with a measuring tape with only two markings, versus using one with a hundred markings. More markings yield a more precise basis for the length measurement.

Applying this idea and taking the example given in the previous section, add $s_3$ to $S$ where $s_3$ is instantiated as $\sigma_3 = \{3,7,8,9\}$ and $X = \{x_1, x_2, x_3, x_4\}$. Aligning the three system instantiations yields the following complete instantiation of $S$.

$$\Sigma = \begin{bmatrix} 1 & 2 & 3 & 0 \\ 4 & 5 & 6 & 0 \\ 3 & 7 & 8 & 9 \end{bmatrix} \tag{17}$$

Again, using $I = Sim_{Real}$ as the interoperability function, and assuming $n = 4$, $r = 2$, $c_{\max} = 9$, and no self-interoperability, the interoperability matrix in (18) is obtained.

$$M = \begin{bmatrix} 0 & 0.207 & 0.162 \\ 0.207 & 0 & 0.276 \\ 0.162 & 0.276 & 0 \end{bmatrix} \tag{18}$$

By adding a new system instantiation to $\Sigma$ , which increased the number of characters used to instantiate $S$, the interoperability measurement of $s_1$ and $s_2$ becomes more precise, changing from $I = 0.259$ to $I = 0.207$. This drop in the interoperability measurement was expected because the interoperability of $s_1$ and $s_2$ is now being measured in the context of $s_3$ which not only adds a new interoperability character to the model but exhibits much higher character state values than the other two system instantiations. In the context of the expanded model, $s_1$ and $s_2$ still appear very similar (i.e., the Modified Minkowski Similarity function shows their similarity is $MMS = 0.8\overline{3}$) but their overall interoperability measurement is penalized by their low interoperability character state values ($w = 0.292$). In the context of the very capable $s_3$, the interoperability measurement of $s_1$ and $s_2$ drops. While this result might be considered non-intuitive, it is nevertheless correct. Indeed, $s_1$ and $s_2$ are not less interoperable because $s_3$ is added to $S$, but their interoperability measurement becomes more precise because of the infusion of the additional characters associated with $s_3$. It can be postulated that as the number of characters used to instantiate $S$ approaches infinity, then the interoperability measurements of the systems in $S$ approach perfect precision.

#### 3.5.3.5 Time-variant

Interoperability is generally time variant. For example, atmospheric effects due to the changes from night to day will degrade the optical interoperability of reconnaissance satellites and ground targets. Similarly, the directional interoperability of an attacker and his target may increase as the attacker has ingressed long enough to come in range of the target. Finally, end-to-end computer interoperability may improve or diminish with changes in network congestion tied to worker shift changes, lunchtime usage, etc. There are two distinct methods of modeling time-variant interoperability. The first method creates a time-continuous basis for the interoperability measurement in which systems are instantiated using interoperability characters which themselves are functions of time. Hence, the resulting interoperability measurement is also a function of time. The second method is a discrete method in which a series of instantiations are created which represent "snapshots" in time. The series of interoperability measurements tied to these instantiations represents a sampled time-varying interoperability measurement. Time-variant interoperability measurements can be directional, self, pure, contextual, confrontational, collaborative, direct, or in-direct interoperability measurements. A time-variant interoperability measurement can be equivalent to an activity-phased measurement if the activities occur in time sequential fashion. Time variant interoperability measurements are useful in determining if/when interoperability lapses cause associated degradation in operational effectiveness.

#### 3.5.3.6 Constrained Upper Bound on Interoperability Measurement

It is not possible, or even desirable, for all systems to interoperate with each other, let alone interoperate perfectly. Furthermore, for those systems which ought to interoperate, there are often many limitations, specific to the operational process, which prevent them from interoperating at their full potential. Some of these limitations are physical (e.g., electromagnetic interference), operational (i.e., rules of engagement), or reliability related (i.e., mission capability), among many others. Therefore, in order to manage expectations on the final interoperability measurement, it is useful to define a realistic upper bound on the interoperability measurement, called the constrained upper bound. This constrained upper bound on the interoperability measurement admits that the best possible interoperability measurement must be less than $m = 1$ due to these various degradations and limitations. The constrained upper bound on the interoperability measurement is calculated by first determining the operational process-specific interoperability limiting factors, then by building an interoperability model which accommodates those limitations. This model includes all interoperability characters the set of systems could conceivably implement with their character states set to their best possible value in light of the predetermined limitations. The difference between the constrained upper bound on the interoperability measurement and the current interoperability measurement is called the interoperability gap and represents the trade space, design space, or funding space in which process or system changes can occur, to the end of improving operational effectiveness.

#### 3.5.3.7 Collaborative

Collaborative interoperability is the type of interoperability most understood by people today. For example, in the Department of Defense the term interoperability is usually associated with the idea of service, joint, and allied systems, units, and forces working together to mutual advantage as opposed to friendly (blue) systems interoperating with adversary (red) systems. Similarly, in the civilian sector, an engineer might consider interoperability to be a property of how well the various systems he operates or designs interface or provide and accept services from each other. Written another way, collaborative interoperability is the interoperability between friendly, or blue systems. Collaborative interoperability also carries a connotation that if one system provides something, another system gives something back in exchange. In other words, the systems interoperate in a collaborative fashion for mutual benefit or to achieve a shared goal. Applying traditional military terminology, collaborative interoperability can also be called blue-to-blue interoperability. The interoperability measurement method presented in this Chapter provides a methodical means of measuring the collaborative interoperability of all types of systems interoperating in all kinds of ways.

It is important to note however, that not all interoperations are collaborative. Indeed, collaborative interoperability often supports the goals of the operational process but does not directly implement them. For example collaborative forms of interoperability such as linguistic, technical, logistics, and cultural interoperability of coalition forces and systems enabled the ouster of Iraq from Kuwait during operation DESERT STORM, however they did not directly cause the ouster—that was done by confrontational interoperability methods such as attack operations. In general, if the operational process implies any form of opposition (i.e., an oppositional or confrontational operational process) between systems (e.g., negotiation, attack, greediness, pushing, removing, limiting, and preventing, among others), then another type of interoperability, called confrontational interoperability can be measured. This type of interoperability measurement is powerful because it can be related directly to operational effectiveness without discrete event, or other types of simulation.

**3.5.3.8 Confrontational**

A unique contribution of this research is the announcement and explanation of confrontational interoperability, which is the interoperability of friendly (blue) and adversary (red) forces. Examples of confrontational interoperability include the actions of a friendly (blue) jammer to degrade the communications of adversary (red) force command and control systems, the efforts of two negotiation teams attempting to resolve an issue, environmental activity which inhibits technology (e.g., gravity vs a rocket, wind vs an airplane, oxidation vs a metal bridge, or sunspot-generated electromagnetic interference vs radios), and marketing aimed at attracting business for one company while preventing it for another, among others. In a confrontational operational process, one set of systems tries to achieve advantage or effectiveness over the remaining systems. Many military processes, such as time critical targeting, psychological operations, or defensive counter air, are inherently confrontational. Indeed, for these processes confrontational interoperability should receive focus as it describes the ability of friendly (blue) systems to control adversary (red) systems and to prevent reciprocation—an inherently military concept.

Confrontational interoperability implies and underpins effects-based operations in which all planning, preparation, execution, and assessment of an operation concentrates on the desired effects on the enemy. Everything that does not contribute toward achieving the desired effect is considered irrelevant and anything that could hinder the effect is eliminated. For example, in a time critical targeting operation, the goal is not to have a high degree of collaborative interoperability of friendly systems (this might be helpful or could be damaging to the operation), but to have a high degree of directional confrontational interoperability from friendly (blue) to adversary (red) systems. In other words, the goal is to ensure that blue systems are able to destroy red systems. Indeed, for certain operational processes, collaborative interoperability ideally is minimized and confrontational interoperability is maximized. For example, during stealth operations, a single stealthy aircraft may conduct a bombing operation without support aircraft, while maintaining radio silence, and while flying without the benefit of active radar.

While too much collaborative interoperability in any type of operational process might result have degrading effects, such as information overload, in a confrontational operational process, a high degree of directional confrontational interoperability from friendly to adversary systems is always desired as it will likely result in decisive success. Furthermore, in the context of a confrontational operational process, when the statement is made that collaborative interoperability must be improved, the implication is that it must be improved in order to increase operational effectiveness (i.e., improve confrontational interoperability). Some have made the dangerous assumption that the more interoperable friendly systems and forces are with each other the more operational success they will enjoy. This is often false. For example, fighter pilots have warned against information overload in the cockpit which might distract them from their main tasks. Similarly, the ability of mid- and senior-level managers to interoperate with each other and their subordinates via e-mail is both a benefit and a detractor if misused. Information overload, distraction, and inefficiencies, among other detractors, are the result of too much collaborative interoperability. The relationship between confrontational interoperability and operational effectiveness is described in succeeding sections and demonstrated in Chapter 4.

### 3.6 Interoperability Impact on Operational Effectiveness

General Hal Hornburg quipped in 2004 that he looks forward "to the day where we can convince a surface-to-air missile that it's a Maytag in a rinse cycle, making it irrelevant to combat." (Tirpak, 2004:31) This statement implies a desire to control the enemy. Stated another way, General Hornburg desires friendly (blue) force operational advantage resulting from improved friendly (blue)-to-adversary (red) directional interoperability and degraded adversary (red)-to-friendly (blue) directional interoperability. Sun Tzu encapsulates this concept by stating "The clever combatant imposes his will on the enemy, but does not allow the enemy's will to be imposed on him." (Giles, 1910:VI-2) The following axiom gives a sufficient condition which relates directional confrontational interoperability to operational advantage.

*AXIOM (Operational Advantage):* Let the subscripts $B, R$ refer to friendly (blue) and adversary (red) forces respectively. Given a set of systems $S = \{S_B, S_R\}$ instantiated as $\Sigma = \{\Sigma_B, \Sigma_R\}$, then a sufficient condition for friendly (blue) force operational advantage over adversary (red) force is for all pairs $(\sigma_B, \sigma_R)$, $I(\sigma_B, \sigma_R) > I(\sigma_R, \sigma_B)$ assuming $\Sigma$ completely characterizes $S$.

While the Operational Advantage axiom states that if the directional interoperability of all friendly (blue) toadversary ( red) systems exceeds that of adversary (red) to friendly (blue), then operational advantage is obtained, it is important to emphasize that this is a sufficient, but not a necessary condition. For example, if a set of friendly (blue) systems includes a home base $\sigma_{HB}$ and a bomber $\sigma_B$, while the set of adversary (red) systems consists of an integrated air defense system $\sigma_{IADS}$ and a target $\sigma_{TGT}$, then probably the home base does not need to have operational advantage over the enemy target in order for the operation to be effective, however the bomber must have operational advantage over both the air defense system and the target. Thus, in this limited example it might be postulated that a necessary condition for friendly (blue) force operational advantage operational advantage over adversary (red) force is that $I(\sigma_B, \sigma_{IADS}) > I(\sigma_{IADS}, \sigma_B)$ and $I(\sigma_B, \sigma_{TGT}) > I(\sigma_{TGT}, \sigma_B)$. Unfortunately, these necessary conditions are not always possible to define, and generally discrete event or some other type of simulation is required in order to determine the minimal set of systems which must enjoy operational advantage over each other in order to ensure operational success.

As MoOEs quantify operational advantage, applying the Operational Advantage axiom, the impact of interoperability on operational effectiveness can be described. This important result is given below as the Interoperability Impact on Operational Effectiveness axiom, which, like the Operational Advantage axiom, describes a sufficient condition. The Interoperability Impact on Operational Effectiveness axiom, 1) applies to confrontational interoperability (noting that collaborative interoperability between friendly systems contributes to confrontational interoperability between opposing forces' systems), 2) requires that the MoOE be written as a diametric pair, and 3) demands that the set of systems be instantiated by a complete set of interoperability characters $X$ which describe all interoperations related to the diametric pair. For example, if $O_B$ is the percent of red targets destroyed and $O_R$ is the percent of red targets protected, then $X$ must characterize all interoperations between all systems in $S$ which contribute to the destruction and protection of red targets.

*AXIOM (Interoperability Impact on Operational Effectiveness):* Let the subscripts $B, R$ refer to friendly (blue) and adversary (red) forces respectively. Given a set of systems $S = \{S_B, S_R\}$ characterized by $X$ and instantiated as $\Sigma = \{\Sigma_B, \Sigma_R\}$ and a diametric MoOE $O = \{O_B, O_R\}$, then if $X$ completely characterizes all interoperations related to $O_B, O_R$ then a sufficient condition for $O_B > O_R$ is that friendly (blue) systems have Operational Advantage over adversary (red) systems, or in other words friendly (blue)-to-adversary (red) directional interoperability exceeds adversary (red)-to-friendly (blue) directional interoperability for all pairs $(\sigma_B, \sigma_R)$ (i.e., $\forall(\sigma_B, \sigma_R), I(\sigma_B, \sigma_R) > I(\sigma_R, \sigma_B) \leftrightarrow O_B > O_R$).

### 3.7 Architecture and Interoperability

Numerous enterprise, system, and operational architectures have been created over the past decade using the DoD Architecture Framework (DoDAF). Many, if not all, of the organizations which created these architectures are also interested in interoperability. This is apparent in the heavy focus on describing needlines, information exchanges, and system functions as well as in documenting the technical standards required for communication and net-centric operation. Unfortunately, only some of the key elements required to perform an interoperability measurement (e.g., operational process and set of systems) can be extracted from a candidate DoDAF architecture description. Additionally, the Core Architecture Data Model (CADM) used as a template for storing DoDAF architecture descriptions (DoD, 2007c) has only a portion of the structure necessary to store the required elements for an interoperability measurement-focused architecture. The CADM designers were definitely considering interoperability when they designed the model. For example, they included a seldom used field called *interoperabilityLevelCode* intended to hold a LISI level. However, using CADM to store the key elements given in Table 8 would be an inefficient force-fit at best. For example, CADM provides for storing systems in multiple places (i.e., what is called a system in the context of this dissertation is called a system, sub-system, system node, operational node, and organization within the CADM model). Possibly even more concerning are fields in CADM which simultaneously store interoperability measurement elements and non-interoperability measurement elements (e.g., operational activities, system functions, needlines, and information exchanges stored in a CADM database *could* be interoperability characters, but not necessarily so). Thus it is concluded that DoDAF and CADM in their current forms (version 1.5) are incapable of storing or representing an architecture whose purpose is interoperability assessment and analysis.

Table 8 Interoperability measurement key elements

| **Key Element** |
| --- |
| **Purpose** |
| **Operational Process** |
| **Measure of Operational Effectiveness** |
| **Set of Systems** |
| **Set of Interoperability Characters** |
| **States of Interoperability Characters** |
| **System Instantiation** |
| **Interoperability Function** |
| **Interoperability Measurement** |

DoDAF and CADM are currently unable to accommodate the elements of Table 8, but it is possible to extend them to do so. An interoperability-focused redesign of CADM is outside the scope of this dissertation, however, embracing the motivations of DoDAF version 2.0 development (architecture with a purpose), a set of views are proposed specifically for the purpose of interoperability assessment (Table 9). The views proposed in the extension are numbered so as to be roughly analogous to existing DoDAF views.  In the table, the name, contents, format, and current DoDAF analogue view are given for each proposed view.

IV-1 Interoperability Purpose and Assumptions is a text- document, augmenting the AV-1, which describes the purpose of the interoperability analysis, the associated MoOE, and critical assumptions such as which interoperability function was used to make the interoperability measurement.  It also includes the final analysis made based upon the IV-4 view.

IV-2 Interoperability Graph visually depicts the systems and their interoperations. A mathematical definition follows.

*DEFINITION (Interoperability Graph): Given a set of systems* $S$ *instantiated as* $\Sigma = \{\Sigma_T, \Sigma_R\}$ *over a set of interoperability characters* $X$ *with character states* $C$*, let* $G$ *be a directed multigraph in which* $V(G) = S$ *and* $E(G)$ *is a set of edges such that for all characters* $x_i \in X$*, there exists a directed edge from* $s'$ *to* $s''$ *labeled with the name of that character if* $s'$ *is able to provide that interoperation and* $s''$ *is able to accept it.*

IV-3 System Instantiation ($\Sigma$) is a system to interoperability character matrix containing states of the characters, IV-4 Interoperability Measurement is the matrix of pairwise system interoperability measurements $M$, and IV-5 Operational Process (i.e., an OV-5) is a SysML activity diagram modeling the operational process.  A simple interoperability architecture is given in Table 10 to illustrate the five interoperability architecture products.

Table 9 Interoperability extension to DoDAF

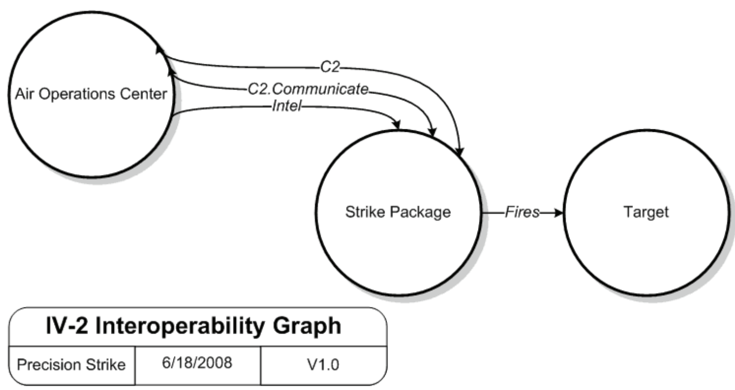
| View | Contents | Format | DoDAF Analogue |
|---|---|---|---|
| IV-1 Interoperability Purpose, Assumptions, and Analysis | Interoperability measurement purpose<br>Measure of operational effectiveness<br>Interoperability function | Text | AV-1 Overview and Summary |
| IV-2 Interoperability Graph | Set of systems<br>Set of interoperability characters<br>States of Interoperability characters | Graph | OV-2 Op. Node Conn. Descr.<br>SV-1 Sys. Interf. Descr.<br>SV-2 Sys. Comm. Descr. |
| IV-3 System Instantiation | Set of systems<br>Set of interoperability characters<br>Interoperability character states | Matrix | OV-3 Op. Info. Exch. Matrix<br>SV-3 System-System Matrix<br>SV-4 Sys. Func. Descr.<br>SV-5 Op. Act. Sys. Func. Matrix<br>SV-6 Sys. Data Exch. Matrix<br>SV-7 Sys. Perf. Parms. Matrix |
| IV-4 Interoperability Measurement | Set of interoperability measurements | Matrix | None |
| IV-5 Operational Process | Operational process | Graph | OV-5 Op. Activity Model |

Table 10 Example interoperability architecture

**IV-1**

**NAME**: Precision Strike Interoperability Measurement
**PURPOSE**: To predict operational success by application of the Interoperability Impact on Operational Effectiveness axiom.
**INTEROPERABILITY FUNCTION**: $I = Sim_{Bin}$
**MoOE**: $O = \{O_B, O_R\}$, $O_B$ is "target destroyed?" and $O_R$ is "target protected."
**ANALYSIS**: Assuming the critical interoperation is $PSP - TGT$, then because $I(\sigma_{PSP}, \sigma_{TGT}) > I(\sigma_{TGT}, \sigma_{PSP})$ then it is assumed that $O_B > O_R$.

**IV-2**



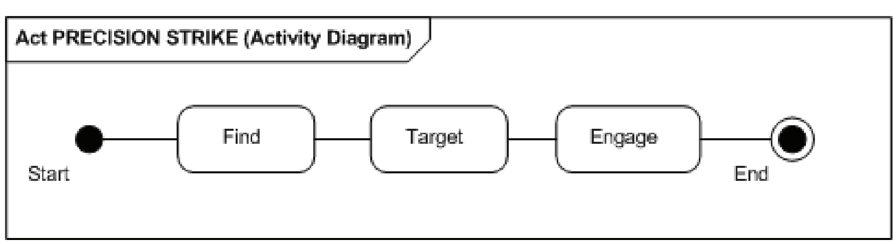

**IV-3**

| | Transmit | | | Receive | | |
|---|---|---|---|---|---|---|
| | *AOC* | *PSP* | *TGT* | *AOC* | *PSP* | *TGT* |
| *C2* | 1 | 1 | 0 | 1 | 1 | 0 |
| *C2.Communicate* | 1 | 1 | 0 | 1 | 1 | 0 |
| *Intel* | 1 | 0 | 0 | 0 | 1 | 0 |
| *Fires* | 0 | 1 | 0 | 0 | 0 | 1 |

**IV-4**

| | ***AOC*** | ***PSP*** | ***TGT*** |
|---|---|---|---|
| ***AOC*** | 0 | 3/4 | 0 |
| ***PSP*** | 1/2 | 0 | 1/4 |
| ***TGT*** | 0 | 0 | 0 |

**IV-5 (OV-5)**



## 3.8 Summary

The general method of interoperability measurement presented in this chapter is foundational and weaves together the best ideas from extant literature with key missing elements described in this research (e.g., system interoperability characters, character states, system instantiations, system similarity, operational advantage, and others). The result is a flexible method suitable for measuring the collaborative and confrontational interoperability of all types of systems interoperating in all types of ways. Because the method is grounded in an operational process, the interoperability measurement is not abstract, but mathematically related to the operational effectiveness of the confrontational operational process. The flexibility of the method supports the instantiation of systems at any level of abstraction, with resultant interoperability measurements at any desired level of precision. In the method of this chapter, numerous weaknesses of extant methods are resolved. For example, no longer is interoperability measurement limited to specific types of systems or interoperations, no longer is an interoperability measurement an abstract measure divorced from the operational circumstances in which the interoperation occurred, and no longer are interoperability measurements restricted to the precision of a limited scale or the accuracy of a limited/outdated set of attributes. In short, the method of this chapter defines a basic theory of interoperability measurement.

# 4. Analysis and Results

*One key way to ensure effectiveness is to ensure that our systems are interoperable.*
*—General Lester Lyles*

## 4.1 Overview

The interoperability measurement method of Chapter 3 is foundational and broadly useful. By applying the method, the interoperability of organizations, coalitions, weapon systems, technology, philosophies, the environment, and uncountable other entities can be measured. While it is not possible to provide an example for all possible applications (Chapter 3, Table 4) of the interoperability measurement method, several are given in this chapter to demonstrate its application.

First, it will be shown that maturity model (leveling) methods are a special case of the more general method of Chapter 3. Specifically, the Organizational Interoperability Model (OIM) will be modeled using the method of Chapter 3 and, using the same example given in Clark & Moon (2001), the interoperability of coalition forces will be measured and the results compared to that of Clark & Moon. Second, to demonstrate the relationship of interoperability with operational effectiveness, the Interoperability Impact on Operational Effectiveness axiom will be applied to a Suppression of Enemy Air Defenses (SEAD) problem. Finally, the time variance of interoperability will be explored through a Precision Strike application.

## 4.2 Application: Coalition Interoperability

Technological interoperability has been commonly discussed in other research, often focusing on network information technology standards, however, other types of interoperability are often more important. For example, the US air strikes against Libya in 1986 not only highlighted equipment interoperability problems (i.e., the Navy lacked HAVE QUICK radios which the Air Force possessed), but more especially joint procedural interoperability problems between the Navy and Air Force. (Clark & Moon, 2001) Similarly, NATO forces experienced secure, tactical voice communication problems in Kosovo, not because of lack of proper radios, but also because of procedural interoperability problems. (Nutwell & Price, 2000). Finally, Lieutenant General Cevic Bir, the commander of United Nations Operations Somalia (UNOSOM II) in 1993 remarked that interoperability was a major problem in every phase of his coalition operation. (Bir, 1997) Joint and coalition interoperability must be addressed, not just at the technical level, but also at the organizational level. Coalition interoperability measurements can focus the commander's efforts on improving joint and coalition warfighting effectiveness by increasing the interoperability of coalition forces.

Clark & Jones recognized the importance of coalition interoperability and described a maturity model, called the Organizational Interoperability Model (OIM), which describes a framework of coalition interoperability attributes and levels. (1999) Their model is based on the structure of the Department of Defense Levels of Information Systems Interoperability (LISI) model and is given in Table 11.

Table 11 Organizational interoperability maturity model (OIM) (Clark & Moon, 2001)

| | Preparedness | Understanding | Command Style | Ethos |
|---|---|---|---|---|
| **Level 4 *(Unified)*** | Complete normal day-to-day working | Shared | Homogeneous | Uniform |
| **Level 3 *(Combined)*** | Detailed doctrine and experience in using it | Shared communications and knowledge | One chain of command and interaction with home organization | Shared ethos but with influence from home organization |
| **Level 2 *(Collaborative)*** | General doctrine in place and some experience | Shared comms and shared knowledge about specific topics | Separate reporting lines of responsibility overlaid with a single command chain | Shared purpose; goals, value system significantly influenced by home organization |
| **Level 1 *(Cooperative)*** | General guidelines | Electronic comms and shared information | Separate reporting lines of responsibility | Shared purpose |
| **Level 0 *(Independent)*** | No preparedness | Voice comms via phone, etc. | No interaction | Limited shared purpose |

The usefulness of the OIM model was demonstrated when Clark & Moon used it to analyze the International Force East Timor (INTERFET) coalition sent to enforce peace in East Timor in 1999. (2001) The coalition consisted of forces from Australia (lead nation), the United States, New Zealand, Thailand, Phillipines, and Republic of Korea among others. Using after-action reports pertaining to the operation, Clark & Moon were able to apply their model to determine qualitatively that the highest levels of interoperability occurred between Australia, the United States, and New Zealand, that Thailand and the Phillipines enjoyed a lower level of interoperability with Australia, and that all other interoperations were at the lowest level.

Clark & Moon assessed the interoperability of INTEREFET coalition forces with respect to the Australian Deployable Joint Force (ADJF) standard, as implemented according to the American, British, Canada, and Australia (ABCA) coalition operations handbook (COH). Obviously, not all INTERFET member nations were capable of adhering, or even desired to adhere completely to this standard, and their interoperability levels, as assessed by Clark & Moon, reflected this. For example, Clark & Moon stated that with respect to the Preparedness attribute, the Thai forces were scored at level 1 with respect to the standard, while the United States was scored at level 2. Similarly, in Clark & Moon's aggregate interoperability measurement, when they state that the interoperability of the US and the Republic of Korea was level 1, it is to be understood that this assessment was made 1) in context of the INTERFET operation, and 2) with respect to the ADJF-ABCA COH standard. For the OIM model, level 0 infers lack of interoperability and level 4 infers full compliance with the standard.

**Hypothesis**: Maturity model (leveling) interoperability assessment methods, such as the OIM model, can be shown to be a special case of the general interoperability method presented in Chapter 3. To demonstrate, the method of Chapter 3 can be used to measure the interoperability of INTERFET coalition forces and to arrive at the same conclusions as those made by Clark & Moon when they applied the OIM model to the INTERFET operation.

### 4.2.1 The Special Case of the Maturity Model Method

A maturity model (or leveling) interoperability method such as LISI or OIM defines a set of entities, interoperability attributes (usually limited to one to four

$X$ which characterize the entities, and the levels are states of those characters $C$. For each of the entities modeled, the maturity model methods take the lowest interoperability level of all the attributes, and call it the generic interoperability $G_i$ of that entity. Then the interoperability measurement for a pair of entities is called the expected interoperability, and is defined as the lesser of the two entities' generic interoperability measurements. In other words, Expected Interoperability $= Min(G_1, G_2)$. For example, in Table 12, the expected interoperability assessment of Entity #1 and Entity #2 is 1 (i.e., the minimum of the two generic interoperability assessments). Using the terminology from Chapter 3, it can be said that the maturity models use an interoperability function $I = Min(G_1, G_2)$ to calculate the interoperability of a pair of systems . Thus, the maturity model method is shown to be a limited case of the general method of Chapter 3 in which entities equate to systems $S$, attributes equate to characters $X$, levels equate to character states $C$, and minimum common generic interoperability is used as an interoperability function $I$.

Table 12 Example OIM interoperability assessments

| | **Preparedness** | **Understanding** | **Command Style** | **Ethos** | **Generic Interoperability** |
|---|---|---|---|---|---|
| **Entity #1** | 3 | 2 | 2 | 1 | 1 |
| **Entity #2** | 4 | 4 | 3 | 3 | 3 |

### 4.2.2 INTERFET Coalition Interoperability Results and Method Comparisons

Clark & Moon applied the OIM model to assess the interoperability of coalition forces participating in the 1999 INTERFET operation. (2001) Drawing from their paper, systems, interoperability characters, and character states can be assigned as in (19), (20), and (21).

$$S = \{AUS, US, NZ, Thai, Phil, ROK\} \tag{19}$$

$$X = \{Preparedness, Understanding, Command\ Style, Ethos\} \tag{20}$$

$$C = \{0, 1, 2, 3, 4\} \tag{21}$$

While the OIM authors limited themselves to four attributes (characters) and five levels (states), using the method of Chapter 3, their model could have been expanded to a much larger number of characters and states, which would result in a better characterization of the coalition forces and a more precise interoperability measurement. Indeed, after the original publication of the OIM model (Clark & Jones, 1999), other researchers debated the number and descriptions of the attributes of the OIM model. Although the final version of the OIM model remained limited to a 4-attribute, 5-level model, at least 35 sub-attributes were further defined. (Fewell & Clark, 2003) The method of Chapter 3 could easily accommodate these 35 sub-attributes as additional characters. Although these 35 additional characters help an analyst assign an interoperability level to each attribute, by not addressing them as individual attributes, fidelity is lost from the model, and their contribution is effectively averaged out. Extracting from Clark & Moon, the set of interoperability characters are defined in Table 13.

Table 13 Explanation of coalition characterization $X$

| | |
|---|---|
| Preparedness | How well does the nation adhere to ADJF standards as implemented by ABCA-COH doctrine and training? |
| Understanding | How well does the nation share information and knowledge according to ADJF practice and ABCA-COH guidelines? |
| Command Style | How well does the nation delegate and share roles according to ADJF and ABCA-COH guidelines? |
| Ethos | How well does the nation seek to assist the East Timorese and to maintain their relationship with Indonesia? |

$S$ is instantiated as in (22) according to Clark & Moon's descriptions of member nations' participation in the INTERFET coalition operation. Although their paper gives enough information to have used more precise real-valued character states, integer states were used to maintain consistency with their model. One decimal precision is given in the interoperability measurement (23) to illustrate the improved measurement fidelity.

$$\Sigma = \left[\begin{array}{c|cccc} & Preparation & Understanding & Command\ Style & Ethos \\ \hline AUS & 2 & 3 & 3 & 1 \\ US & 2 & 3 & 3 & 1 \\ NZ & 2 & 3 & 3 & 1 \\ Thai & 1 & 1 & 1 & 1 \\ Phil & 1 & 1 & 1 & 1 \\ ROK & 0 & 1 & 1 & 1 \end{array}\right] \quad (22)$$

Selecting $I = Sim_{\mathrm{Re}al}$ as the interoperability function, with $c_{\max} = 4$, $r = 2$, and $n = 4$, the following coalition interoperability measurement $M$ results.

$$M = \left[\begin{array}{c|cccccc} & AUS & US & NZ & Thai & Phil & ROK \\ \hline AUS & 0.6 & 0.6 & 0.6 & 0.3 & 0.3 & 0.2 \\ US & 0.6 & 0.6 & 0.6 & 0.3 & 0.3 & 0.2 \\ NZ & 0.6 & 0.6 & 0.6 & 0.3 & 0.3 & 0.2 \\ Thai & 0.3 & 0.3 & 0.3 & 0.3 & 0.2 & 0.2 \\ Phil & 0.3 & 0.3 & 0.3 & 0.2 & 0.3 & 0.2 \\ ROK & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \end{array}\right] \quad (23)$$

If the interoperability measurement $M$ is scaled from its current $[0,1]$ scale to the OIM $[0,4]$ scale, then the measurement (24) can be compared to Clark & Moon's original results (Table 14).

$$M_{scaled} = \left[ \begin{array}{c|cccccc} & AUS & US & NZ & Thai & Phil & ROK \\ \hline AUS & 2.3 & 2.3 & 2.3 & 1.0 & 1.0 & 0.9 \\ US & 2.3 & 2.3 & 2.3 & 1.0 & 1.0 & 0.9 \\ NZ & 2.3 & 2.3 & 2.3 & 1.0 & 1.0 & 0.9 \\ Thai & 1.0 & 1.0 & 1.0 & 1 & 0.9 & 0.8 \\ Phil & 1.0 & 1.0 & 1.0 & 0.9 & 1 & 0.8 \\ ROK & 0.9 & 0.9 & 0.9 & 0.8 & 0.8 & 0.8 \end{array} \right] \qquad (24)$$

Table 14 Clark & Moon's original INTERFET interoperability measurements

| | **AS** | **US** | **NZ** | **Thai** | **Phil** |
|---|---|---|---|---|---|
| **US** | 2 | | | | |
| **NZ** | 2 | 2 | | | |
| **Thai** | 1 | 0 | 0 | | |
| **Phil** | 1 | 0 | 0 | 0 | |
| **ROK** | 0 | 0 | 0 | 0 | 0 |

Clark & Moon noted the best coalition interoperability among the US, Australia, and New Zealand (OIM 2) and the worst among Thailand, the Phillipines, and the Republic of Korea (OIM 0). Similar measurements (24) result from the method of Chapter 3, but with more accuracy and precision. For example, whereas the OIM model scored the interoperability of the Republic of Korea with Australia as a zero, meaning the nations were operating completely independently of each other, the method of Chapter 3 gives a more accurate result of 0.9. An OIM score of zero indicates the two nations 1) had no level of preparedness to operate in a coalition together, 2) had no interaction amongst their commanders and forces, 3) were limited to telephone communication, and 4) shared a common purpose only in a limited fashion. However, Clark & Moon's paper indicates that although the Koreans did have preparation issues, they 1) did jointly attend briefings and planning meetings, 2) understood at least half of the material presented at those briefings and meetings, 3) received taskings from HQ INTERFET, but operated in their own area of responsibility, 4) had personal contact between commanders, and 5) were not willing to participate in all aspects of the INTERFET operation, but strongly supported the humanitarian aspect of the operation. Considering that an OIM score of one indicates 1) preparation was made by learning general guidelines (not met by Koreans), 2) understanding is obtained through electronic communication and shared information (partially met by Koreans), 3) command is implemented through separate lines of responsibility (met by Koreans), and 4) the ethos of the operation is shared (partially met by Koreans), it seems reasonable to assume that the Australian-Korean interoperability score should probably be somewhere between zero and one. Thus, the Chapter 3-derived measurement of 0.9 is appropriate and more precisely and accurately reflects the true interoperability of the Republic of Korea with Australia than the assessment originally given by Clark & Moon.

#### 4.2.3 Analysis of INTERFET Interoperability Measurements

INTERFET coalition interoperability $M$ is shown graphically in Figure 7. It can be seen that among INTERFET member nations were three clusters $\{AUS, US, NZ\}$, $\{Thai, Phil\}$, and $\{ROK\}$. Expectedly the nations with Western-type philosophies, and presumably more familiar with ADJF standards as implemented by the ABCA-COH, enjoyed a high degree of interoperability with each other, but less so with the Asian nations and vice versa. Coalition interoperability could improve in the future among these Western and Eastern nations if common philosophies on doctrine, training, information sharing, delegation, and cultural values and goals, acceptable to both East and West, are agreed upon, practiced, and implemented prior to future operations.

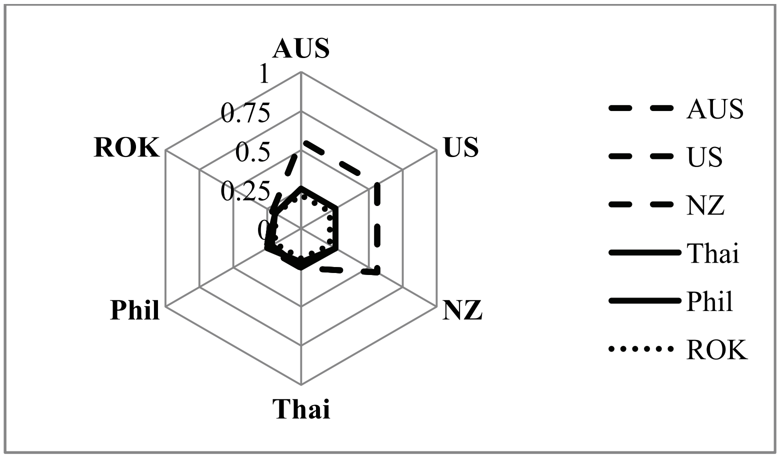



Figure 7 INTERFET coalition interoperability

The lack of coalition interoperability between the Western and Eastern nations participating in INTERFET manifested itself in the fact that "the Thais, South Koreans, and Filipinos had their own areas of operation…and conducted their own operations." (Clark & Moon, 2001:32) Similarly, the "divergent nature of the operational philosophies of the participating countries" was one of the "most difficult aspects of assembling and maintaining the coalition." (Ibid) Furthermore, some of the coalition officers "only understood half of what was said at briefings and conferences and…the Australians were unaware of this." (Ibid:33)

### 4.3 Application: Suppression of Enemy Air Defenses (SEAD)

The following application further demonstrates the interoperability measurement method of Chapter 3, explores confrontational interoperability, and illustrates the

Interoperability Impact on Operational Effectiveness axiom which states that improved friendly (blue)-to-adversary (red) directional interoperability combined with degraded adversary (red)-to-friendly (blue) interoperability results in higher operational effectiveness.

**Hypothesis**: Applying the Interoperability Impact on Operational Effectiveness axiom, it can be shown that operational effectiveness of the SEAD mission is improved by 1) the addition of friendly (blue)-force precision strike and electronic attack capability (i.e., increased friendly (blue)-to-adversary (red) interoperability) and 2) the addition of friendly (blue)-force stealth (i.e., decreased adversary (red)-to-friendly (blue) interoperability).

SEAD is defined by JP 1-02 *Department of Defense Dictionary of Military and Associated Terms* as "activity that neutralizes, destroys, or temporarily degrades surface-based enemy air defenses by destructive and/or disruptive means." (JP 1-02, 2008:523) In this application, the definition is further refined to include only activity which destroys enemy air defenses by destructive means. An operational process for this application is given in Figure 8 and is based upon the targeting process given in JP 3-60 *Joint Targeting* and AFDD 2-1.9 *Targeting*. (2007; 2006)

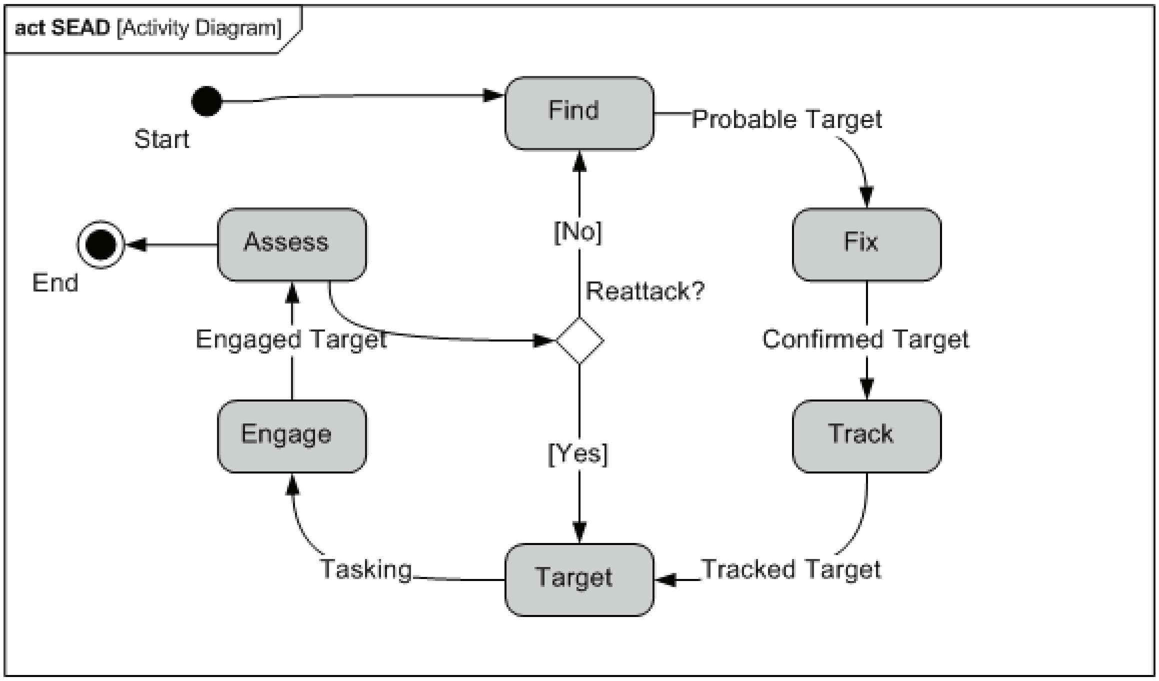


Figure 8. SEAD operational process

A MoOE "Percent of enemy air defenses destroyed" for the process is taken from CJCSM 3500.04D *Universal Joint Task List* task OP 3.2.4 "Suppress Enemy Air Defenses" measure M1. (2006) This MoOE can be written as the diametric pair given in (25) which obeys the relationship $O_B + O_R = 1$.

$$O = \{O_B, O_R\} = \left\{ \begin{matrix} \text{Percent of enemy air defenses destroyed,} \\ \text{Percent of enemy air defenses protected} \end{matrix} \right\} \tag{25}$$

Typical SEAD systems are associated with the activities and decisions of the operational process (Figure 8) and are given in (26). The $ISR$ system performs the Find, Fix, and Track activities, the $AOC$ system performs the Target, Assess, and Reattack? activities and decision, and the $PSP$ (precision strike package) system performs the Engage activity. Two enemy $IADS$ systems are targets for the mission. An operational view of the mission is given in Figure 9.

$$S = \{S_B, S_R\} = \{\{HB, ISR, AOC, PSP\}, \{IADS_1, IADS_2\}\} \qquad (26)$$

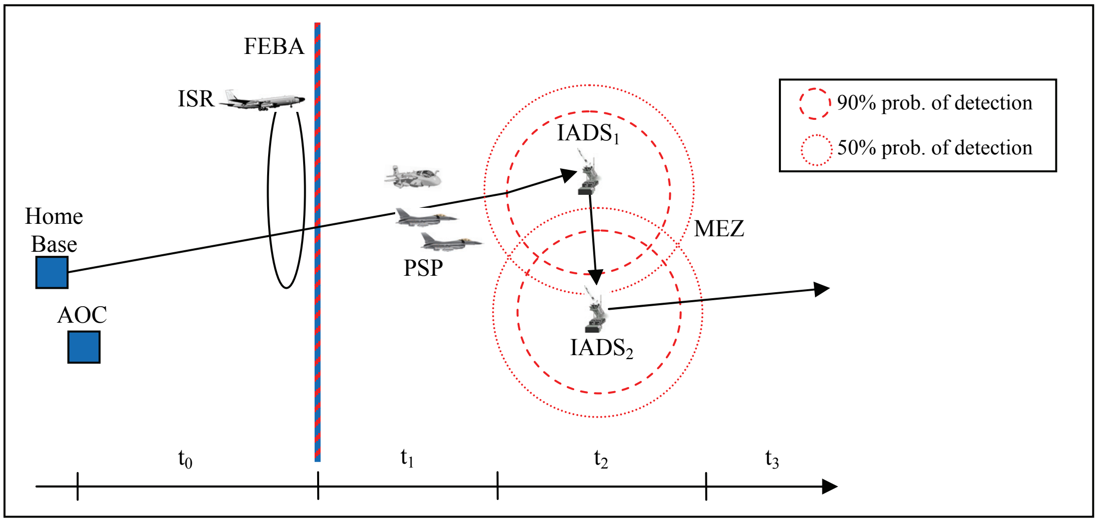



Figure 9. Operational view of SEAD mission

In order to apply the Interoperability Impact on Operational Effectiveness axiom, the characterization $X$ of $S$ must include all interoperability characters which describe every interoperation (collaborative and confrontational) between systems in $S$ related to $O$. In other words, all interoperability characters related to the destruction and protection of the IADS systems must be included in $X$. This hierarchical set of directional interoperability characters $X$ is given in Table 15. In order to ensure the set of interoperability characters $X$ chosen for the SEAD application in this section is complete and authoritative, they have been methodically identified and extracted from Joint Publications and Air Force Doctrine Documents related not just to suppression of enemy air defenses, but to Joint and Air Force operations in general. The top level of the hierarchy is the set of joint operational functions given in JP 3-0 *Joint Operations* (2006) and the second level is a pertinent subset of the operational functions of air and space power given in AFDD 1 Air Force Basic Doctrine. (2003) Lower levels of the interoperability character hierarchy have been extracted from JP 3-0 *Joint Operations* (2006), AFDD 2 *Operations and Organization* (2007), JP 3-01 *Countering Air and Missile Threats* (2007), AFDD 2-1 *Air Warfare* (2000), AFDD 2-1.1 *Counterair Operations* (2002), JP 3-13.1 *Electronic Warfare* (2007), AFDD 2-5.1 *Electronic Warfare* (2002), AFDD 2-9 *Intelligence, Surveillance, and Reconnaissance Operations* (2007), JP 3-60 *Joint Targeting* (2007), AFDD 2-1.9 *Targeting* (2006), and JP 3-13.4 *Military Deception*. (2006) In order to maintain the ability to assess the value of future capabilities (e.g., precision ground attack and electronic attack), those interoperability characters are included in $X$ as well, but their states are zeroed out in the initial system instantiation $\Sigma$. An explanation of the interoperability characters in $X$ is given in Table 16.

Table 15 SEAD hierarchical characterization $X$

<table>
<tr><td>1</td><td colspan="2">C2</td><td colspan="2">Intel</td><td colspan="6">Fires</td></tr>
<tr><td>2</td><td colspan="2">Comm</td><td colspan="2">ISR</td><td colspan="3">Counterair (CA)</td><td colspan="3">Info Ops (IO)</td></tr>
<tr><td>3</td><td>Blue</td><td>Red</td><td colspan="2">Detect</td><td colspan="2">OCA</td><td>DCA</td><td colspan="2">EW</td><td>Infl. Ops</td></tr>
<tr><td>4</td><td>Target</td><td></td><td>Blue</td><td>Red</td><td colspan="2">Ground</td><td></td><td colspan="2">EA</td><td>MILDEC</td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td>Cluster</td><td>Precision</td><td></td><td>Barrage</td><td>Reactive</td><td></td></tr>
</table>

Table 16. Explanation of SEAD characterization $X$

| Interoperability Character | Source | Explanation |
|---|---|---|
| *C2* | JP 3-0 | command & control/be commanded & controlled |
| *C2.Comm* | Ibid | communicate(T)/communicate(R) |
| *C2.Comm.Blue* | Ibid | communicate(T) on blue channels/communicate(R) on blue channels |
| *C2.Comm.Blue.Target* | Ibid | communicate(T) red targets on blue channels/communicate(R) red targets on blue channels |
| *C2.Comm.Red* | Ibid | communicate(T) on red channels/communicate(R) on red channels |
| *Intel* | JP 3-0 | intel(T)/intel(R) |
| *Intel.ISR* | JP 3-0 | ISR(T)=collect, and ISR(R)=collected against |
| *Intel.ISR.Detect* | AFDD 2-9 | detect = (collect)/be detected by (= collected against) |
| *Intel.ISR.Detect.Blue* | Ibid | detect blue systems (=identify blue)/be detected as a blue system (identified as blue) |
| *Intel.ISR.Detect.Red* | Ibid | detect red systems (identify red)/be detected as a red system (identified as red) |
| *Fires* | JP 3-0 | attack/be attacked |
| *Fires.CA* | JP 3-0<br>AFDD 1<br>AFDD 2-1.1 | attack threats to airborne systems/be attacked as a threat to airborne systems |
| *Fires.CA.OCA* | JP 3-0<br>AFDD 1<br>AFDD 2-1.1 | attack threats to airborne systems prior to their employment/be attacked, prior to employment, as a threat to airborne systems |
| *Fires.CA.OCA.Ground* | JP 3-01<br>AFDD 2-1.1 | attack ground-based threats to airborne systems prior to their employment/be attacked, prior to employment, as a ground based threat to airborne systems |
| *Fires.CA.OCA.Ground.Cluster* | | attack ground-based threats to airborne systems using cluster bombs/be attacked as a ground-based threat to airborne systems using cluster bombs |
| *Fires.CA.OCA.Ground.Precision* | | attack ground-based threats to airborne systems using precision guided munitions/be attacked as a ground-based threat to airborne systems using precision guided munitions |
| *Fires.CA.DCA* | JP 3-01<br>AFDD 2-1.1 | attack threats to airborne systems after weapon employment/be attacked as a threat to airborne systems after weapon employment |

| Interoperability Character | Source | Explanation |
|---|---|---|
| *Fires.IO* | JP 3-0<br>AFDD 1 | attack via info operations/be attacked via information operations |
| *Fires.IO.EW* | JP 3-0 | attack via info operations using electronic warfare/be attacked via info operations by electronic warfare |
| *Fires.IO.EW.EA* | JP 3-0 | jam/be jammed |
| *Fires.IO.EW.EA.Barrage* | | jam by barrage method/be jammed by barrage method |
| *Fires.IO.EW.EA.Reactive* | | jam precisely by reactive method/be jammed precisely by reactive method |
| *Fires.IO.InflOps* | AFDD 1 | apply influence operations/receive influence operations |
| *Fires.IO.InflOps.MILDEC* | JP 3-13.4<br>AFDD 1 | apply military deception/receive military deception |
| *Movement&Maneuver* | JP 3-0 | not used in this scenario |
| *Protection* | JP 3-0 | not used in this scenario |
| *Sustainment* | JP 3-0 | not used in this scenario |

Assign the set of states of $X$ as absence/presence states $C = \{0,1\}$ then the instantiation of $S$ is given as $\Sigma$ in Table 17. Although the joint operational functions $Movement\,\&\,Maneuver$, $Protection$, and $Sustainment$ are included in the instantiation for completeness, they have been assigned zero states as their functionality is not critical to the following analysis.

Table 17. SEAD instantiation $\Sigma$

| | Transmit | | | | | | Receive | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *HB* | *ISR* | *AOC* | *PSP* | *IADS1* | *IADS2* | *HB* | *ISR* | *AOC* | *PSP* | *IADS1* | *IADS2* |
| *C2* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *C2.Comm* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *C2.Comm.Blue* | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| *C2.Comm.Blue.Target* | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| *C2.Comm.Red* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| *Intel* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR.Detect* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR.Detect.Blue* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| *Intel.ISR.Detect.Red* | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires* | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA* | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA.OCA* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA.OCA.Ground* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.OCA.Ground.Cluster* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.OCA.Ground.Precision* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.DCA* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW.EA* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW.EA.Barrage* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW.EA.Reactive* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.InflOps* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| *Fires.IO.InflOps.MILDEC* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| *Movement&Maneuver* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Protection* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Sustainment* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

If the interoperability function $I = Sim_{Bin}$ is chosen, then assuming no self-interoperability, the resulting directional interoperability measurements are given in (27).

$$M = \left[\begin{array}{c|cccccc} & HB & ISR & AOC & PSP & IADS_1 & IADS_2 \\ \hline HB & 0 & 1/9 & 1/9 & 1/9 & 2/27 & 2/27 \\ ISR & 1/9 & 0 & 5/27 & 8/27 & 2/9 & 2/9 \\ AOC & 1/9 & 1/9 & 0 & 4/27 & 2/27 & 2/27 \\ PSP & 1/9 & 1/9 & 1/9 & 0 & 7/27 & 7/27 \\ IADS_1 & 2/27 & 5/27 & 5/27 & 10/27 & 0 & 1/3 \\ IADS_2 & 2/27 & 5/27 & 5/27 & 10/27 & 1/3 & 0 \end{array}\right] \tag{27}$$

For this application, the appropriate analysis of $M$ is the comparison of friendly (blue)-to-adversary (red) and adversary (red)-to-friendly (blue) interoperability (i.e., confrontational interoperability) to the end of applying the Interoperability Impact on Operational Effectiveness axiom to determine if the friendly (blue) systems will enjoy operational effectiveness over the adversary (red) systems. Four friendly (blue)-adversary (red) system pairs are possible and must be considered, $HB \leftrightarrow IADS$, $ISR \leftrightarrow IADS$, $AOC \leftrightarrow IADS$, and $PSP \leftrightarrow IADS$. The Interoperability Impact on Operational Effectiveness axiom (see Table 18 summary) shows only one friendly (blue) system ($ISR$) is operationally effective over the adversary (red) $IADS$ systems. Two others ($AOC, PSP$) do not possess operational advantage over the $IADS$ and a third ($HB$) is at a standoff (i.e., equivalent directional interoperability measurements).

Table 18. SEAD interoperability analysis

| Blue-Red System Pair | Analysis | B>R |
|---|---|---|
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 2/27 = I(IADS, HB) \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 2/9 > I(IADS, ISR) = 5/27 \rightarrow O_B > O_R$ | Yes |
| $AOC \leftrightarrow IADS$ | $I(AOC, IADS) = 2/27 < I(IADS, AOC) = 5/27 \rightarrow O_B \leq O_R$ | No |
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 7/27 < I(IADS, PSP) = 10/27 \rightarrow O_B \leq O_R$ | No |

The directional interoperability measurements in Table 18 indicate that adversary (red) targets are able to be detected, but not effectively destroyed by friendly (blue) systems. Additionally, the measurement of the directional confrontational interoperability from $IADS$ to $PSP$ indicates that the $PSP$ is vulnerable to destruction by the $IADS$ systems. According to the Interoperability Impact on Operational Effectiveness axiom, in order to give friendly (blue) systems operational effectiveness over adversary (red) systems, friendly (blue)-to-adversary (red) directional interoperability must exceed adversary (red)-to-friendly (blue) interoperability. To this end, according to the hypothesis in the introduction to this section, friendly (blue)-to-adversary (red) interoperability will be increased by adding precision strike and electronic attack capability to the $PSP$ system. Additionally, adversary (red)-to-friendly (blue) interoperability will be decreased by adding stealth capability to the $PSP$ system (manifested in the model as an inability of the $IADS$ to detect the $PSP$). Assuming that adversary (red) systems are also capable of being upgraded, the ability to resist all but reactive jamming will be given to the $IADS$ systems. The upgraded instantiation $\Sigma_U$ is given in Table 19. Changes from the original instantiation are highlighted.

Table 19. Upgraded SEAD instantiation $\Sigma_U$

| | Transmit | | | | | | Receive | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *HB* | *ISR* | *AOC* | *PSP* | *IADS1* | *IADS2* | *HB* | *ISR* | *AOC* | *PSP* | *IADS1* | *IADS2* |
| *C2* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *C2.Comm* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *C2.Comm.Blue* | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| *C2.Comm.Blue.Target* | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| *C2.Comm.Red* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| *Intel* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR.Detect* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Intel.ISR.Detect.Blue* | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| *Intel.ISR.Detect.Red* | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires* | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA* | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA.OCA* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| *Fires.CA.OCA.Ground* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.OCA.Ground.Cluster* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.OCA.Ground.Precision* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.CA.DCA* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW.EA* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.EW.EA.Barrage* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Fires.IO.EW.EA.Reactive* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| *Fires.IO.InflOps* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| *Fires.IO.InflOps.MILDEC* | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| *Movement&Maneuver* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Protection* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Sustainment* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Again using $I = Sim_{Bin}$ as the interoperability function, a set of interoperability measurements $M_U$ for the upgraded systems is obtained and given in (28). As above, changes from the original interoperability matrix are highlighted.

$$M_U = \begin{array}{c|c} & \begin{array}{cccccc} HB & ISR & AOC & PSP & IADS_1 & IADS_2 \end{array} \\ \hline \begin{array}{c} HB \\ ISR \\ AOC \\ PSP \\ IADS_1 \\ IADS_2 \end{array} & \begin{bmatrix} 0 & 1/9 & 1/9 & 1/9 & 2/27 & 2/27 \\ 1/9 & 0 & 5/27 & \boxed{7/27} & 2/9 & 2/9 \\ 1/9 & 1/9 & 0 & 4/27 & 2/27 & 2/27 \\ 1/9 & 1/9 & 1/9 & 0 & \boxed{4/9} & \boxed{4/9} \\ 2/27 & 5/27 & 5/27 & \boxed{1/3} & 0 & 1/3 \\ 2/27 & 5/27 & 5/27 & \boxed{1/3} & 1/3 & 0 \end{bmatrix} \end{array} \tag{28}$$

After upgrading the $PSP$ system with precision strike, electronic attack, and stealth and countering with an adversary (red) force upgrade of the $IADS$ systems with resistance to all but reactive jamming, then $I(PSP, IADS) = 4/9 > I(IADS, PSP) = 1/3$ $\rightarrow O_B > O_R$. Hence the friendly (blue) force now has a slight edge over the adversary (red) force, implying that the percentage of adversary (red) targets destroyed will be greater than the percentage of adversary (red) targets protected. Thus, the original hypothesis of this application is confirmed. Finally, it is interesting to note that one element of friendly (blue)-to-friendly (blue) interoperability (i.e., collaborative interoperability) decreased as a result of the system upgrades. Specifically, $I(ISR, PSP)$ decreased from $8/27$ to $7/27$. The interpretation of this is that due to the addition of stealth capability the $PSP$ system is also less detectable by the friendly (blue) force $ISR$ system.

### 4.4 Application: Precision Strike

Time variance of the interoperability of a set of systems is caused by progression through the activities and decisions of the operational process, by time variant characters, or by random effects. Interoperability decreases due to time variance are not always bad. For example, a process may call for a certain system to be periodically turned off, which causes its interoperability with other systems to drop to zero. On the other hand, some interoperability decreases are undesirable, such as those due to time varying electromagnetic interference. It is useful to analyze interoperability with respect to time in order to highlight process bottlenecks, discover previously unknown environmental impacts, or to determine minimum required interoperability to meet operational goals to the end of optimizing monetary investment.

The following application illustrates the time variance of interoperability measurements by repeated application of the method of Chapter 3 at various stages of the Precision Strike mission and demonstrates that perfect interoperability of all systems at all stages of a mission is not desired or necessary, but that appropriate levels of interoperability should be achieved at the appropriate times.

**Hypothesis**: The interoperability of Precision Strike systems varies during different mission time periods. Furthermore, if the constrained upper bound on the interoperability of each system pair is achieved in each time period, then the sufficient condition for operational effectiveness given by the Interoperability Impact on Operational Effectiveness axiom can be relaxed, yet still be appropriately applied to predict operational effectiveness. In other words, during a specific time period some friendly (blue)-to-adversary (red) and adversary (red)-to-friendly (blue) operational advantage can be ignored if it is not pertinent to that time period.

In this application (Figure 10), a penetrating strike package (PSP) attacks its target kinetically after being escorted part way to the target by a modified escort jammer (MEJ). A static baseline interoperability measurement is first made, then interoperability is measured at four different time periods, ($t_0$) prior to the PSP and MEJ crossing the forward edge of the battle area (FEBA), ($t_1$) when the PSP and MEJ are between the FEBA and the missile engagement zone (MEZ), ($t_2$) while the PSP is over the target (within the MEZ), and ($t_3$) after the PSP attacks the target and is egressing the MEZ.

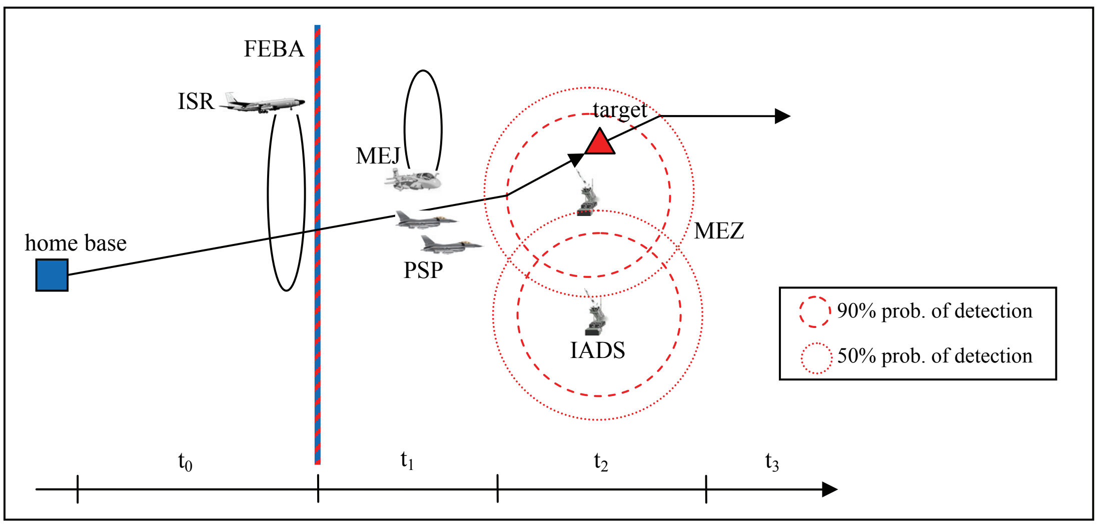


Figure 10. Operational view of time-phased precision strike mission

The precision strike operational process (Figure 11) is derived from the following use case. “A PSP launches from home base and proceeds towards its target accompanied from base, across the FEBA and up to the MEZ by a MEJ, which jams enemy radar and communications signals detected by a stand-off intelligence, surveillance, and reconnaissance (ISR) platform orbiting on the friendly side of the FEBA. The PSP crosses into the MEZ, leaving the MEJ outside the MEZ to orbit and jam, proceeds to the target, destroys it kinetically, and quickly egresses, recovering on a safe route.”

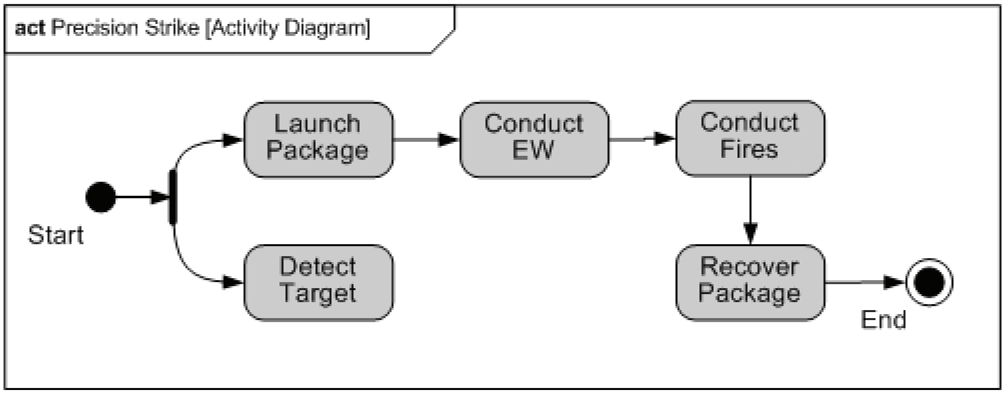



Figure 11 Precision strike operational process

Finally, define the diametric MoOE for the precision strike operational process is $O = \{O_B, O_R\}$ where $O_B$ is "target destroyed" and $O_R$ is "target protected."

### 4.4.1 Static Unconstrained Interoperability Model

For comparison purposes, a static interoperability model is provided first which is later perturbed to demonstrate time-variant interoperability. Given a set of systems $S = \{PSP, MEJ, IADS, ISR, HB, TGT\}$ let each system $s_j$ be characterized by a set of interoperability characters $X = \{X_T, X_R\}$ (29) where $X_T$ and $X_R$ are directional (transmit/receive) interoperability characters. Let the set of interoperability character states be given as absence/presence states $C = \{0,1\}$.

$$X = \left\{ \begin{matrix} \left\{ \begin{matrix} Comm.EM(T), Detect.EM.Radar(T), Attack.EM.Jam(T), \\ Attack.KM.Ground(T), Attack.KM.Air(T) \end{matrix} \right\}, \\ \left\{ \begin{matrix} Comm.EM(R), Detect.EM.Radar(R), Attack.EM.Jam(R), \\ Attack.KM.Ground(R), Attack.KM.Air(R) \end{matrix} \right\} \end{matrix} \right\} \tag{29}$$

Assuming no time, space, or other constraints (e.g., IADS radar has unlimited reach, MEJ jams continuously regardless of position, etc.) then $S$ is instantiated as $\Sigma$ (30).

$$\Sigma = \left[\Sigma_T \mid \Sigma_R\right] = \left[\begin{array}{ccccc|ccccc} 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{array}\right] \tag{30}$$

Using $I = Sim_{Bin}$ as the interoperability function, and assuming no self-interoperation, the interoperability measurement $M$ is given by (31).

$$M = \left[\begin{array}{ccccccc} & PSP & MEJ & IADS & ISR & HB & TGT \\ PSP & 0 & \frac{2}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} \\ MEJ & \frac{2}{5} & 0 & \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ IADS & \frac{2}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ ISR & \frac{1}{5} & \frac{1}{5} & 0 & 0 & \frac{1}{5} & 0 \\ HB & \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ TGT & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right] \tag{31}$$

The interoperability measurement $M$ shows the direct, contextual interoperability (both collaborative and confrontational) of all system pairs in $S$. The average interoperability of $S$ is $\bar{M} = 0.1\bar{3}$. Applying the Interoperability Impact on Operational Effectiveness axiom, the results in Table 20 show that while some operational advantage is enjoyed (e.g., $PSP$ should be effective in attacking the $TGT$ and the $MEJ$ should be effective in jamming the $IADS$), the sufficient condition for operational effectiveness is not met. However, the model raises some questions. For example, does the $PSP$ always need to have operational advantage over the $IADS$? Likewise, does the $MEJ$ need to have operational advantage over the $TGT$? Similar questions can be asked for the $(ISR, IADS)$ and $(ISR, TGT)$ pairs. And most likely $HB$ requires no direct operational advantage over any enemy system. Hence a time-variant interoperability measurement is indicated. For each time period, systems are instantiated according to operational and other constraints associated with that time period. Additionally, the interoperability measurement taken in each time period is the constrained upper bound for that period because each system is instantiated by character states which represent the best the system can and is expected to do in that time period.

Table 20. Precision strike static model interoperability analysis

| Blue-Red System Pair | Analysis | $O_B > O_R$ |
|---|---|---|
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 1/5 < I(IADS, PSP) = 2/5 \rightarrow O_B \le O_R$ | No |
| $PSP \leftrightarrow TGT$ | $I(PSP, TGT) = 1/5 > I(TGT, PSP) = 0 \rightarrow O_B > O_R$ | Yes |
| $MEJ \leftrightarrow IADS$ | $I(MEJ, IADS) = 2/5 > I(IADS, MEJ) = 1/5 \rightarrow O_B > O_R$ | Yes |
| $MEJ \leftrightarrow TGT$ | $I(MEJ, TGT) = 0 = I(TGT, MEJ) \rightarrow O_B \le O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 0 < I(IADS, ISR) = 1/5 \rightarrow O_B \le O_R$ | No |
| $ISR \leftrightarrow TGT$ | $I(ISR, TGT) = 0 = I(TGT, ISR) \rightarrow O_B \le O_R$ | No |
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 0 = I(IADS, HB) \rightarrow O_B \le O_R$ | No |
| $HB \leftrightarrow TGT$ | $I(HB, TGT) = 0 = I(TGT, HB) \rightarrow O_B \le O_R$ | No |

### 4.4.2 Time Variant Interoperability Model

Let $S, X, C$ remain unchanged from the static model and modify the system instantiation $\Sigma$ for the four time periods described in Figure 10. For each time period, the modifications to $\Sigma$ are changes to the states of the interoperability characters which describe exactly what the systems are expected to do in that time period.

#### 4.4.2.1 Prior to Crossing the FEBA ( $t_0$ )

At time $t_0$ , all friendly (blue) systems are safe on their own side of the FEBA. Let $\Sigma_{t_0}$ be given (32) with the assumptions of Table 21. In this time period it is appropriate to assume that only the $ISR$ system should have operational advantage over the adversary (red) systems.

$$\Sigma_{t_0} = \left[\begin{array}{ccccc|ccccc} 1 & 0^a & 0 & 0^b & 0 & 1 & 0^c & 0 & 0 & 0^d \\ 1 & 0^e & 0^f & 0 & 0 & 1 & 0^g & 0 & 0 & 0^h \\ 0 & 1 & 0 & 0 & 0^i & 0 & 0^j & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0^k & 0 \end{array}\right] \tag{32}$$

Table 21. Precision strike $t_0$ assumptions

| |
|---|
| a) PSP not detectable by radar until $t_1$ at the soonest |
| b) PSP can't kinematically attack until $t_2$ |
| c) see a) |
| d) PSP not susceptible to missile attack until $t_2$ |
| e) MEJ not detectable by radar until $t_1$ at the soonest |
| f) MEJ doesn't jam until $t_1$ |
| g) see e) |
| h) MEJ not susceptible to missile attack until $t_2$ |
| i) IADS has nothing to attack until $t_1$ |
| j) IADS can't detect anything until $t_1$ at the soonest |
| k) TGT can't be kinematically attacked until $t_2$ |

Using $I = Sim_{Bin}$ as the interoperability function, an interoperability measurement at $t_0$ is obtained (33). Average interoperability of $S$ at $t_0$ is $\bar{M}_{t_0} = 0.07\overline{2}$ and an interoperability analysis follows in Table 22. The analysis shows that no friendly (blue) systems enjoy operational advantage over adversary (red) systems in the first phase of the mission. This is only worrisome in one point, the $ISR$ system is less interoperable with the $IADS$ than vice versa. In other words, the $ISR$ system may not be able to accurately detect the threat for the $PSP$. All other system pairs are achieving desired levels of interoperability (i.e., their interoperations are not required until later time periods).

$$M_{t_0} = \begin{array}{cc} & \begin{array}{cccccc} PSP & MEJ & IADS & ISR & HB & TGT \end{array} \\ \begin{array}{c} PSP \\ MEJ \\ IADS \\ ISR \\ HB \\ TGT \end{array} & \begin{bmatrix} 0 & \frac{1}{5} & 0 & \frac{1}{5} & \frac{1}{5} & 0 \\ \frac{1}{5} & 0 & 0 & \frac{1}{5} & \frac{1}{5} & 0 \\ 0 & 0 & 0 & \frac{1}{5} & 0 & 0 \\ \frac{1}{5} & \frac{1}{5} & 0 & 0 & \frac{1}{5} & 0 \\ \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array} \tag{33}$$

Table 22. Precision strike interoperability analysis ($t_0$)

| **Blue-Red System Pair** | **Analysis** | $O_B > O_R$ |
|---|---|---|
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 0 = I(IADS, PSP) \to O_B \le O_R$ | No |
| $PSP \leftrightarrow TGT$ | $I(PSP, TGT) = 0 = I(TGT, PSP) \to O_B \le O_R$ | No |
| $MEJ \leftrightarrow IADS$ | $I(MEJ, IADS) = 0 = I(IADS, MEJ) \to O_B \le O_R$ | No |
| $MEJ \leftrightarrow TGT$ | $I(MEJ, TGT) = 0 = I(TGT, MEJ) \to O_B \le O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 0 < I(IADS, ISR) = 1/5 \to O_B \le O_R$ | No |
| $ISR \leftrightarrow TGT$ | $I(ISR, TGT) = 0 = I(TGT, ISR) \to O_B \le O_R$ | No |
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 0 = I(IADS, HB) \to O_B \le O_R$ | No |
| $HB \leftrightarrow TGT$ | $I(HB, TGT) = 0 = I(TGT, HB) \to O_B \le O_R$ | No |

#### 4.4.2.2 Prior to Entering the MEZ ($t_1$)

At time $t_1$, the $PSP$ and $MEJ$ have crossed the FEBA and have entered enemy territory. Let $\Sigma_{t_1}$ be given (34) constrained by the assumptions of Table 23. In this time period, it is appropriate to assume that the $ISR$ and $MEJ$ systems should have operational advantage over the adversary (red) systems. Any adversary (red) system operational advantage over the $PSP$ system can be ignored as the $PSP$ system is neither in range to attack the $TGT$, nor within the range of $IADS$ defensive counter-air attack.

$$\Sigma_{t_1} = \left[\begin{array}{ccccc|ccccc} 1 & 1^a & 0 & 0^b & 0 & 1 & 1^c & 0 & 0 & 0^d \\ 1 & 1^e & 1^f & 0 & 0 & 1 & 1^g & 0 & 0 & 0^h \\ 0 & 1 & 0 & 0 & 0 & 0 & 1^i & 1^j & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0^k & 0 \end{array}\right] \tag{34}$$

Table 23. Precision strike $t_1$ assumptions

| |
|---|
| a) PSP has small, but finite chance of reflecting IADS radar signal |
| b) PSP can't kinematically attack until $t_2$ |
| c) PSP has small, but finite chance of being hit by IADS radar signal |
| d) PSP still outside MEZ |
| e) MEJ has small, but finite chance of reflecting IADS radar signal |
| f) MEJ turns on jamming in $t_1$ |
| g) MEJ has small, but finite chance of being hit by IADS radar signal |
| h) MEJ not susceptible to missile attack until $t_2$ |
| i) IADS has small, but finite chance of detecting a target |
| j) IADS can be jammed |
| k) TGT can't be kinematically attacked until $t_2$ |

Using $I = Sim_{Bin}$ as the interoperability function, an interoperability measurement at $t_1$ is obtained (35). Average interoperability of $S$ increased during $t_1$ to $\overline{M}_{t_1} = 0.1\overline{2}$ largely due to more system interoperations occurring during this time period than in the previous period. An interoperability analysis follows in Table 24. The $ISR$ system's lack of operational advantage over the $IADS$ system remains unchanged, however, in $t_1$, the $MEJ$ is beginning to disrupt the $IADS$ system's ability to counter the inbound $PSP$ (highlighted in the table).

$$M_{t_1} = \begin{array}{c} \\ PSP \\ MEJ \\ IADS \\ ISR \\ HB \\ TGT \end{array} \begin{bmatrix} PSP & MEJ & IADS & ISR & HB & TGT \\ 0 & \frac{2}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ \frac{2}{5} & 0 & \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ \frac{1}{5} & \frac{1}{5} & 0 & 0 & \frac{1}{5} & 0 \\ \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{35}$$

Table 24. Precision strike interoperability analysis ($t_1$)

| **Blue-Red System Pair** | **Analysis** | $O_B > O_R$ |
|---|---|---|
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 1/5 = I(IADS, PSP) \rightarrow O_B \leq O_R$ | No |
| $PSP \leftrightarrow TGT$ | $I(PSP, TGT) = 0 = I(TGT, PSP) \rightarrow O_B \leq O_R$ | No |
| $MEJ \leftrightarrow IADS$ | $I(MEJ, IADS) = 2/5 > I(IADS, MEJ) = 1/5 \rightarrow O_B > O_R$ | Yes |
| $MEJ \leftrightarrow TGT$ | $I(MEJ, TGT) = 0 = I(TGT, MEJ) \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 0 < I(IADS, ISR) = 1/5 \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow TGT$ | $I(ISR, TGT) = 0 = I(TGT, ISR) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 0 = I(IADS, HB) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow TGT$ | $I(HB, TGT) = 0 = I(TGT, HB) \rightarrow O_B \leq O_R$ | No |

#### 4.4.2.3 Within the MEZ ($t_2$)

At time $t_2$, the $PSP$ is within the MEZ. Let $\Sigma_{t_2}$ be given (36) using the assumptions in Table 25. During this key time period, it is highly desired that all friendly (blue) systems (except $HB$) have operational advantage over the adversary (red) systems as the $PSP$ is within the MEZ (i.e., vulnerable to defensive counter-air attack).

Additionally, success of the mission is contingent upon the friendly (blue) force maintaining operational advantage over the adversary (red) force in this time period.

$$\Sigma_{t_2} = \left[\begin{array}{ccccc|ccccc} 1 & 1 & 0 & 1^a & 0 & 1 & 1 & 0 & 0 & 1^b \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1^c & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1^d & 0 \end{array}\right] \tag{36}$$

Table 25. Precision strike $t_2$ assumptions

| |
|---|
| a) PSP can attack TGT<br>b) PSP vulnerable to kinematic airborne attack<br>c) IADS can attack airborne targets<br>d) TGT vulnerable to kinematic ground attack |

Using $I = Sim_{Bin}$ as the interoperability function, the interoperability measurement at $t_2$ (37) shows that the average interoperability of $S$ increased slightly to $\overline{M}_{t_2} = 0.1\overline{3}$ during this critical phase of the mission indicating an increase in the number of interoperations (i.e., increased operational intensity). However, the continued lack of operational advantage of the $PSP$ over the $IADS$ in this time period is especially concerning in as the $PSP$ is within the MEZ and subject to attack. Hence, the $ISR$ system's continued inability to detect threats endangers the $PSP$ (i.e., a pop-up surface-to-air missile system may emerge, yet remain undetected by the $ISR$ system). Assuming the $PSP$ survives the $IADS$, however, the $PSP$ will likely be successful in destroying the $TGT$ as it possesses operational advantage over the $TGT$ in this time period.

$$M_{t_2} = \begin{array}{c|cccccc} & PSP & MEJ & IADS & ISR & HB & TGT \\ \hline PSP & 0 & \frac{2}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} \\ MEJ & \frac{2}{5} & 0 & \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ IADS & \frac{2}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ ISR & \frac{1}{5} & \frac{1}{5} & 0 & 0 & \frac{1}{5} & 0 \\ HB & \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ TGT & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \tag{37}$$

Table 26. Precision strike interoperability analysis ($t_2$)

| Blue-Red System Pair | Analysis | $O_B > O_R$ |
|---|---|---|
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 1/5 < I(IADS, PSP) = 2/5 \rightarrow O_B \leq O_R$ | No |
| $PSP \leftrightarrow TGT$ | $I(PSP, TGT) = 1/5 > I(TGT, PSP) = 0 \rightarrow O_B > O_R$ | Yes |
| $MEJ \leftrightarrow IADS$ | $I(MEJ, IADS) = 2/5 > I(IADS, MEJ) = 1/5 \rightarrow O_B > O_R$ | Yes |
| $MEJ \leftrightarrow TGT$ | $I(MEJ, TGT) = 0 = I(TGT, MEJ) \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 0 < I(IADS, ISR) = 1/5 \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow TGT$ | $I(ISR, TGT) = 0 = I(TGT, ISR) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 0 = I(IADS, HB) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow TGT$ | $I(HB, TGT) = 0 = I(TGT, HB) \rightarrow O_B \leq O_R$ | No |

#### 4.4.2.4 Returning to Base ($t_3$)

During the final time period, $t_3$, the target has been attacked and the $PSP$ and $MEJ$ are returning to base and are out-of-range of the $IADS$ system. The $ISR$ system is still on-orbit ready for the next mission and the $IADS$ system was not attacked, so it is still functioning. Let $\Sigma_{t_3}$ be given by (38) assuming the MEJ stops jamming in $t_3$ (a). In this final time period, it is appropriate to assume that only the $ISR$ system should maintain operational advantage over the adversary (red) systems (the $IADS$ system in particular) as it is the only aircraft remaining on-station (onstensibly to support the next mission).

$$\Sigma_{t_3} = \left[\begin{array}{ccccc|ccccc} 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0^a & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right] \tag{38}$$

Using $I = Sim_{Bin}$ as the interoperability function, an interoperability measurement at $t_3$ is obtained (39) with an average interoperability of $S$ of $\bar{M}_{t_3} = 0.11\overline{6}$. By design, during this final phase of the mission, no friendly (blue) system has operational advantage over the adversary (red) systems. Table 27 shows, however, that the $PSP$ and $IADS$ systems appear to be at a standoff, i.e. $I\left(PSP, IADS\right) = 1/5 = I\left(IADS, PSP\right)$. A review of which interoperability character state caused the measure to be non-zero reveals that the $PSP$ system can still be detected by the $IADS$ system. However, the $PSP$ is outside the MEZ, so, while it can still be detected, it is safe from an $IADS$ attack. In other words, the $PSP$ makes no effort to hide itself from detection since it can't be attacked anyway. Similar logic applies to the $MEJ$.

$$M_{t_3} = \left[\begin{array}{ccccccc} & PSP & MEJ & IADS & ISR & HB & TGT \\ PSP & 0 & \frac{2}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ MEJ & \frac{2}{5} & 0 & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & 0 \\ IADS & \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ ISR & \frac{1}{5} & \frac{1}{5} & 0 & 0 & \frac{1}{5} & 0 \\ HB & \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{5} & 0 & 0 \\ TGT & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right] \tag{39}$$

Table 27. Precision strike interoperability analysis ($t_3$)

| Blue-Red System Pair | Analysis | $O_B > O_R$ |
|---|---|---|
| $PSP \leftrightarrow IADS$ | $I(PSP, IADS) = 1/5 = I(IADS, PSP) \rightarrow O_B \leq O_R$ | No |
| $PSP \leftrightarrow TGT$ | $I(PSP, TGT) = 0 = I(TGT, PSP) \rightarrow O_B \leq O_R$ | No |
| $MEJ \leftrightarrow IADS$ | $I(MEJ, IADS) = 1/5 = I(IADS, MEJ) \rightarrow O_B \leq O_R$ | No |
| $MEJ \leftrightarrow TGT$ | $I(MEJ, TGT) = 0 = I(TGT, MEJ) \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow IADS$ | $I(ISR, IADS) = 0 < I(IADS, ISR) = 1/5 \rightarrow O_B \leq O_R$ | No |
| $ISR \leftrightarrow TGT$ | $I(ISR, TGT) = 0 = I(TGT, ISR) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow IADS$ | $I(HB, IADS) = 0 = I(IADS, HB) \rightarrow O_B \leq O_R$ | No |
| $HB \leftrightarrow TGT$ | $I(HB, TGT) = 0 = I(TGT, HB) \rightarrow O_B \leq O_R$ | No |

#### 4.4.2.5 Precision Strike Conclusions

An important conclusion can be made as a result of the analysis in previous sections—although the sufficiency condition given by the Interoperability Impact on Operational Effectiveness axiom was relaxed in each mission time period by neglecting some interoperations and demanding others critical to that time period, the operational effectiveness concerns listed in Table 28 were apparent in each mission time period. Specifically, the lack of $ISR$ operational advantage over the $IADS$ throughout all time periods combined with the $IADS$ operational advantage over the $PSP$ during $t_2$ when the $TGT$ is to be attacked indicates that the mission could likely not be successful. Finally, a minor conclusion that can be drawn that because the $HB$ system's only role is to launch the $PSP$ and $MEJ$ aircraft, once it successfully does so, it can be neglected throughout the remainder of the analysis.

Table 28 Precision strike operational effectiveness concerns

| Time Period | Operational Effectiveness Concern |
|---|---|
| $t_0$ | *ISR* can't clearly detect *IADS* |
| $t_1$ | *ISR* can't clearly detect *IADS*<br>*IADS* can detect the inbound *PSP* |
| $t_2$ | *IADS* has operational effectiveness over the *PSP* which is in-range of the *IADS*<br>*ISR* can't clearly detect *IADS* |
| $t_3$ | None |

The operational effectiveness concerns listed in Table 28 can possibly be alleviated by improving the *ISR* detection capability (i.e., increasing its confrontational interoperability) or by decreasing the *PSP*'s detectability by either adding stealth or improving the *MEJ*'s jamming ability. Figure 12 shows the change in the directional interoperability of each friendly (blue) system with each adversary (red) system over time and Figure 13 shows the change in average confrontational interoperability (i.e., friendly (blue)-to-adversary (red) vs. adversary (red)-to-friendly (blue) interoperability) with time.

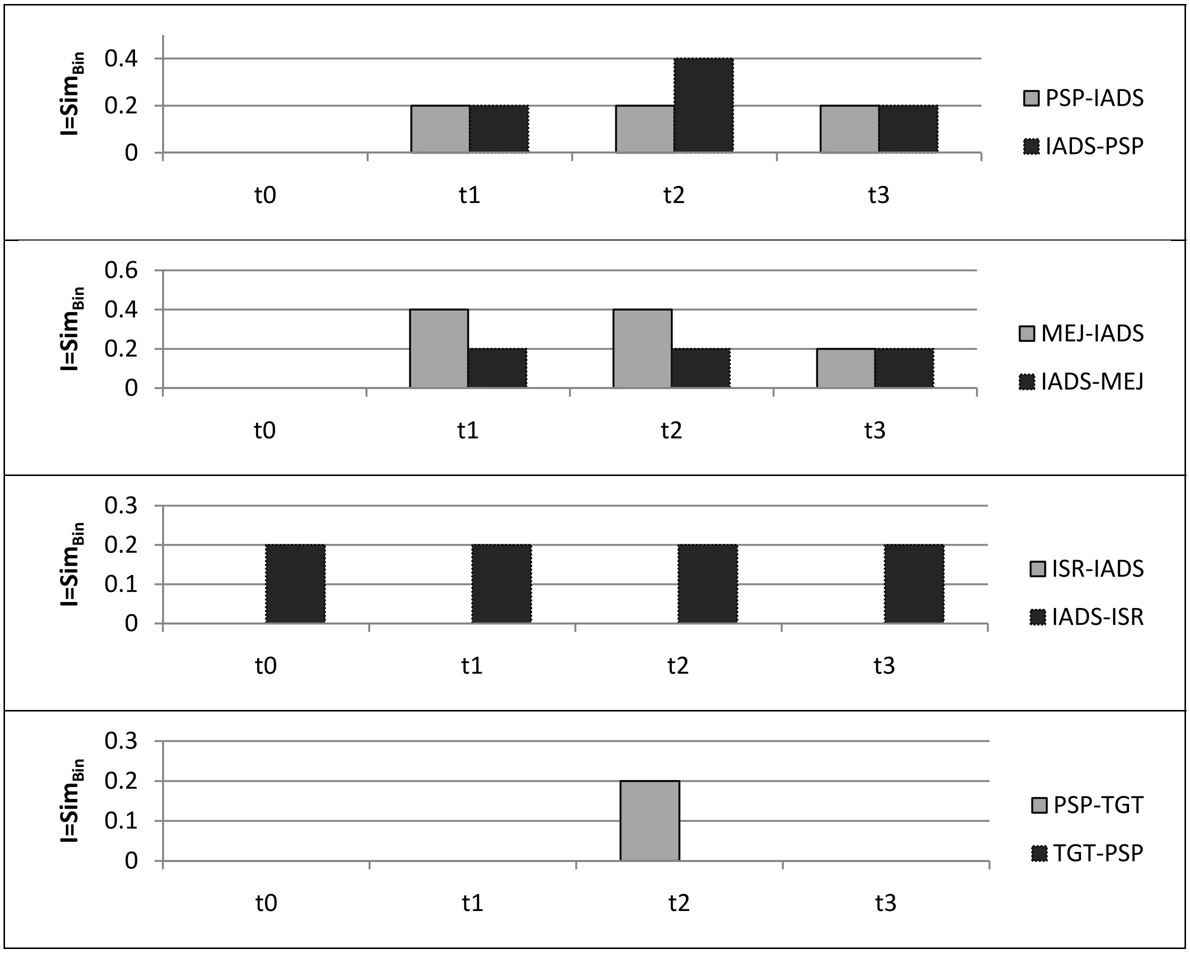



Figure 12 Precision strike blue systems directional interoperability with red systems

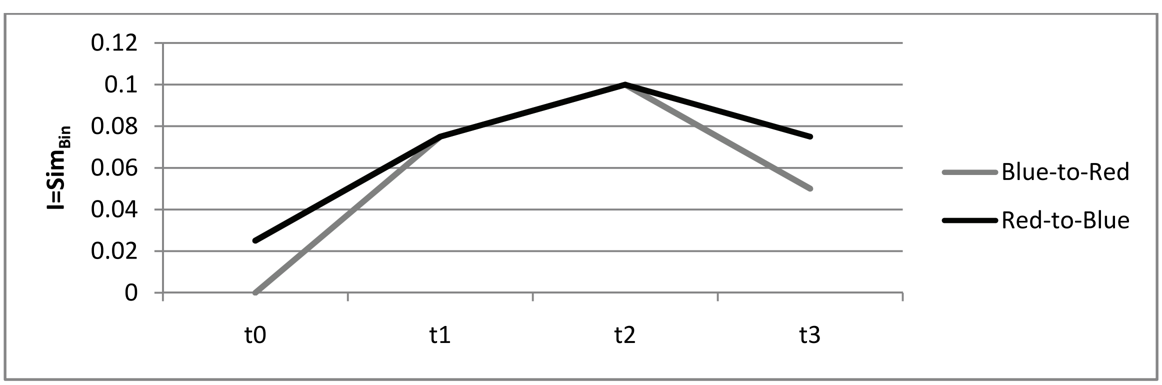



Figure 13 Precision strike average interoperability versus time

## 4.5 Summary

In this chapter, three applications were given—Coalition Interoperability, Suppression of Enemy Air Defenses (SEAD), and Precision Strike. In the Coalition Interoperability application, it was hypothesized and shown that maturity model (leveling) interoperability measurement methods are a special case of the more general method given in Chapter 3. Specifically, it was shown that attributes of models such as LISI and OIM can be used as interoperability characters and LISI and OIM levels can be equated to character states. The SEAD application further demonstrated the interoperability measurement method of Chapter 3 and illustrated that the Interoperability Impact on Operational Effectiveness axiom can be used to relate interoperability to the operational effectiveness of a confrontational operational process. The resultant interoperability measurement can be used to identify areas for system upgrade or for doctrine, tactics, techniques, or procedures change. Finally, the Precision Strike application further exemplified the sufficient conditions given by the Interoperability Impact on Operational Effectiveness and Operational Advantage axioms and showed how they can be relaxed within the bounds of operational and time constraints.

# 5. Conclusion

*Everything we do…we do with an eye toward jointness and interoperability.*
*—K. Krieg, recent USD(AT&L)*

## 5.1 Conclusions of Research

Measuring interoperability has long been considered unquantifiable because of its complex nature. (Kasunic & Anderson, 2004) While interoperability has been defined and described, it is multifaceted and permeates many disciplines in many ways. In fact, it is reasonable to assume that interoperations occur in all human endeavors. Previous approaches to measuring or describing interoperability relied upon problem decomposition and several researchers designed limited methods (Chapter 2) of measuring specific types of interoperations of certain types of entities. The result was an eclectic set of somewhat related models useful within limited spheres. While the problem decomposition method was helpful in the short term for certain applications, it prevented the creation of a general interoperability measurement method because it fractured "interoperability thinking" into compartments. The answer to the problem could not be found by creating "a set of compatible models that collectively address all the dimensions of interoperability" (Morris, et. al, 2004:12) because the set would never be complete, but by looking at interoperability holistically, generally, and fundamentally and then describing a flexible method. Such a method was proposed in Chapter 3—a method which accommodates all types of systems and interoperations, produces a quantitative interoperability measurement as realistic and precise as desired, and is limited only by the desires and attentiveness of those who will use it.

## 5.2 Recommendations for Application

Chapter 1, Table 4 lists approximately fifty applications of the interoperability measurement method presented in Chapter 3. The list is small subset of a complete list, containing military applications extracted from only six DoD publications. While some of the applications in Table 4 pertain to technical system interoperability, many concern non-technical interoperability or cross-domain (i.e., mixed system) interoperability. These three areas are ripe for application of the method given in Chapter 3. Additionally, problems which have not traditionally been viewed as interoperability related can also be analyzed in a new way with the method of this dissertation. Discussion follows.

### 5.2.1 Technical Interoperability

With some exceptions, historically interoperability has largely been associated with technical systems. It is expected that this focus will remain into the foreseeable future because of the importance of technical interoperability (both collaborative and confrontational) to military concepts such as Network Centric Warfare, Enterprise Integration, and Warfighting Transformation. The need to analyze technical interoperability will not diminish although there will be an increased emphasis on viewing technical interoperability within the context of operational art. (Alberts, et. al., 2000) This interest in interoperability constrained by operations endears itself to the method of Chapter 3. Previous interoperability assessments, such as the LISI profiles formerly required by CJCSI 6212.01C (2003) can now be repeated in the context of the operational process in which the systems were designed to function and the measurement can be made with more fidelity. Additionally, technical interoperability measurements for new systems can be made which don't rely solely upon technical standards, but upon interoperability characters associated with the operational processes of newer concepts such as Systems-of-Systems Integration.

### 5.2.2 Non-technical Interoperability

One of the most important types of non-technical interoperability is coalition interoperability. The United States often fights as a coalition and because not all of our allies possess the same advanced equipment that the United States military does, interoperability of doctrine, procedures, and culture rise in importance relative to technical interoperability. These non-technical types of interoperability facilitate integration and synchronization of coalition forces. JP 3-16, Multinational Operations states that "coalition partners using very different national doctrines will obviously have problems harmonizing their efforts, even if they enjoy a high degree of technical interoperability." (2007:III-8) The method in Chapter 3 can be used to predict the impact of language and cultural differences among coalition forces, to innovate compatible tactics, techniques, and procedures, to measure the usefulness of liaison officers, or to troubleshoot coalition operations problems. A sample of this type of analysis was given in Section 4.2.

### 5.2.3 Cross-domain Interoperability

Power lies in the ability of the interoperability method in Chapter 3 to measure cross domain interoperability, such as investigating how well non-technical systems interoperate with technical ones. For example, when engineers design a human-computer interface (HCI), they are trying to optimize the interoperability of the human and the machine. Asking the question, "how efficiently are the flight controls laid out?" is equivalent to saying "how interoperable is the pilot with the airplane?" The popular human factors engineering terms, "designing for human use" and "optimizing working conditions" (Sanders & McCormick, 1987:5) are statements of a desire for non-technical-to-technical interoperability. Because the method of Chapter 3 admits a set of systems of any type, this type of mixed-system interoperability measurement is now possible.

### 5.2.4 Non-traditional Interoperability

Applying the method of Chapter 3, a host of problems not previously viewed as interoperability related can now be looked at as such. This means that many old problems can be solved in a new way, possibly lending insight or providing a means of reporting progress not previously available. For example, when studying the relations between two countries, often the disciplines of history, political science, diplomacy, business, and economics provide the tools for the analysis. If interoperability is a relationship between two systems, then two countries can be modeled as systems, and instantiated with characters representing all the ways in which the two countries interact. The degree of these interactions can also be captured. Thus, a measure of the interoperability of the two countries is a measure of the quality of their relationship. If separate interoperability measurements are taken with respect to cultural interoperations, business interoperations, technical interoperations, and others, then a portfolio is created which describes the full spectrum of relations between the two countries. The resulting set of measurements can be used to drive policy, motivate trade, encourage cultural interchange, or encourage cooperation in technical development. The method of Chapter 3 can be used to perform "what if" analyses to predict the efficiency, cost, or other ramifications of diplomatic, economic, or military policy changes.

## 5.3 Recommendation for Future Research

As a general method for interoperability measurement, this research might be the impetus for other research projects. Two topics immediately present themselves. First, while this research focused on direct interoperability measurement, many important interoperations occur through a translator system (i.e., indirect interoperability). Although a preliminary method of measuring the indirect interoperability of systems was given by Ford, et. al., (2007a, 2008b) this method is not complete and can be further extended. Second, while this research related confrontational interoperability (i.e., friendly (blue)-to-adversary (red) system interoperability) with operational effectiveness, no analogue was given which associates the change in friendly (blue)-to-friendly (blue) system interoperability with changes in operational effectiveness. Each of these future research areas is discussed in detail in subsequent sections.

### 5.3.1 Indirect Interoperability Measurement

The method in Chapter 3 measures the direct interoperation of systems, however an enhancement to the method could possibly be made which supports measuring the indirect interoperability of systems. Indirect interoperation infers that a pair of systems cannot interoperate without the assistance of another system. For example, $m_{1,2}$ is the measure of the direct interoperability of $s_1$ and $s_2$. Indirect interoperation, on the other hand, implies an intermediary system. In other words, given $S = \{s_1, s_2, s_3\}$, if $m_{1,3} = 0$ but $m_{1,2} > 0$ and $m_{2,3} > 0$ then it may be possible for $s_1$ and $s_3$ to interoperate indirectly (i.e., influence each other) via $s_2$ which is called a translator system.

Alberts & Hayes stated this concept in a different fashion, noting three types of interoperation—common language, direct translation, and translation via reference language. (2003) The first type, common language interoperation, equates to the term direct interoperation in this research. Unfortunately, Alberts & Hayes used the oxymoronic term, direct translation, to refer to an interoperation that is not direct, but in-direct with an intermediary providing translation. Finally, their third type, translation via reference language, is just a special case of the first. Alberts & Hayes used a language example in their text to illustrate the three types noting that common language means that two people can converse in the same language. Direct translation was exemplified as a group of English speakers communicating with a group of French speakers via a translator versed in both languages. Finally, translation via reference language was illustrated as two groups speaking different languages who communicate with each other by speaking a third (reference) language.

Being able to measure the indirect interoperation of systems is important because something done by one system may or may not impact its adjacent neighbors, but may have a drastic effect on a "distant" system. For example, an e-mail from one person to another might result in no action, but the same e-mail forwarded from the second person to a third could cause an uproar. In other words, the first person in-directly interoperated with the third, causing an effect. Similarly, a ground system interoperating with the Global Information Grid (GIG) has the potential to indirectly interoperate with the myriad of space- and airborne systems also networked to the GIG. This is especially true if the ground-based system is a service provider (i.e., a weather, geospatial, or intelligence providing system). Thus, indirect interoperability is measured to analyze distant effects as opposed to adjacent effects. For example, indirect interoperability measurements might help determine the impact of US domestic policy on foreign countries or it could be used to measure the impact that a mix of legacy systems and technologically advanced systems have on each other as documents are constantly translated between them. The ability to measure indirect interoperability facilitates effects-based action where one system impacts distant systems.

Ford, et al., addressed indirect interoperability in their i-Score papers. (2007a; 2008b) They described a single measure of the interoperability of a set of systems implementing one sequential pass through an operational process. Each system was viewed as a translator and was assigned an interoperability "spin" which indicated how it interacted with the succeeding system in the process (i.e., no translation needed, human translation needed, or machine translation needed). The overall interoperability score was impacted each time a translation (interoperation) took place. It was noted that each time an interoperation occurs, there is a potential loss (change) in physical, syntactic, or semantic structure of the original input to the process. This loss only gets magnified each time the original input is translated. Hence, translations occurring early in the process have more potential possibility for change than those occurring late in the process. To account for this, each translation was given a case-specific penalty usually resulting from a performance overlay. In essence, the i-Score measurement was a measure of the interoperability of the first system in the sequence with the last. More work remains to be done in order to define a general method of measuring indirect interoperability.

### 5.3.2 Collaborative Interoperability Impact on Operational Effectiveness

Section 3.6 provided an axiom which relates the impact of interoperability on operational effectiveness. However, the axiom only applies to confrontational (friendly (blue)-to-adversary (red) system) interoperability. In other words, it relates an improvement in friendly (blue)-to-adversary (red) directional interoperability $I(\sigma_B, \sigma_R)$ to an improvement in friendly (blue) operational effectiveness $O_B$. But the question remains as to the impact of collaborative (i.e., friendly (blue)-to-friendly (blue)) interoperability improvements on operational effectiveness. To date, there is no analogue to the Interoperability Impact on Operational Effectiveness axiom which relates a change in collaborative interoperability to a change in friendly (blue) operational effectiveness.

It is reasonable to assume that if collaborative system interoperability $I(\sigma_B, \sigma_B)$ improves, that $O_B$ will usually also increase. A recognized researcher in the area of network centric warfare, John Garstka, speaking specifically on interoperations in which information is passed, wrote that there is "a strong correlation between information sharing…and significantly increased combat power." (2000:1) He further states that while this is intuitive to the warfighter, quantifying the relationship is "an analytical challenge of the first order." (Ibid:3) Hence, he resorts to providing empirically observed evidence of the relationship between a particular network centric improvement and increased combat power as gleaned from experiments, exercises, demonstrations, and real-life conflicts to justify his assertion. (Ibid) Interestingly, Keenan wrote a decade earlier that the contribution of interoperability initiatives on battlefield effectiveness can be assessed quantitatively. (1988) He gave six measures of effectiveness (functional area performance, personnel requirements, systems cost, supporting-to-supported ratio, reconstitution capability, and satisfaction of CINC's priorities), which, when properly measured and weighted, can be used to generate an assessment of improvement in battlefield effectiveness. (Ibid) Unfortunately, Keenan's six measures cannot be shown to be a complete, nor a correct list, making his resulting interoperability impact assessment a subjective measure.

While no simple and complete relationship between collaborative interoperability and operational effectiveness has yet been published, such an axiom could be on the horizon. The key to discovering it likely lies in the area of indirect interoperability measurement discussed in the previous section. While a change in the interoperation of friendly (blue) systems has no direct impact on the directional confrontational interoperability of friendly (blue)-to-adversary (red) systems, it most definitely has an indirect impact. For example, Garstka noted that F-15Cs equipped with the Joint Tactical Information Distribution System (JTIDS) experienced a kill ratio 2.5 times higher than that of non-JTIDS equipped F-15Cs. (2000) In other words, an improvement in collaborative (F-15C-to-E-3 and F-15C-to-F-15C) interoperability indirectly increased confrontational (F-15C-to-Target) interoperability, resulting in an improvement in operational effectiveness. A rigorous method of measuring indirect interoperability of systems might result in an axiom describing the impact of collaborative interoperability on operational effectiveness.

While early proponents of network centric warfare and other interoperability improvement initiatives noted empirical evidence of improved operational effectiveness resulting from interoperability improvements, other researchers have identified the problem of information overload (Toffler, 1970) and its effects. (Keller & Staelin, 1987) Noting that information-based interoperations are only a subset of the overall set of interoperations, the problem is extrapolated from the more specific term of information overload to the general term of interoperability overload. It is postulated that a future axiom relating collaborative interoperability to operational effectiveness will describe a relation similar to that graphed in Figure 14 which shows an initial operational benefit of increased collaborative interoperability followed by a decrease as interoperability overload sets in with an optimum in between.

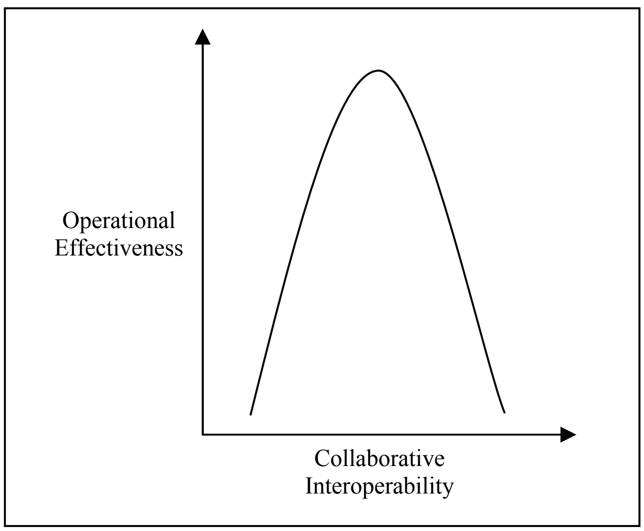



Figure 14. Hypothetical relationship of collaborative interoperability with operational effectiveness

## 5.4 Final Thoughts

The Department of Defense has been pursuing interoperability for decades. While some might argue that the pursuit has not been aggressive enough (GAO, 1987), interoperability of defense systems has most definitely improved. Whereas early goals reflected concerns about equipment commonality (i.e., NATO standard equipment), the focus eventually moved at the turn of the millennium to assessment of system-to-system interoperability via verification testing. (Hutchens, 2007) Architecures documented information exchange requirements which defined how systems interoperated with each other and the interoperations were described in the Interoperability Key Performance Parameter (I-KPP). (CJCSI 6212.01B, 2000) While the Department of Defense still relies upon certification testing, the newer Net-Ready KPP (NR-KPP) concept (CJCSI 6212.01C, 2003) emphasizes compliance with the Net-Centric Operations and Warfare Reference Model (NCOW-RM), the use of highly integrated architectures, the definition of interface profiles, and adherence to information assurance precepts to ensure systems are interoperable and born joint (i.e., network centric). (Hutchens, 2007)

In spite of all this progress, these efforts have been focused on qualitatively describing technical interoperability. The general method of this dissertation provides a means to finally quantitatively measure the interoperability of not only technical systems, but non-technical systems or mixed sets of systems. Because the method draws upon existing data already mandated by the Joint Capabilities Integration and Development System (JCIDS) (e.g., integrated architectures, interface profiles, operational processes, measures of effectiveness) it becomes an efficient extension to the current state-of-the-practice in interoperability assessment. The ability to put the interoperability measurement in the context of operations and determine the impact of system interoperability on those operations is an added bonus and it is hoped that the general method of measuring system interoperability presented in this research will greatly improve defense systems and military operations for years to come.

## A1. A Selection of Interoperability Definitions (adapted from Ford, et. al., 2007b)

| Origin | Definition | Source |
|---|---|---|
| DoD | The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together. | (DoDD 2010.6, 1977),<br>(DoDD 2010.6, 1980:Encl. 2, p. 2),<br>(Amanowicz & Gajewski, 1996:280),<br>(DoD 1998),<br>(Leite, 1998:3),<br>(Curts 1999:5.),<br>(JV2020, 2000:15),<br>(Clark & Moon, 2001:2),<br>(Fewell & Clark, 2003:2),<br>(Kasunic & Anderson, 2004: 2, 32),<br>(Morris, et al., 2004:3, 7) |
| Other | The ability of one system to receive and process intelligible information of mutual interest transmitted by another system. | (Kasunic & Anderson, 2004:32) |
| DoD | Electronic Interoperability. A special form of interoperability whereby two or more electronic equipments, especially communications equipments, can be linked together, usually through common interface characteristics and so operate the one to the other. | (DoDD 2010.6, 1980:Encl. 2, p. 2) |
| DoD | Logistic Interoperability. A form of interoperability whereby the service to be exchanged is assemblies, components, spares, or repair parts. Logistic interoperability will often be achieved by making such assemblies, components, spares, or repair parts interchangeable, but can sometimes be a capability less than interchangeability when a degradation of performance or some limitations are operationally acceptable. | (DoDD 2010.6, 1980:Encl. 2, p. 3) |
| Other | The effort required to couple one system with another. | (Kasunic & Anderson, 2004:32) |

| Origin | Definition | Source |
|---|---|---|
| Other | Interoperability means the ability of two or more parties, machine or human, to make a perfect exchange of content. Perfect means no perceptible distortions or unintended delays between content origin, processing and use. | (Poppel, 1987:1) |
| Standard | The ability of two or more systems or components to exchange information and to use the information that has been exchanged. | (Kasunic & Anderson, 2004:32), (Kosanke, 2005:2) |
| Other | Interoperability among components of large-scale, distributed systems is the ability to exchange services and data with one another. | (Heiler, 1995:1) |
| Other | The ability to communicate with peer systems and access their functionality. | (Vernadat, 1996), (Kosanke, 2005:2) |
| DoD | Technical Interoperability. The condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users. The degree of interoperability should be defined when referring to specific cases. | (DoD 1998), (Leite, 1998:3), (Morris, et. al., 2004:7-8), (JP 1-2, 2004:277) |
| DoD | JCS defines interoperability as the condition achieved between systems when information or services are exchanged directly and satisfactorily between the systems ad/or their users. | (Curts, 1999:9) |
| Standard | The ability of two or more systems of elements to exchange information and to use the information that has been exchanged. | (Morris, et. al., 2004:3) |
| Standard | The capability for units of equipment to work together to do useful functions. | (Morris, et. al., 2004:3) |
| Standard | The capability, promoted but not guaranteed by joint conformance with a given set of standards, that enables heterogeneous equipment, generally built by various vendors, to work together in a network environment. | (Morris et. al., 2004:7) |
| Standard | The ability of two or more systems or components to exchange information in a heterogeneous network and use that information. | (Morris, et. al., 2004:7) |

| Origin | Definition | Source |
|---|---|---|
| DoD | (1) Ability of information systems to communicate with each other and exchange information. (2) Conditions, achieved in varying levels, when information systems and/or their components can exchange information directly and satisfactorily among them. (3) The ability to operate software and exchange information in a heterogeneous network (i.e., one large network made up of several different local area networks). (4) Systems or programs capable of exchanging information and operating together effectively. | (USJFCOM, 2001:76), (Morris, et al., 2004:4) |
| DoD | Programmatic Interoperability. Programmatic interoperability encompasses the activities related to the management of one program in the context of another program. | (Levine, et. al., 2003:4) |
| DoD | Constructive Interoperability. Constructive interoperability addresses those activities related to construction and maintenance of one system in the context of another system. Constructive interoperability includes the common use of architecture, standards, data specifications, communication protocols, languages, and COTS products to build interoperable systems. | (Levine, et. al., 2003:5) |
| DoD | Operational Interoperability. Operational Interoperability refers to the activities related to the operation of a system in the context of other systems. These activities include: doctrine governing the way the system is used, conventions for how the user interprets information derived from interoperating systems (i.e., the semantics of interoperation), and strategies for training personnel in the use of interoperating systems. | (Levine, et. al., 2003:6) |
| DoD | The ability of systems to work together. | (Levine, et. al., 2003:26) |
| DoD | The ability of systems to exchange and use services. | (Levine, et. al., 2003:26) |
| DoD | The degree to which a set of communicating systems are (i) able to exchange specified state data, and (ii) operate on that state data according to specified, agreed to, operational semantics. | (Levine, et. al., 2003:26) |
| DoD | Ability to achieve “cooperation” is generally termed “interoperability.” | (Carney & Oberndorf, 2004:3) |
| DoD | The ability of one services' system to receive and process intelligible information of mutual interest transmitted by another service's system. | (Kasunic & Anderson, 2004:32) |

| Origin | Definition | Source |
|---|---|---|
| DoD | The ability of a set of communicating entities to (1) exchange specified state data and (2) operate on that state data according to specified, agreed-upon, operational semantics. | (Morris, et al., 2004:4) |
| Other | Ability of two or more devices to work together in one or more applications. | (Kosanke, 2005:4) |
| DoD | The ability to operate in synergy in the execution of assigned tasks. | (JP 1-02, 2008:277) |

## A2. A Selection of Interoperability Types

| Interoperability Type | Source |
|---|---|
| Application | (Kasunic & Anderson, 2004:34), (Kosanke, 2005:4) |
| Architecture | (Curts, 1999:10) |
| C4I | (Kasunic & Anderson, 2004:9) |
| Cities | (Kinder, 2002:18) |
| Coalition | (USJFCOM, 2001:48), (Fewell & Clark, 2003, p. 1) |
| Communications | (LaVean, 1980:1448), (Kasunic & Anderson, 2004:34) |
| Conceptual | (Carney & Oberndorf, 2004:18) |
| Connected | (DoD, 1998) |
| Constructive | (Levine, et. al., 2003:5), (Carney & Oberndorf, 2004:19), (Morris, et al., 2004:11) |
| Constructive | (Morris, et al., 2004:35) |
| Cultural | (Clark & Moon, 2001:2) |
| Data | (Curts, 1999:4), (USJFCOM, 2001:30), (Kasunic & Anderson, 2004:4, 7, 34) |
| Domain | (DoD, 1998) |
| Electronic | (DoDD 2010.6, 1980:Encl. 2, p. 2) |
| Enterprise | (DoD, 1998), (Kosanke, 2005: 8) |
| Flexible | (Clark & Moon, 2001:2) |
| Force | (Clark & Moon, 2001:1) |
| Functional | (DoD, 1998), (USJFCOM, 2001:22), (Clark, 2001:2) |
| Higher-layer | (Kasunic & Anderson, 2004:34) |
| Horizontal | (Kinder, 2002:27) |
| Information | (Curts, 1999:4) |
| Information Systems | (DoD, 1998) |
| Intra-organisational | (Kinder, 2002:23) |
| Isolated | (DoD, 1998) |
| Joint | (Leite, 1998:1), (USJFCOM, 2001: 49), (Kasunic & Anderson, 2004:13-14) |
| Joint Information | (Nutwell, 2000) |
| Logistics | (DoDD 2010.6, 1980:Encl. 2, p. 3) |
| Lower-layer | (Kasunic & Anderson, 2004:34) |
| Model | (Clark & Moon, 2001:1) |
| Multidatabase | (Litwin & Abdellatif, 1986:1) |

| | |
|---|---|
| Non-GIG | (USJFCOM, 2001:29) |
| Non-technological | (Clark & Moon, 2001:1) |
| Object Oriented | (Konstantas, 1993:i) |
| Operational | (Levine, et. al., 2003:6),<br>(Carney & Oberndorf, 2004:19),<br>(Kasunic & Anderson, 2004:2),<br>(Morris, et al., 2004:11) |
| Organizational | (Clark & Jones, 1999:1),<br>(Clark & Moon, 2001:1) |
| Peacetime | (LaVean, 1980:1450) |
| Planned | (Clark & Moon, 2001:3) |
| Plug-and-Play | (USJFCOM, 2001:47) |
| Procedure Oriented | (Konstantas, 1993:4) |
| Process | (Clark & Moon, 2001:2) |
| Product-to-Product | (Kasunic & Anderson, 2004:37) |
| Programmatic | (Levine, et. al., 2003:4),<br>(Carney & Oberndorf, 2004:19),<br>(Morris, et al., 2004:11) |
| Programmatic | (Morris, et al., 2004:33) |
| Public Administration | (Kinder, 2002:6) |
| Public Service | (Kinder, 2002:7) |
| Responsive | (Clark & Moon, 2001:2) |
| Secure-Voice | (USJFCOM, 2001: 33) |
| Semantic | (Heiler, 1995:1) |
| Specification Level | (Wileden, et. al., 1989:74) |
| System-of-Systems | (Morris et. al., 2004:Cover) |
| Systems | (LaVean, 1980:1449),<br>(Leite, 1998: 1),<br>(Curts, 1999: 3),<br>(USJFCOM, 2001:32),<br>(Clark & Moon, 2001: 2),<br>(Kasunic & Anderson, 2004: 1) |
| System-to-System | (Amanowicz & Gajewski, 1996:280),<br>(Kasunic & Anderson, 2004, p. 17) |
| Technical | (Clark & Jones, 19994),<br>(USJFCOM, 2001:22),<br>(Clark & Moon, 2001:1),<br>(Kinder, 2002:25),<br>(Carney & Oberndorf, 2004:16),<br>(Kasunic & Anderson, 2004:2) |
| Telecommunications | (LaVean, 1980:1449) |
| Total | (Curts, 1999:1) |
| Transitive | (Morris, et. al., 2004:28) |
| Vertical | (Kinder, 2002:27) |

## A3.Summary of Interoperability Measurement Models

Sixteen interoperability measurement models (Table 29) are surveyed in succeeding paragraphs with the main contributions of each model highlighted. Appendix A4 summarizes the models' measurement formats. The succeeding review and analysis is modified from Ford, et. al. (2007b). Some model nicknames (e.g., SoIM, QoIM, MCISI, and IAM) were not used by the model authors, but have been assigned by the author of this research for ease of reference.

Table 29 Interoperability measurement model publishers (adapted from Ford, et. al., 2007b)

| Publishing Organization | Model |
|---|---|
| Defense Information Systems Agency (DISA) | SoIM ('80) |
| MITRE Corporation | QoIM ('89)<br>LISI ('98) |
| Military University of Technology, Warsaw, Poland | MCISI ('96) |
| Joint Theater Air & Missile Def. Org. (JTAMDO) Contractor SIM | IAM ('98) |
| Australian Defence Science & Technology Organisation (DSTO) | OIM ('99)<br>OIAM ('05) |
| Joint Forces Cmd (JFCOM) Joint Forces Program Office (JFPO) | Stoplight ('02) |
| Old Dominion Univ. Virginia Modeling Analysis & Simulation Center (VMASC) | LCI ('03)<br>LCIM ('03) |
| North Atlantic Treaty Organization (NATO) | NMI ('03) |
| DoD Command and Control Research Program | NCW ('03) |
| Carnegie Mellon Software Engineering Institute (CMU-SEI) | SoSI ('04) |
| Defence Science & Technology Lab. (Dstl) Contractor, QinetiQ | NTI ('04) |
| Research Establishment for Applied Science (FGAN) | NID ('05) |
| Air Force Institute of Technology (AFIT) | i-Score ('07) |

### Spectrum of Interoperability Model (SoIM)

MAIN CONTRIBUTION: Interoperability can be measured in levels.

In 1980, LaVean acknowledged in the *IEEE Transactions on Communications* that inter-system interoperability was poor because there existed a "lack of a measure of interoperability by which to state goals for specific systems." (1980:1449) To combat this deficiency, he created a spectrum of interoperability model (SoIM). (Ibid:1448) He defined the two most important measures of interoperability (technical possibility and management/control possibility), assigned levels (Table 30), and stated that by "combining these two measures, it is possible to derive a spectrum of interoperability that permits cost-versus-benefits tradeoffs." (Ibid) Recognizing that the level of interoperability may be different for each service that pairs of systems provide to each other, he proposed a visualization method, called an interoperability matrix, which lists services on the rows of the matrix and levels of interoperability on the columns. He further proposed a current view and a "future" view of the interoperability matrix in order to show evolution of the systems over time. Thus, the purpose of SoIM was to provide a simple tool for program managers to assess current interoperability of their systems and services, to set goals for future interoperability, and to visualize the current and future states of interoperability. Although SoIM was groundbreaking and is possibly the earliest method for measuring interoperability, there is no further mention of his model after its original publication and it is unknown whether or not it was used by program managers to improve inter-system interoperability.

Table 30 SoIM levels of interoperability

| Level | Name | Technical Measure | Management/Control Measure |
|---|---|---|---|
| 1 | Separate Systems | 1 | 1 |
| 2 | Shared Resources | 1 | 2 |
| 3 | Gateways | 2 | 3 |
| 4 | Multiple Entry Points | 2 | 4 |
| 5 | Conformable/Compatible Systems | 3 | 4 |
| 6 | Completely Interoperable Systems | 3 | 5 |
| 7 | Same System | 4 | 6 |

## Quantification of Interoperability Methodology (QoIM)

MAIN CONTRIBUTION: Interoperability is correlated to measures of effectiveness.

In 1989, Mensh, Kite, and Darby published a method in the *Naval Engineer's Journal* called "The Quantification of Interoperability" (QoIM)  Working for MITRE Corp., they may have laid some of the groundwork for the well-known LISI model published by MITRE nine years later although they were never credited.  Mensh, et. al.'s approach to interoperability measurement is unique because they associated interoperability with measures of effectiveness (MOE).  Their goal was to assess interoperability issues for three mission areas: wide area surveillance (WAS), over-the-horizon targeting (OTH-T), and electronic warfare (EW) by quantifying seven interoperability components. (Mensh, et. al., 1989)  They stated that "interoperability of systems, units, or forces can be factored into a set of components that can quantify interoperability" (Ibid:251) and identified the seven components as media, languages, standards, requirements, environment, procedures, and human factors.  They specified an arbitrary MOE logic function for each component and used that logic function to create a truth table populated via discrete event simulation.  For example, the MOE logic function for the Language component was defined as "Message Correctness = Intelligibility and Manual Intervention & Error." (Ibid:255-256)  The truth table listed the binary MOE value (e.g., Message Correctness, Intelligibility, and Manual Intervention and Error) for various "significant events" which occurred during an exercise or simulation—the presence of zeros indicated lack of interoperability during certain component events and the presence of ones indicated that some level of interoperation occurred. (Ibid:254-255)

A final Interoperability Data Table was formed showing the truth table results for all seven interoperability components, which "illustrates the overall quantification of interoperability," and "for specific events it enables an evaluation of the interoperability of…systems in terms of the seven interoperability components…[and] corresponding…events," and finally, "having this type of table for two different…architectures enables a comparison of the relative goodness of each architecture." (Ibid:259) Although Mensh, et. al. state that their "methodology for quantifying interoperability is being pursued," they admit that "additional exercises will be required and are currently in the planning stages." (Ibid) Aside from one citation by Leite in 1998 (and revised paper in 2003), there are no further mentions or apparent use of this model beyond the original journal in which it was published.

**Military Communications and Information Systems Interoperability (MCISI)**

MAIN CONTRIBUTION: The distance between systems modeled as points in space indicates their interoperability.

In 1996, Amanowicz & Gajewski published an interoperability measurement model (MCISI) designed to model communications and information systems (CIS) interoperability mathematically. Noting that interoperability modeling combines operational requirements, CIS data, standards, interfaces and modeling facilities, they use a colored cube to visualize their model in which one axis is level of command, the second is CIS services, and the third is transmission medium. (Amanowicz & Gajewski, 1996) The color of the intersections is red, yellow, or green representing none, partial, or full interoperability of a specific service through a specific medium at a specified level of command. Amanowicz & Gajewski further describe a set of systems as points in multi-dimensional space with features of these systems as the coordinates of the points. Defining a normalized "distance" between two points as $d(A,B)$, they state that when $d(A,B)=0$ systems A and B achieve full interoperability and when $d(A,B)>1$, the system pair's interoperability decreases. (Ibid) They accommodate a set of systems by creating dendrite (a broken line which connects all points of a set) arrangements of the systems and state that the best arrangement is the one with the shortest dendrite length. MCISI was not institutionalized after its publication.

### Levels of Information System Interoperability (LISI) Model

MAIN CONTRIBUTION: Interoperability attributes of information systems.

LISI is the most prominent interoperability measurement model within the Department of Defense. It began development at the MITRE Corporation in 1993 and was published in 1998 by the C4ISR Architecture Working Group (AWG) co-chaired by the Joint Staff J6I and the Director, Architectures Directorate of the C4ISR Integration Support Activity (CISA) under the direction of OSD(ASD(C3I)). (DoD, 1998) The LISI report stated, "We lack a practical assessment process for determining the interoperability maturity level or 'metric' of a given system or system pair…The LISI Assessment Process, with its associated tool, system profiles, and data repository, fills these needs." (Ibid: ES-7) LISI is a system focused vice mission focused method applicable only to information systems.

While CJCSI 6212.01C, *Interoperability and Supportability of Information Technology and National Security Systems*, (2003) required program managers to ensure that they complied with LISI requirements, that mandate expired in the latest version, CJCSI 6212.01D. (2006) Although LISI was originally to be institutionalized in DoDD 4630.5, DoDI 4830.8, DoDI 5000.2, and DoDD 5000.1, this was never accomplished. (DoD, 1998) The Joint Staff maintained a repository of LISI profiles for acquisition programs for several years. (CJCSI 6212.01C, 2003)

Like SoIM, LISI describes levels of interoperability called maturity levels. Whereas SoIM has seven levels, LISI has five—Level 0 (Isolated), Level 1 (Connected), Level 2 (Functional), Level 3 (Domain), and Level 4 (Enterprise). However, LISI improves upon SoIM by giving four attributes of the levels described by the acronym PAID—Procedures, Applications, Infrastructure, and Data. The LISI Reference Model is shown in Figure 3. A web-based questionnaire is completed in order to generate the Interoperability Profile which contains information about a system for all four interoperability attributes. From the profile, an Interoperability Metric can be obtained which is a triplet of metric type (Generic, Expected, & Specific), Level (0…4), and Sub-level (a…z). The metric describes the level of interoperability for one system (generic) or a pair of systems (expected and specific). The generic metric is the best level of interoperability a single system is capable of whereas the expected metric describes the highest common level of interoperability for a system pair. The specific metric describes the highest common level of interoperability between two information systems across all PAID attributes. LISI has been reviewed and critiqued by many other researchers since its publication. Recent reviews have been written by Brownsword, et al. (2004), Carney & Oberndorf (2004), Clark & Jones (1999), Clark & Moon (2001), Kasunic & Anderson (2004), Morris, et al. (2004), and Tolk (2003), among others.

### Interoperability Assessment Methodology (IAM)

MAIN CONTRIBUTION: Attributes of interoperability.

Leite's Interoperability Assessment Methodology was initially published in the pProceedings of the 66th Military Operations Research Society (MORS) Symposium three months after LISI was published and was revised again in 1999 and 2003. It is unknown if the author was aware of the LISI effort, however he did reference Mensh, et. al.'s QoIM in his paper. Like QoIM, IAM is based upon the idea of "measurement and quantification of a set of interoperability system components." (Leite, 2003:1) IAM identified nine components (vice QoIM's seven) which are requirements, standards, data elements, node connectivity, protocols, information flow, latency, interpretation, and information utilization. Each of the nine components has either a "yes/no" answer or a mathematical equation associated with it. Leite also defines "degrees of interconnection" which are connectivity, availability, interpretation, understanding, utility, execution, and feedback. (Ibid:3-8) He summarizes IAM in the form of a flowchart and applies the process to the Navy's Tactical Ballistic Missile Defense Program as an example. His methodology was not institutionalized, but was referenced by Kasunic and Anderson in 2004 who state that IAM's quality attributes can be used to extend the LISI model at the mission slice level. (Kasunic & Anderson, 2004)

### Organisational Interoperability Maturity Model for C2 (OIM)

MAIN CONTRIBUTION: Organizations interoperate, but have different interoperability attributes than technical systems.

In 1998, the Australian Defense Science and Technology Organisation (DSTO) completed a Command and Control Support (C2S) study in which they described five layers of C2 Support (Telecommunications, Info Technology, Info Management, C2 Process, and C2 Framework). (Clark & Jones, 1999)  In this study, they pointed out that LISI) is strongly technological, 2) focuses on system and technical compatibility, and 3) does not address higher layers of C2 support.  As a result, Clark & Jones determined to create an organizational extension to LISI.  The result of their labors is the Organisational Interoperability Maturity Model (OIM) first introduced in June 1999 at the International Command and Control Research and Technology Symposium (ICCRTS), then revised in 2003 at the same conference by Fewell and Clark.

OIM was used to "identify problems and evaluate interoperability in a coalition operation" (Fewell & Clark, 2003:3)  Like LISI, OIM defined five levels of interoperability (independent, cooperative, collaborative, combined, and unified). However, unlike LISI's technically-associated PAID attributes, OIM defined four attributes of organizational interoperability—1) preparation, 2) understanding, 3) command and coordination, and 4) ethos (Socio-Cultural factors).  Fewell & Clark supplied detailed descriptions of the attributes, identified multiple sub-attributes for each of the four main attributes and used the revised model to analyze the operational interoperability of three scenarios: 1) the multi-national force participating in the Australian led, 1999-2000 International Force East Timor (INTERFET) operation, 2) an Australia-US interoperability review, and 3) the Multinational Limited Objective Experiment 2 (MNLOE2) held in February 2003.  OIM was reviewed by several researchers after its initial introduction in 1999.  Some examples are: Briscombe, et al.

(2006), Brownsword, et al. (2004), Clark & Jones (1999), Clark & Moon (2001), Fewell, et al. (2004), Kasunic & Anderson (2004), and Morris, et al. (2004) Dekker published a modification to the model which he uses to analyze the Black Hawk Down incident in Mogadishu in 1993. (2005) It is unknown whether the OIM model has been institutionalized by the Australian Department of Defence.

## Stoplight

MAIN CONTRIBUTION: Operations & acquisition have interoperability requirements.

In 2002, Hamilton, et. al. published a very uncomplicated interoperability measurement model which they simply called a Stoplight model. They stated that "interoperability is notoriously difficult to measure," yet gave a "simplified model" to measure it. (Ibid:20-21) The model's purpose is to help decision makers understand whether or not their legacy systems meet operational and acquisition interoperability requirements and is designed as a two-dimensional matrix in which "meets operational requirements (yes/no)" appears on the rows of the matrix and "meets acquisition requirements (yes/no)" appears on the columns. The intersections of the matrix are colored red, yellow, orange, and green depending on how well the specific type of requirement is met. Hamilton, et. al. give an example of how the color codings can be overlaid on a timeline to show the plan to achieve improved interoperability in the future. This model has not been institutionalized within the Department of Defense.

## Levels of Conceptual Interoperability Model (LCIM)

MAIN CONTRIBUTION: Conceptual interoperability bridges system interoperability.

The Levels of Conceptual Interoperability Model (LCIM) was published by Tolk & Muguira in 2003 with the intent that it be used to "become a bridge between the conceptual design and the technical design for implementation, integration, or federation," and that it be used to "enhance the…DoD Net-Centric Data Strategy for the Global Information Grid (GIG)." (Tolk & Muguira, 2003:1) Additionally, they state that it can be used as a framework "to determine in the early stages of the federation development process whether meaningful interoperability between systems is possible." (Ibid) LCIM focuses on the world of modeling and simulation, and initially gave five levels of interoperability but later extended to seven as a result of "new research at VMASC and as the response to critique by the scientific community." (Turnitsa & Tolk, 2006:1) The final levels are Level 0—No interoperability, Level 1—Technical interoperability, Level 2—Syntactic Interoperability, Level 3—Semantic Interoperability, Level 4—Pragmatic Interoperability, Level 5—Dynamic Interoperability, and Level 6—Conceptual Interoperability. LCIM has traction within the modeling and simulation community. LCIM reviewers include Brownsword, et al. (2004), Kasunic & Anderson (2004), and Morris, et al. (2004).

### Layers of Coalition Interoperability (LCI)

MAIN CONTRIBUTION: Operational interoperability is an extension of technical interoperability.

Also in 2003, Tolk introduced a different, but similarly acronymed, Layers of Coalition Interoperability (LCI) model which defines nine layers of interoperability. He shows that there is a continuum between technical interoperability and operational interoperability rather than a distinct breakpoint between the two and that the interface between technical and operational interoperability is made at the knowledge/awareness layer. The nine layers in LCI are, from lowest to highest, 1) Physical Interoperability, 2) Protocol Interoperability, 3) Data/Object Model Interoperability, 4) Information Interoperability, 5) Knowledge/Awareness, 6) Aligned Procedures, 7) Aligned Operations, 8) Harmonized/Strategy Doctrines, and 9) Political Objectives. These layers are framed by a "common model of the operation." Tolk proposes possible metrics for his model as those contained in the NATO Code of Best Practice for C2 Assessment (Stenbit, et. al., 2002a), Code of Best Practice for Experimentation (Stenbit, et. al., 2002b), and Network Centric Warfare Metrics Framework (Alberts, et. al., 2000) LISI and NMI were referenced by Tolk, but OIM was not. Tolk claims that LCI is not meant to be a "universal replacement" for other frameworks, but is meant to be used to "help formulate layered models." (Tolk, 2003:17) LCI has been cited and briefly reviewed by Morris, et al. (2004).

**NATO C3 Technical Architecture Reference Model for Interoperability (NMI)**

MAIN CONTRIBUTION: Same as LISI.

Version four of this NATO reference model was published in March 2003 and according to Morris, et al., it was updated to closely reflect the LISI model in December 2003. (2004) It is no longer available on the NATO website. NMI originally described four degrees of interoperability (not including degree 0 which was no interoperability). The four degrees mapped directly to LISI's top four levels and were given as: 1) unstructured data exchange, 2) structured data exchange, 3) seamless sharing of data, and

4) seamless sharing of information which. NMI was reviewed by Brownsword, et al. (2004), Kasunic & Anderson (2004), Morris, et al. (2004), Tolk & Muguira (2003), and Tolk (2003).

## Net Centric Warfare Maturity Model (NCW)

MAIN CONTRIBUTION: Interoperability occurs in physical, information, cognitive, and social domains; lack of interoperability increases difficulty in accomplishing the mission.

Alberts & Hayes published *Power to the Edge* in 2003 and included a Net Centric Warfare Maturity Model (NCW) in their chapter on interoperability. Besides emphasizing the need for interoperability in military operations, they point out that interoperability underpins the tenents of net-centric warfare. (Alberts & Hayes, 2003) Specifically, they state that interoperability must be present in four domains: physical, information, cognitive, and social. They correlate interoperability to mission effectiveness by stating that "a lack of…interoperability on the part of an entity…makes it difficult for them to contribute to the mission." (Ibid:108) NCW models the maturity of situational awareness and command and control in the context of interoperability levels (Table 31). The five interoperability levels in the model are defined as Level 0 – limited interoperability, Level 1—more entities share information, Level 2—collaborative environments and processes, Level 3—shared awareness in the information and cognitive domains, and Level 4—interoperability in the social domain.

Table 31 NCW maturity model (Alberts & Hayes, 2003)

| | | Command and Control | | |
|---|---|---|---|---|
| | | Traditional | Collaboration | Self-synchronization |
| Developing Situational Awareness | Shared Awareness | | **3** | **4** |
| | Information Sharing | **1** | **2** | |
| | Organic Sources | **0** | | |

### System-of-Systems Interoperability (SoSI) Model

MAIN CONTRIBUTION: System-of-system interoperability research is founded upon operational, conceptual, and programmatic interoperability.

This simple model was published in 2004 by the Carnegie-Mellon University Software Engineering Institute (CMU-SEI) and was developed to facilitate system-of-systems interoperability research. (Morris, et al., 2004) SoSI is founded upon three types of interoperability (operational, constructional, and programmatic) and the activities associated with each. While it is a useful way of developing and integrating systems-of-systems, SoSI lacks metrics to specifically measure interoperability, however it provides a framework in which an analyst can use his/her own metrics. The SoSI report also summarizes LISI, OIM, NMI, LCIM, and LCI. SoSI has not been institutionalized within the Department of Defense.

### Non-Technical Interoperability (NTI) Framework

MAIN CONTRIBUTION: Social, personnel, and process interoperability, as well as organizational interoperability, are valid types of non-technical interoperability.

Stewart, et al., introduced the Non-Technical Interoperability (NTI) framework in 2004 to allow the United Kingdom's (UK) Ministry of Defence (MOD) "to understand these aspects of interoperability better and to mitigate potential frictional factors in multinational forces." They felt that OIM was a "useful top-level framework" for the data they captured in their own research, but recognized that it did not cover social, personnel, and process interoperability. The four enabling OIM attributes form the core of the NTI framework which provides a more detailed breakdown of these attributes. While a complete set of metrics was not provided by Stewart, et al., they did propose a Multinational Forces Cooperability Index which provides a score of 1, 2, 4, 8, 12, or 16 for two (preparedness and understanding) of the four attributes. The NTI framework was developed as result of 45 interviews with UK military officers ranging in rank from Army Captain to 3-star General. It is unknown if NTI has been institutionalized within the UK Ministry of Defence.

**Revised NATO Interoperability Directive (NID)**

MAIN CONTRIBUTION: Levels of interoperability can be given in linguistic terms.

Schade notes that LISI takes a system view of interoperability and NCW takes a force view. (2005) He points out that the NATO Interoperability Directive also uses a system view of interoperability, but documents poorly labeled levels of interoperability. He updates the NID labeling scheme, by applying linguistic terminology extracted from Alberts & Hayes (2003), with the following, Level 0— missing interoperability, Level 1—physical interoperability, Level 2—syntactic interoperability, Level 3—semantic interoperability, Level 4—pragmatic interoperability.

## Organisational Interoperability Agility Model (OIAM)

MAIN CONTRIBUTION: There are levels of ability of organizations to be agile in their interoperation.

Kingston, et. al. of the Australian Defence Science and Technology organization (DSTO) published the Organisational Interoperability Agility Model (OIAM) in 2005. It "builds on the Organizational Interoperability Model developed by Clark and Jones" and "aims to capture the dynamic aspects of working in coalitions including the ability of an organization to contribute to the rapid formation and reformation of coalitions, including novel ones." (Kingston, et. al., 2005:2) Organizational agility is defined as "a single organization's potential to have agile interfaces to other organizations in future coalition operations" and "assesses an organization's ability to adapt to changing circumstances." (Ibid:3) Aligning with OIM, OIAM uses five levels of organizational agility (Static, Amenable, Accommodating, Open, and Dynamic) as well as the four OIM attributes, combining preparation and understanding. The model's developers state they are at the beginning of their research on organizational agility and that they plan to develop additional metrics and perform case studies in order to refine the model. As a new model, it has not yet been institutionalized by the Australian Department of Defence.

## The Layered Interoperability Score (i-Score)

MAIN CONTRIBUTION: Interoperability measurements are operational process specific and have a maximum value.

The Layered Interoperability Score (i-Score) is a quantitative method of measuring the interoperability of all types of systems in the context of an operational process. (Ford, et. al., 2007a; 2008b) It makes use of existing architecture data and accommodates more than one type of interoperability. Unique to the i-Score method is a means of determining a realistic upper limit on interoperability for the systems supporting the operational process. The i-Score method accommodates custom layers which allow the analyst to compensate the i-Score measurement for any number of interoperability-related performance factors such as bandwidth, protocols, mission capability rate, probability of connection, or atmospheric effects, among others. Also possible are cost, schedule, reliability, and performance layers to measure the impact of various programmatic changes on the interoperability of the process. The method can be used to make non-traditional interoperability measurements such as organizational or policy interoperability measurements. The i-Score method has not been institutionalized within the Department of Defense.

## A4. Summary of Extant Interoperability Measure Formats

| Method | Acronym | Date | Measure |
|---|---|---|---|
| Spectrum of Interoperability | SoIM | 1980 | {1,2,3,4,5,6,7} per system pair |
| Quantification of Interoperability | QoIM | 1989 | x/y ratio for each of 7 components where x, y are positive integers |
| Mil Comm. & Info Systems Interoperability | MCISI | 1996 | Positive integer per system pair |
| Levels of Information System Interoperability | LISI | 1998 | Xny per info system where $X \in$ {General, Expected, Specific}, $n \in \{0,1,2,3,4\}$, $y \in \{a \ldots z\}$ |
| Interoperability Assessment | IAM | 1998 | Various number & non-number measures per system attribute |
| Organisational Interoperability | OIM | 1999 | (0,1,2,3,4} per organization |
| NATO Reference Model for Interoperability | NMI | 1999 | {0,1,2,3,4} per info system |
| Stoplight | Stoplight | 2002 | {Red, Yellow, Orange, Green} per legacy system |
| Layers of Coalition Interoperability | LCI | 2003 | {1,2,3,4,5,6,7,8,9} per coalition |
| Levels of Conceptual Interoperability | LCIM | 2003 | {0,1,2,3,4} per model |
| Net-Centric Warfare | NCW | 2003 | {0, 1, 2, 3, 4} per system |
| System of Systems Interoperability | SoSI | 2004 | User defined |
| Non-technical Interoperability | NTI | 2004 | {1,2,4,8,12,16} per attribute per force (for Terminology and ROE attributes only) |
| Revised NATO Interoperability Directive | NID | 2005 | {0, 1, 2, 3, 4} per system |
| Organisational Interoperability Agility | OIA | 2005 | {0,1,2,3,4} per organization |
| Interoperability Score | i-Score | 2007 | Real number per system, operational thread, network, or mission |

## A5. A Survey of System Taxonomies

### System Science System Taxonomies

Ludwig von Bertalanffy, a biologist accepted by many as the father of general systems theory (GST), noted that systems are everywhere. (1955) He defined them as "complexes of elements standing in interaction," and promptly classified them as open or closed, a classification which certainly originated long before von Bertalanffy's time in the disciplines of physics, chemistry, and biology.

Kenneth Boulding, an economist and the first president of the Society for General Systems Research (now known as the International Society for the Systems Sciences) and cofounder of GST, published a creative and more detailed classification of systems which hierarchically classifies systems as 1) frameworks, 2) clockworks, 3) thermostats, 4) cells, 5) plants, 6) animals, 7) human beings, 8) social organizations, and 9) transcendental systems. (1956) Boulding's classification scheme was self-described both as a hierarchy of complexity and as a systematic framework in which he referred to each of the nine classifications in the hierarchy as a level. Approximately thirty years later, Boulding proposed a new, but related classification, stating that systems were either static or dynamic and that "something of a hierarchy" of all systems which "correspond to something in the real world" included systems which were either mechanical, cybernetic, positive-feedback, creodic, reproductive, demographic, ecological, evolutionary, human, and social. (1985: 18) He then agglomerates these ten as physical, biological, or social systems and organizes the remainder of his book around discussions of the world as not just a physical, biological, and social system, but also as an economic, political, communication, and evaluative system.

Twelve years after Boulding published his first classification scheme, Jordan published a taxonomy of systems which grouped systems according to "intuitive guesses" of three "organizing principles" each holding two "polar opposite" properties. (1968: 44) Jordan defined eight cells (classifications) in his taxonomy, which were derived from his principle-property framework, by taking one property from each of the three principles—1) rate of change (structural/static or functional/dynamic), 2) purpose (purposive, non-purposive), and 3) connectivity (mechanistic/organismic). As an example, Checkland uses the taxonomy to classify a road network as a structural, purposive, mechanically-connected system but a mountain range as a structural, non-purposive, mechanically connected set of entities. (1981) Checkland uses this logic to critique Jordan, noting that in his belief, Jordan erroneously "ascribes the purpose, or lack of it, to the system itself" rather than to the system's creator. (Ibid: 108)

Thus, Checkland takes Jordan's taxonomy as a foundation, merges some ideas from Boulding and creates what he calls a systems typology which includes five classes of systems (natural, design physical, design abstract, human activity, and transcendental systems). The purpose of his typology is to identify classes of entities based upon their origin. According to Checkland's typology, the set of natural systems, which includes both types of designed systems as well as the human activity systems, and the set of transcendental systems are disjoint sets. Checkland is quite confident in the completeness of his typology and declares that it "completes a simple systems map of the universe which, as far as system classes is (sic) concerned, is itself complete." (Ibid, 111)

Wilson, a colleague of Checkland, adopted a revision of Checkland's typology, calling it a system classification instead. (1990) He removed transcendental systems from the classification and restated the four remaining classes of systems as natural, designed, human activity, and social and cultural systems. Wilson created his classification of systems in order to help refine the definition of the word system to a level that would be useful in modeling.

Probably without prior intention, Ackoff, in his oft-cited "Toward a System of Systems Concepts," published a system taxonomy of sorts, formed by definitions of various types of systems. (1971) While definitely not hierarchical nor mutually exclusive, his list of system types is never-the-less useful. Ackoff defines abstract, concrete, closed, open, static (one-state), dynamic (multi-state), homeostatic, state-maintaining, goal-seeking, multi-goal seeking, purposive, purposeful, ideal-seeking, variety-increasing, and variety-decreasing systems. Without explicitly stating so, he infers that other types exist, but states that he defined "the most important types of systems." (Ibid: 661)

Valdma recently published a classification scheme for information, but noted that an analogous scheme exists for classifying systems. (2007) His four-level, hierarchical classification of systems directly mirrors his information classification model and puts deterministic systems at the lowest level, followed by probabilistic systems, then uncertain systems (sub-grouped into uncertain-deterministic, and uncertain-probabilistic), and finally, fuzzy systems (sub-grouped into fuzzy-deterministic and fuzzy probabilistic). His stated purpose in creating the classification is as a "first step in studying the non-deterministic phenomena" in the universe. (Ibid, 265)

## Systems Engineering System Taxonomies

In 1957, Goode and Machol wrote in System Engineering, that systems should be classified “on the basis of the types of inputs with which they must cope.” (1957: 299) They further defined this set of inputs as 1) input which is always the same or is of many types, 2) input which occurs periodically (or very infrequently), and 3) input which does or does not seek to destroy the system. Their rationale for developing the classification was to aid in the definition of steps to be followed in order to find the “solution of the problem of a large-scale or complex system.” (Ibid: 302)

Hall’s A Methodology for Systems Engineering, published five years later, has no direct reference to system classification, but indirectly describes a classification of natural vice man-made systems, discusses open and closed systems, and references von Bertalanffy’s property of the hierarchical order of systems, (1962) Interestingly, Hall interprets von Bertalanffy’s classification as a method useful in partitioning systems into subsystems, loosely inferring classification can be used in design, and also states that a system classification is useful in “enhancing the meaning of system.” (Ibid: 63, 68)

Martin, in his Systems Engineering Guidebook, indirectly classifies systems by classifying product types, relating them to systems by stating that systems are comprised of components, and components are comprised of one or more basic product types. (1997) His basic product types, which he correctly notices are not mutually exclusive, are hardware, software, personnel, facilities, data, materials, services, and techniques. His rationale for creating a taxonomy of product types is to create a checklist “to ensure that bases are covered” meaning that the required behavior for a system should not just be allocated to hardware and software. (Ibid: 24)

Shenhar, and Shenhar & Bonen proposed a taxonomy of systems in order to demonstrate that system engineering design and management methods, as well as the type of system engineering culture and style, which are appropriate for one type of system are inappropriate for another. (1995, 1997) Their taxonomy is two-dimensional and classifies systems "according to four levels of technological uncertainty (low, medium, high, and super-high tech), and three levels of system scope (assembly, system, and array)." (Ibid: 137) They cite the space shuttle as an example of a system which NASA initially advertised to Congress as high-tech but making use of existing technologies, but which, in hindsight, should have been managed as a super-high-tech system making use of many not yet developed technologies and methods. Shenhar & Bonen state that an understanding of their taxonomy and a proper classification of the space shuttle as a system could possibly have prevented schedule delays and even might have prevented the Challenger tragedy as NASA would have been "more keenly aware of the possibility of trouble." (Ibid, 144) Shenhar & Bonen admit that their framework "is not conclusive" and requires further refinements and investigation, but believe that it is useful in "finding better and more effective ways to manage the creation of different kinds of systems." (Ibid, 145)

Maier focused his research on the topic of architecting systems-of-systems. (1999) He argued that systems-of-systems must possess "operational and managerial independence of the systems components" and provided a "limited taxonomy" in which system-of-systems are considered a "useful taxonomic distinction" separate from monolithic systems. (1999:267-284) He further subdivided the taxonomic grouping of system-of-systems into virtual, voluntary, and directed categories.

Kovacic's taxonomy provides "definition to the variety of fields that hold claim to the term systems" and reduces the set of systems into "meaningful related clusters." (2005) He erroneously states that his taxonomy uniquely uses complexity as its basis, as Boulding, whom Kovacic cites, called his taxonomy "a hierarchy of complexity." (Boulding, 1956: 200), Kovacic makes a unique application of complexity theory, but more importantly notes that a good taxonomy must be inclusive, definitive, reductive, and applicable. (2005) Additionally, he notes that systems are difficult to classify because they are perceptions of the observer. Kovacic's taxonomy is three-dimensional with decomposed/un-decomposed, complex/simple, and loosely bounded/tightly bounded as the three dichotomous categorizations.

Gideon et al., published a taxonomy of systems-of-systems in order to aid in the understanding of the nature and attributes of systems-of-systems and because "a clearly defined classification scheme is essential in developing common systems engineering architectures and methodologies." (2005) While they admit that their taxonomy "may not be complete or even necessarily correct," it represents one of the first attempts at a classification scheme specifically for systems-of-systems. Their final taxonomy subordinates systems-of-systems to systems in general, then defines sub-classifications of acquisition type (dedicated or virtual), operational type (chaotic, collaborative, or directed), and domain type (social, conceptual, or physical).

Blanchard and Fabrycky discuss classification of systems in *Systems Engineering and Analysis*, but caveat by saying that the classifications they included are "only some of those that could be presented" and indicate that systems can be classified "for convenience and to provide insight into their wide range." (2006: 6) They take the path of dichotomies as Jordan did and defined systems as natural and man-made, physical and conceptual, static and dynamic, and closed and open. As is the case with others who have classified systems, their classification scheme proposes agglomerations which overlap—a property to be expected and one that is useful. Blanchard and Fabrycky acknowledged tie-in between systems engineering and systems science and partially aligned their system classifications to the nine levels of complex systems proposed by Boulding.

## A6. Operational Process Modeling Methods

Table 32 Operational process modeling methods

| |
|---|
| ACT Formalism |
| A Language for Process Specification (ALPS) |
| AP213 Protocol within ISO 10303 |
| UML 2.0 Behavior Diagram |
| EPFL’s Petri Net Representation |
| Core Plan Representation (CPR) |
| Entity-Relationship (E-R) Model |
| Functional Flow Block Diagram (FFBD) |
| Gantt Chart |
| Generalized Activity Network (GAN) |
| Hierarchical Task Networks (HTN) |
| Integration Definition for Function Modeling (IDEF0) |
| Process Flow and Object State Description Capture Method (IDEF3) |
| Issues, Nodes, Ordering, Variable, and Auxiliary (<I-N-OVA>) Constraint Model |
| Knowledge Interchange Format (KIF) |
| Open Planning Architecture (O-Plan) Task Formalism |
| OZONE |
| Parts and Action (PAct) |
| Product-Activity-Resource Model for Realiz. of Electro-Mech. Assemblies (PAR2) |
| Part 49 of ISO 10303 |
| Program Evaluation and Review Technique (PERT) Network |
| Petri Net |
| Process Flow Representation (PFR) |
| Process Interchange Format (PIF) |
| Quirk Models |
| Visual Process Modeling Language (VPML) (pre-1998 version) |
| Visual Process Modeling Language (VPML) (post-1998 version) |
| AND/OR Graph |
| Data Flow Diagram (DFD) |
| Digraph |
| State Transition Diagram (STD) |
| SysML Activity Diagram |
| Tree Structure |
| Process Specification Language (PSL) |
| Flow Chart |
| DoD Architecture Framework (DoDAF) Functionally Decomposed Activity Diagram |

## A7. Operational Effectiveness Measurement

### Hierarchy of Measures of Operational Effectiveness

A hierarchy of measures was first described by the Military Operations Research Society (Sweet, et. al., 1985) and was later adopted by the Department of Defense with minor modification (Grimes, 2006). This hierarchy also seems to be widely accepted outside these two communities, with slight modifications, and describes a hierarchical set of measures ranging from dimensional parameters, to measures of performance, to measures of effectiveness, to measures of force effectiveness, and finally to measures of policy effectiveness (Green, 2001; Stenbit, et. al., 2002). This hierarchy is often rendered as a pyramid or onion-skin model although it shouldn't be viewed that rigidly. Similarly, many authors strictly apply dimensional parameters to objects, measures of performance to systems, measures of effectiveness to systems within an environment, measures of force effectiveness to systems as part of a force, and measures of policy effectiveness to high-level policy decisions, but there should be flexibility in order to accommodate different system types (e.g., organizational systems). The preferred term in this research, measure of operational effectiveness (MoOE), fits in the range of measurements between measure of performance and measure of force effectiveness, inclusive.

### Operational Effectiveness Assessment

Operational effectiveness assessment occurs during operational planning, operational execution, and post-operation analysis. This is well documented in DoD joint operational planning and joint operations publications (JP 5-0, 2006; JP 3-0, 2006). A common means of determining operational effectiveness is through measurement of appropriate factors related to the operation. Although these measures can be qualitative, Keeney states that quantifying the measures “clarifies the meaning of the (operational) objectives, and this clarity…facilitates all aspects of decisonmaking.” (Keeney, 1992:129).

JP 3-0 *Joint Operations* (2006) and JP 5-0, *Joint Operational Planning* (2006) define assessment as “the process that measures progress of the joint force toward mission accomplishment” and state that commanders “continuously assess…the progress of operations, and compare them to their initial vision and intent.” (Ibid:III-57) Operational assessment uses both measures of effectiveness (MOE) and measures of performance (MoP) (Ibid:III-59). Although JP 3-0 and JP 5-0 associate MOEs with strategic assessment and MOPs with tactical assessment, since an operation in the context of this dissertation can be strategic or tactical, the generalized term, measure of operational effectiveness (MoOE), will be used from here onward. Since the two joint publications state that an MoP is used to measure task performance and an MoE is used to “determine progress of an operation toward achieving objectives,” (Ibid:III-60) it is appropriate to say that an MoOE, although retaining some characteristics of an MoP (e.g., measurement of level of operational tasks, or thread, completion), is more closely aligned with the definition of an MOE, and hence is appropriately named.

The initial MOEs defined during operational planning are also called success criteria (JP 5-0, 2006:III-27). Indeed, MOEs are defined early (Step #2, Mission Analysis of 7 steps) in the operational planning process and become “the basis for reports to senior commanders and civilian leaders on the progress of the operation" (Ibid) because they measure "the attainment of an end state, achievement of an objective, or creation of an effect" (JP 3-0, 2006:IV-32; JP 5-0, 2006:III-60). In fact, according to Murray in *A Will to Measure*, the desire to measure quantitatively is "irresistible" to modern society and the armed forces use quantitative methods to explain actions to leaders, politicians, and the public (2001:134). Murray aptly states that "the interpretation of the MOE frequently forms the structure on which senior leaders base their orders." (Ibid)

JP 5-0 gives an example of an operation (evacuate all US personnel from an embassy) and two associated MOEs ("are all personnel evacuated?" and "have any rules of engagement been violated?") which highlights the fact that MOEs are operation dependent and that there are often more than one MOE associated with the operation. (2006:III-27)

An appropriate MOE must be carefully selected. According to Murray, MOEs which "adequately reflect and distill reality help decisionmakers make informed and timely decisions," while "poorly chosen measures have a multitude of negative effects" (2001:134).

## MoOE Characteristics

Multiple researchers give desirable characteristics of MoOEs. Fourteen characteristics are consolidated below (in no special order) in Table 33 and are discussed individually in succeeding paragraphs.

Table 33 MoOE characteristics

| Characteristic |
|---|
| 1) Relevant<br>Also called "operational"<br>Also called "mission-oriented" |
| 2) Measurable |
| 3) Responsive<br>Also called "sensitive" |
| 4) Resourced |
| 5) Understandable |
| 6) Discriminatory |
| 7) Quantitative |
| 8) Realistic |
| 9) Objective |
| 10) Appropriate |
| 11) Inclusive |
| 12) Independent |
| 13) Valid |
| 14) Reliable (Precision) |

*Relevant*. An MOE must be relevant to the operation, or in other words, mission-oriented. For example, during the Kosovo campaign, NATO's focus on counting the number of vehicles and weapons destroyed and the number of sorties flown and bombs dropped "did not provide a sense of whether Yugoslavian leaders were ready to accede to NATO demands" but instead validated "performance requirements" of weapons—an irrelevant indicator of operational effectiveness of the campaign. (Murray, 2001:134). A positive change in the MOE value should indicate greater operational success. Similarly, a negative change in the value of the MOE value should indicate a decline in operational success.

It should not be assumed, however, that an MOE must be a direct (also called natural by Keeney (1992:101) measure of the success of the operation. Indeed, often direct measures violate criteria #2 (measurability), but measurable inferential (also called indicative, indirect, or constructed) measures may be available. For example, the MOE “level of the morale of the enemy” cannot be directly measured, but an inferential measure such as “number of attacks per month made by the enemy” may be an adequate estimate of enemy morale in that it indicates the enemy’s desire to continue the fight. If a commander or leader must resort to using inferential MOEs, extra care must be taken to ensure that the MOE is relevant. For example, Secretary McNamara used body count as an inferential measure of operational effectiveness during the Vietnam war, but that measure not only did not reflect progress in winning the war, but had many unintended effects (Murray, 2001) such as failure of commander integrity, and possibly the unnecessary killing of civilians.

Murray writes that it can be difficult to discover good MOEs which accurately reflect the positive and negative trends in operational effectiveness because the “underlying causal mechanisms are exceedingly difficult to determine” (Ibid:138). He accurately observes that rarely is one measure appropriate but that most operational effectiveness must be measured from a complex set of factors.

*Measurable*. An MOE must be measurable (Bornman, 1993; JP 3-0, 2006; JP 5-0, 2006). Although JP 5-0 acknowledges that MOEs can be qualitative or quantitative, quantitative MOEs are preferred because they are “less susceptible to subjective interpretation.” (2006:III-61) Qualitative measures can usually be quantized. For example, the MOE, “are all personnel evacuated,” is a yes or no question which can be rendered as a 1 or 0. Similarly, the MOE, “to what level has the enemy’s ability to place improvised explosive devices (IED) been degraded,” appears qualitative, but infers that a scale can be applied by using the word level. If a scale of 0 to 10 IEDs per day is used, then the MOE becomes quantitative and measurable.

*Responsive (Sensitive)*. An MOE must be responsive, or sensitive, to changes in the operation. (Bornman, 2001; JP 3-0, 2006; JP 5-0, 2006) In order to give the commander fidelity of understanding on how the effectiveness of the operation is changing, the MOE must be sensitive to changes in operational effectiveness. For example, if the operational goal is to assist democratic revolutionaries in overthrowing their country's dictatorship, a measurable and relevant, yet insensitive MOE could be, "number of machines guns provided to the revolutionaries each month." Although machine guns may eventually help revolutionaries overthrow the dictatorship, the time required for training and planning may result in delayed progress toward the goal of the operation. In fact, more machine guns than necessary may be provided in successive months as the operation's commander attempts to accelerate the overthrow of the dictatorship.

*Resourced*. An MOE must have the necessary resources (i.e., manpower, money, time, etc.) allocated for data collection, analysis, and reporting (JP 3-0, 2006; JP 5-0, 2006). If resources are not allocated for assessment, it won't matter how appropriate the MOEs are, because the measurements will not be able to be made, or the measurements may be incomplete or inaccurate. For example, if a commander desires to improve war fighting efficiency of his unit, but does not have enough people on staff to dedicate to data gathering and analysis, the commander may find that the efficiency analysis eventually provided is shallow, too narrowly focused, or downright erroneous.

*Understandable*. This characteristic is self explanatory and is also called simple by Bornman (2001) and Green & Johnson (2002). An MOE must be understandable (Keeney, 1992; Campbell, 2004) not only to the person making the measurement, but also to the leader whose decisions are based upon the measurement.

*Discriminatory*. Bornman states that an MOE must be discriminatory in order to "identify real differences between alternatives" (1993:2-3). This characteristic is related to the characteristics of objectivity and independence described below.

*Quantitative*. Keeney writes that objectives are qualitative and attributes (MOEs) are quantitative (1992). JP 3-0 states that MOEs are qualitative and MOPs are quantitative (2006), however JP 5-0 states that MOEs are either qualitative or quantitative (2006). Bornman insists that MOEs are quantitative (1993).

*Realistic*. Although Bornman calls out realistic as a separate characteristic of a desirable MOE, "realistic" is largely implied in the more important characteristics of measurable, resourced, and understandable—all of which, if missing, result in a MOE which is not realistic. Murray reminds that realistic measures which "adequately distill and accurately reflect reality help decisionmakers make informed, timely decisions." (2001:134)

*Objective*. Bornman states that measures can be objective or subjective, but lists objectivity as a desirable characteristic. (1993) Keeney mentions that a subjective, or qualitative, "structure" can be quantified using a value model. (1992) Keeney's philosophy is that any qualitative measure can be rendered quantitatively. This usually is accomplished by applying a scale, or other type of model, to give meaning to the values of the measure. Non-objective measures are often constructed or proxy measures.

*Appropriate*. Bornman states that a measure of effectiveness should be appropriate, which he defines as relating to “acceptable standards and analysis objectives.” (1993:2-3)

*Inclusive*. Bornman also mentions that a desirable measure of effectiveness is inclusive, meaning it “reflect(s) those standards required by the analysis objectives.” (1993:2-3) No further clarification is offered although a reference is made to a 1985 Military Operations Research Society workshop which developed some (or possibly all) of the characteristics listed in the Bornman (Army TRADOC) handbook. Unfortunately, no bibliography was included in the handbook, so it is difficult to accurately identify the source which Bornman referenced, although it likely was the 1985 document referenced by Green & Johnson. (2002)

*Independent*. Independence is an important characteristic of an MOE, because it drives the analyst to find measures of operational effectiveness which are not confounded with each other. This is desirable from a commander’s perspective since it results in measures which are distinct from each other. This allows commanders to change certain aspects of their operation and measure that change without affecting other aspects of the operation. In practice, it is difficult to describe independent MOEs. Design of experiments and response surface methodology theory recommend if independence of factors is impossible (i.e., due to cost, ease of measurement, or other reasons), then care should be taken to ensure important factors are confounded with negligible factors. This minimizes the impact due to variable dependence.  This same philosophy can be applied to MOE selection by choosing measures of important effects which are not confounded with a measure of another equally important effect.

Measure independence was listed as "desired but not essential" by Bornman (1993) and was listed as a desired characteristic of MOEs by Green & Johnson. (2002) The NATO Code of Best Practice for C2 Assessment states that analysis of operations is challenging due to "the number of confounded variables" (Stenbit, et. al., 2002:191) and and further states that independent measures are controllable.

*Valid*. Bullock states that a measurement is valid if it "reflects the…attributes it was supposed to represent." (2006:8)

*Reliable*.  Finally, Bullock writes that a measure must be reliable (which he also calls precision), meaning that the measurement process must be able to yield a consistent and repeatable measurement.

## MOE Types and Domains

Keeney lists three types of MOEs (which he called attributes)—natural, constructed, and proxy. (1992)  A natural MOE is one which has "a common interpretation to everyone" such as annual profit in millions of dollars. (Ibid:101)  A constructed MOE is not a direct or natural measure, but includes a subjective judgment. (Campbell, 2004)  For example, the Richter scale for measuring earthquake intensity is a constructed measure. (Ibid)  Campbell points out that constructed measures, as they become commonly known and understood can become natural measures (e.g., the Dow Jones Industrial Average and the Gross National Product).  Finally, the proxy MOE is an inferential, or indicator, measure which describes something related to what is actually wanted to be measured. For example, the level of Carbon 14 is an indicator of the age of an object. A natural measure is often objective whereas constructed and proxy measures are often subjective. (Bornman, 1993) Although natural MOEs are the most desirable, more often than not, constructed or proxy MOEs 1) more readily meet the MOE criteria, 2) cost less to gather data and measure, or are 3) more easily discovered. An MOE is measured in the physical, information, or cognitive domain .(Stenbit, et. al., 2002) Generally, measurements in the physical domain are easier to make and those in the cognitive domain are more difficult.

## MOE Summary

An MOE is defined as "a standard used to assess changes in the production of a desired operational effect." It is exists within the range of measure of performance, measure of effectiveness, and measure of force effectiveness in the hierarchy of measures. The three types of MOE—natural, constructed, and proxy—exist within the physical, information, and cognitive domains. The best MOEs are relevant, measurable, responsive, resourced, understandable, discriminatory, quantitative, realistic, objective, appropriate, inclusive, independent, valid, and reliable. An MOE associates proper units of measurement and includes limits on the range of the measurement as appropriate.

## A8. Example Interoperability Character Framework

Table 34 Example interoperability character framework

| | **Physical** | **Technological** | **Biological** | **Conceptual** | **Organizational** | **Environmental** |
|---|---|---|---|---|---|---|
| **Physical** | *Accommodate* | *Accommodate* | *Accommodate* | | | *Accommodate* |
| **Technological** | *Transform* | *Communicate*<br>*Service* | *Communicate*<br>*Somaction*<br>*Audition*<br>*Visualization* | | | *Transform* |
| **Biological** | *Accommodate*<br>*Transform* | *Communicate*<br>*Somaction*<br>*Audition*<br>*Visualization* | *Dance*<br>*Nourish*<br>*Influence*<br>*Command* | *Implement*<br>*Influence* | *Dance* | *Transform* |
| **Conceptual** | | | *Influence** | | | |
| **Organizational** | | | *Dance*<br>*Interact* | | *Service* | |
| **Environmental** | *Influence*<br>*Transform* | *Influence* | *Influence* | | | *Influence* |

*Conceptual systems can only interoperate with humans

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**14. ABSTRACT**

This research presents an inaugural general method of measuring the collaborative and confrontational interoperability of a heterogeneous set of systems in the context of an operational process. The method is holistic, fundamental, flexible, and mathematical in nature and accommodates all types of systems and interoperations. The method relates the interoperability measurement to measures of operational effectiveness for confrontational operational processes. Extant leveling methods of describing interoperability are shown to be a special case of the more general method given in this research and the general interoperability measurement method is demonstrated through the presentation of coalition interoperability, suppression of enemy air defenses, and precision strike applications. Further application is recommended in technical, non-technical, cross-domain, and non-traditional interoperability areas and additional research is suggested on the topics of indirect interoperability measurement and collaborative interoperability impact on operational effectiveness.


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