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Title: A Survey on Interoperability Measurement

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Abstract

A Survey on Interoperability Measurement

For nearly thirty years, both government and industry have actively explored research on interoperability measurement with the goal of creating a straightforward way of measuring, reporting, then improving the interoperability of complex networks of people, equipment, processes and organizations. Researchers have created frameworks and models, proposed measures, described levels, and listed a variety of qualitative factors in support of an interoperability measure. Within extant interoperability research, the authors' research has uncovered nearly three dozen definitions of interoperability, over five dozen distinct types of interoperability, numerous interoperability attributes, and fourteen foundational interoperability measurement models and methodologies. At least eleven research groups have been the centers-of-gravity for interoperability measurement research. This survey paper summarizes and focuses the current body of knowledge on interoperability measurement and identifies areas where further research is needed.

Background

Interoperability has been highlighted as a problem within the Department of Defense (DoD) since 1965 when the Special Subcommittee on Tactical Air Support of the House Armed Services Committee stated that with regards to close air support, the "incompatibility of Army and Air Force radios was "appalling" and they called the situation a "communications fiasco." [GAO, 1987, p. 20] The DoD responded in 1967 by publishing an interoperability directive, DoD Directive 4630.5 which "established policy and procedures to ensure that C3 equipment [could] interoperate." [Ibid] But after continued Congressional criticism regarding the directive and its implementation throughout the 1970s, "the Secretary of Defense informed the Congress [in 1977] that the directive would be revised." [Ibid] By 1985 "the directive had still not been revised" prompting the Senate Armed Services Committee to warn the Secretary of Defense that they might "consider a legislative restriction on the expenditure of any funds for communications equipment unless meaningful progress is made." [Ibid] The Directive was revised and published that same year.

Although the basic policies were now established, in April 1987 the GAO responded to a request by the Chairman of the Legislation and National Security Subcommittee within the House of Representatives asking the GAO to describe "the extent to which communications interoperability problems have been identified during exercises and past operations" and "the impediments preventing interoperability and how much they can be overcome" [GAO, 1987, p. 1] The GAO responded that interoperability has been a "longstanding problem," and that the "services historically have been unable to communicate effectively among themselves during joint operations and exercises." [GAO, 1987, p. 8] The GAO stated examples of interoperability failures in operations in "Korea, the Dominican Republic Landing, Vietnam, and…the Grenada intervention in 1983." [Ibid] Half a decade later in response to another Congressional request, the GAO acknowledged that the DoD "has worked hard over the years to achieve greater interoperability," but it continued to experience interoperability problems during…the Persian Gulf War in 1991." [GAO, 1993, p. 2] In 1992, the Chairman of the Joint Chiefs of Staff "announced a new initiative called 'Joint C4I for the Warrior,'" which was created to provide a "common global vision" for the services. [Ibid] Major results of this initiative were the Defense Information Services Agency (DISA) interoperability certification process in 1992, the C4ISR

Architecture Framework published in 1996, the Defense Information Infrastructure (DII) Master Plan published in 1994, and the 1993 Levels of Information Systems Interoperability (LISI) initiative which was completed in 1998. [GAO, 1998, pp. 20-21] Great progress on the interoperability front had been made and now that policies, procedures, organizations, and oversight mechanisms were in place, it was time to refine interoperability improvement. The way ahead was interoperability measurement—a trail partially blazed by LISI. As Kasunic and Anderson put it, "management must be able to measure what they wish to change." [Kasunic & Anderson, 2004, p. 16] Further, DoD Instruction 4630.8, Procedures for Interoperability and Supportability of Information Technology (IT) and National Security Systems (NSS), requires interoperability assessment through "measurable, performance-based criteria." [DoDI 4630.8, 2004, p. 29]

To this end, this paper describes a survey of research on interoperability measurement spanning nearly three decades. This paper not only summarizes the extant research, but identifies gaps and areas for further research.

Introduction

Although a comprehensive survey on a topic as broad as interoperability is impossible, our survey was extensive and we limited it to the sub-topic of interoperability measurement. We occasionally reference a paper which, while not focused on interoperability measurement, indirectly supported the topic. Also, although we did not constrain our literature search to DoD-focused interoperability measurement, we discovered that much has been published either in support of the DoD or by the DoD and its associated organizations. We've organized our research in the following manner. To set the stage, we first give an analysis and history of interoperability definitions from the past thirty years and then present a short, but comprehensive survey of all the different types of interoperability mentioned in research work over the same time period. With definitions and types of interoperability as the foundation, we then name what we call interoperability measurement "centers-of-gravity" which are the organizations which have produced a method for measuring interoperability. We then describe and provide a critique of their fourteen major interoperability measurement models, methodologies, and processes. We end this research paper with a discussion of the mathematics of interoperability measurement, the lack of institutionalization of twelve of the fourteen methods, and identification of and recommendation for filling the current gaps in interoperability measurement research.

Interoperability Definitions

As expected, there have been numerous definitions of interoperability put forth by researchers, standards bodies, and the government over the past thirty years. While a comprehensive listing would be unproductive, we have identified thirty-four distinct definitions of interoperability used in research papers, standards, and other government documents during the time period. These definitions are listed in the appendix in chronological order. Next to each definition is a list of sources which either introduce or reference the definition. Although most of the definitions pertain to interoperability in general, eight define specific types of interoperability (e.g., technical interoperability, logistic interoperability, and operational interoperability). The definitions pertaining to a specific type of interoperability are clearly annotated in the table. Finally, the origin of the definition are marked as either DoD, Standard, or Other where DoD refers to any DoD or DoD-related/contracted organization, Standard refers to any standard making body such as the Institute of Electrical and Electronics Engineers (IEEE), and Other refers to all other sources.

Besides the number of interoperability definitions, it is interesting to note the obvious similarities and differences between many of the definitions. To begin our analysis of these interoperability definitions, we begin by presenting a histogram in Figure 1 which shows how many different interoperability definitions were proposed in research papers, reports, standards, or government documents each year since 1977. This histogram gives us a feel for where in time interoperability became a focus not only within the DoD, but without as well.

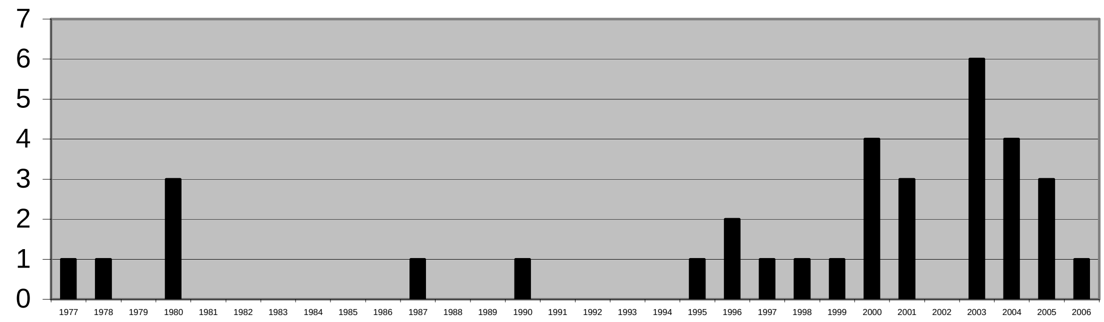


Figure 1 Number of Interoperability Definitions per Year

An apparent surge in interest in interoperability is evident beginning in 1995 and ending in 2003. This is corroborated by the vignette on the history of interoperability presented in the background section of this paper. As we will show later in this paper, 1995-2003 is the time period in which most research on interoperability measurement also occurred. The implication is obvious—before creating a model for interoperability measurement, one had to first understand what interoperability was. Much of the remainder of this paper will focus on this time period.

The histogram in Figure 1 also shows that there has been an apparent decrease in the number of interoperability definitions put forward in research, reports, standards, and government documents since 2004. We believe this decline signals the beginning of a time period in which one or more definitions have become accepted by a wide variety of researchers, standards organizations, and the government. Figure 2 substantiates this by showing the popularity of each definition—in other words, the number of research papers, reports, standards, or government documents using the definition. Definition #1, by far, is referenced the most.

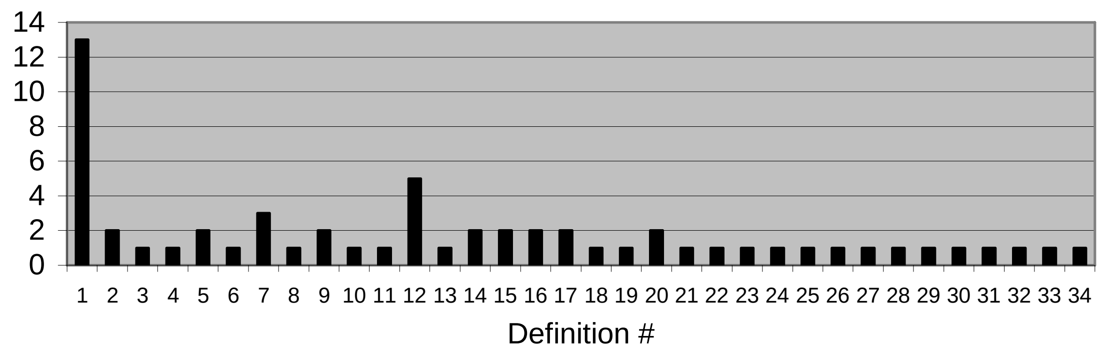


Figure 2 Interoperability Definition Popularity

Definition #1 was the oldest definition of interoperability we found in our literature search, and it is still commonly used in DoD documents today. This 1977 definition of interoperability was likely in use within the DoD as far back as 1967 when the first publication of DoD Directive 4630.5 was made. A close reading of all the interoperability definitions presented in this paper indicates that many of them, especially the DoD-related definitions, represent re-wordings or subsets of the 1977 definition. Definition #1 is repeated below for convenience.

> 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.

Interoperability Types

We believe one reason this definition of interoperability has been well accepted over the past thirty years is that it is flexible enough to cover many different types of interoperability. Its wording talks about systems, possibly implying technical types of interoperability, yet also mentions units and forces, implying operational types of interoperability. Our research supports the idea that most (if not all) types of interoperability can be classified as either technical or non-technical. Examples of technical interoperability types are communications, electronic, application, and multi-database interoperability. Examples of non-technical interoperability types include organizational, operational, process, cultural, and coalition interoperability. Although we have stated these examples of technical and non-technical interoperability, note that the classification of an interoperability type as technical versus non-technical is subject to interpretation. In fact the "binning" of interoperability types may be situation dependent. For example, Public Service interoperability may be considered non-technical from an enterprise point of view, but would be categorized as technical when considering water pipe capacities, electric line loads, or telephone switches. Another reason definition #1 is so versatile is that it talks in generalities about services rather than specifics such as packets, messages, orders, deliveries, or procedures. Finally, it simply makes the point that the exchange of services creates an effective operation of the systems, units, or forces.

Our research produced a list of sixty-four different types of interoperability mentioned in research papers, reports, standards, and government documents over the past thirty years. Very few of these types were specifically defined in their source document, but all demonstrate the richness of the interoperability field of study. These interoperability types are listed, along with their source in the appendix in chronological order of their appearance.

Interoperability Measurement Research Centers of Gravity

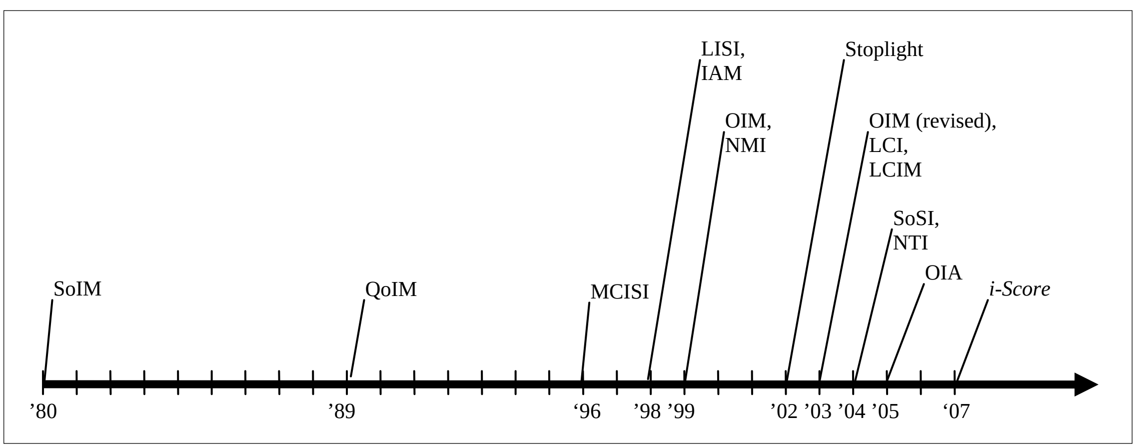
Over the past thirty years there have been numerous research papers, magazine articles, and presentations published and conferences held on interoperability-related topics. Many of these have only marginally extended the body of knowledge, adding just a change in context or capitalized on interoperability as a "buzzword." Substantially fewer papers, articles, presentations, and conferences have focused on the topic of interoperability measurement. Through our literature search, we have determined that there are eleven organizations which have contributed substantially to the area of interoperability measurement by publishing one or more interoperability measurement models, methodologies, or processes (hereafter referred to as models). These organizations are listed in Table 1 in chronological order of when they published their first interoperability measurement model. Of the eleven organizations listed, ten are either part of, or directly support the Departments of Defense of the United States, Australia, and Poland. The one non-DoD-related organization (VMASC) is a center within a public university which has military modeling and simulation as one of its six core capabilities [VMASC '07]. Of the ten DoD-related centers-of-gravity, two (MITRE Corp. and CMU-SEI) are Federally Funded Research and Development Centers (FFRDC). Four (VMASC, CMU-SEI, Military University of Technology, and AFIT) centers-of-gravity are either educational institutions or part of educational institutions.

Table 1 Interoperability Measurement Research Centers-of-Gravity

Organization	**Model**
Defense Information Systems Agency (DISA)	SoIM ('80)
MITRE Corporation	QoIM ('89) LISI ('98)
Military University of Technology, Warsaw, Poland	MCISI ('96)
Joint Theater Air and Missile Defense Organization (JTAMDO) Contractor SIM, Inc.	IAM ('98)
Australian Defence Science and Technology Organisation (DSTO)	OIM ('99) OIAM ('05)
Joint Forces Command (JFCOM) Joint Forces Program Office (JFPO)	Stoplight ('02)
Old Dominion University Virginia Modeling Analysis and Simulation Center (VMASC)	LCI ('03) LCIM ('03)
North Atlantic Treaty Organization (NATO)	NMI ('03)
Carnegie Mellon Software Engineering Institute (CMU-SEI)	SoSI ('04)
Defence Science and Technology Laboratory (Dstl) and Contractor, QinetiQ, plc	NTI ('04)
Air Force Institute of Technology (AFIT)	*i-Score* ('07)

Interoperability Measurement Models

Although many papers, articles, and presentations would have us believe that LISI is the only interoperability measurement model available, there are actually at least fourteen models available for use. Each one of the models has a specific focus and some are more capable than others. Some have been widely accepted, and others are rarely used. There have been technical reports published which summarize some, but not all, of the interoperability measurement models listed in Table 1. This section of the paper seeks to describe all fourteen models, point out the strengths and uses of each, and reference the reader to other critiques or reviews of these models, including their original source documents. We frame our analysis of these fourteen models with a timeline.



Spectrum of Interoperability Model (SoIM)

Gilbert LaVean, an employee of a predecessor organization to the current Defense Information Systems Agency (DISA), acknowledged in 1980, 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." [Gilbert, 1980, p. 1449] In order to combat this deficiency, he created a spectrum of interoperability model (which we nickname SoIM). [Ibid, p. 1448] He began his model by defining the two most important measures of interoperability (technical possibility and management/control possibility). [Ibid] The technical measure was a number between 1 (impractical to interface) and 4 (common equipment used) and the management/control measure was a number from 1 (complete independence between systems) and 6 (separate systems placed under common management/control, thus becoming the same system). [Ibid] He then stated that by "combining these two measures, it is possible to derive a spectrum of interoperability that permits cost-versus-benefits tradeoffs." His combination of these two measures resulted in seven levels of interoperability which are listed in Table 2. [Ibid] Mr. LaVean recognizes that the level of interoperability may be different for each service that pairs of systems provide to each other, so he proposes a visualization method, which he calls an interoperability matrix, which lists services on the rows of the matrix and levels of interoperability on the columns. [Ibid] He further proposes a current view and a "future" view of the interoperability matrix in order to show evolution of the systems over time. [Ibid] Thus, the purpose of the LaVean Spectrum of Interoperability Model 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 Mr. Gilbert's Spectrum of Interoperability Model was groundbreaking and is the earliest model for measuring interoperability that we have discovered, we were able to find no further mention of his model after its original publication and whether or not it was used by program managers to improve inter-system interoperability is unknown. Our literature search did not reveal that Mr. LaVean's model was further refined by other researchers after its original publication.

Table 2 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)

In 1989, Dennis Mensh, Robert Kite, and Paul Darby published a paper in the *Naval Engineer's Journal* called "The Quantification of Interoperability." For ease of reference, we nickname this model "QoIM." Messrs. Mensh and Kite worked for MITRE Corporation at the time this article was published and may have laid some of the groundwork for the well-known LISI model which was published by MITRE nine years later although they were never cited as a source in the LISI paper. Mensh, Kite, and Darby's approach to interoperability measurement published in 1989 is unique. Their specific goal was to create a means of "(1) assessing interoperability issues for three mission areas: wide area surveillance (WAS), over-the-horizon targeting (OTH-T), and electronic warfare (EW); and (2) quantifying…seven interoperability components." [Mensh, Kite, & Darby, 1989, p. 252] They stated that "interoperability of systems, units, or forces can be factored into a set of components that can quantify interoperability." [Ibid, p. 251] They identified and defined seven components as media, languages, standards, requirements, environment, procedures, and human factors. [Ibid, pp. 253-254] They defined a Measure of Effectiveness (MOE) logic function for each component and used that logic function to create a truth table for each component. For example, the MOE logic function for the Language component was defined as "Message Correctness = Intelligibility and Manual Intervention & Error." [Ibid, pp. 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 truth table could be analyzed—the presence of zeros indicated lack of interoperability during certain component events and the presence of ones indicated some level of interoperation occurred. [Ibid, pp. 254-255] In the end, a final Interoperability Data Table was formed showing the truth table results for all seven interoperability components. Rather than provide a final measure for interoperability, this table gives seven ratios (one for each component) which show the number of significant events scoring a one divided by the total number of events. Mensh, Kite, and Darby state three benefits of this table: "(1) It illustrates the overall quantification of interoperability. (2) For specific events it enables an evaluation of the interoperability of…systems in terms of the seven interoperability components in terms of the corresponding…events. (3) Having this type of table for two different…architectures enables a comparison of the relative goodness of each architecture." [Ibid, p. 259] Although Mensh, Kite, and Darby state in their paper that their "methodology for quantifying interoperability is being pursued," they also state 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), we have been unable to find any further mention or use of this model beyond the original journal article in which it was proposed. [Leite, 2003]

Military Communications and Information Systems Interoperability (MCISI)

Another interesting interoperability measurement model was published in 1996 which was designed to model communications and information systems (CIS) interoperability in a mathematical way. Based upon the title of the article the methodology was introduced in, we give it the acronym MCISI. Amanowicz and Gajewski recognized that "a great amount of data is needed as well as the appropriate methodology of interoperability modeling." [Amanowicz and Gajewski, 1996, p. 281] They stated that interoperability modeling is "a multistaged process which combines operational requirements, CIS data, standards, interfaces and modeling facilities." [Ibid] They mention that "the results of interoperability modeling are most often presented in the (sic) three-level scale starting from full through partial to non-interoperable systems for particular services (operational procedures)." [Ibid, p. 282] They use a colored cube to visualize the model in which one axis is level of command, the second is CIS services, and the third is transmission medium. 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. The mathematics of their methodology comes next as Amanowicz and Gajewski describe a set of systems as "points in multi-dimensional space" and the features of these systems as "coordinates of these points." [Ibid] They then define the normalized "distance" between two points as $d\left(A,B\right)=\frac{\sum_{i=1}^{n}\left|a_i-b_i\right|}{n}$, where a_i, b_i are features of system A and system B, respectively. [Ibid] They state that when $d\left(A,B\right)=0$ systems A and B achieve full interoperability and when $d(A,B) > 1$, the system pair's interoperability decreases. [Ibid] Amanowicz and Gajewski then expand this model to accommodate a set of Z systems by creating dendrite (a broken line which connects all points of a set) arrangements of the systems. [Ibid] They state that the best arrangement is the one with the shortest dendrite length. [Ibid, p. 283] While their abridged paper could not fully provide all the details of their method, they enjoy the distinction of being the first to recognize that the upper/lower limits of interoperability of a given set of systems can be measured and to infer that optimization can be performed in order to determine the best arrangement of systems in order to maximize interoperability. [Ibid] Unfortunately, like SoIM and QoIM, we were unable to find proof of any further institutionalization of Amanowicz' and Gajewski's MCISI model after publication.

Levels of Information System Interoperability (LISI) Model

LISI model development began under contract at the MITRE Corporation in 1993 and was published in final form by the C4ISR Architecture Working Group (AWG) in 1998. The AWG was co-chaired by the Joint Staff J6I and the Director, Architectures Directorate of the C4ISR Integration Support Activity (CISA) which was under the direction of OSD(ASD(C3I)). [C4ISR AWG, Apr. 1998, p. 5] In their report on LISI, the AWG 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." [C4ISR AWG, Mar. 1998, p. ES-7] Thus, LISI is system or system pair-focused vice mission, scenario, or operational thread focused. The LISI report also states that LISI is a "process for defining, evaluating, measuring, and assessing information systems interoperability," implying that LISI is best suited for measuring information systems interoperability. [IBID, p. 1-2]

While CJCSI 6212.01C, Interoperability and Supportability of Information Technology and National Security Systems, required program managers to ensure that they complied with a range of LISI profile requirements, the latest version of that document, CJCSI 6212.01D, "deletes requirements associated with Levels of Information Systems Interoperability (LISI)." [CJCSI 61212.01C, 2003, p. A-6], [CJCSI 6212.01D, 2006, p. 5] Although the AWG had originally stated a goal of having LISI institutionalized in DoDD 4630.5, DoDI 4830.8, DoDI 5000.2, and DoDD 5000.1, our review of all versions of these documents published since 1998 indicates no mention of LISI. However, the Joint Chiefs of Staff did maintain a repository of LISI profiles for acquisition programs as a result of the CJCSI 6212.01C requirement (on classified SIPRNet http://lisi.ncr.disa.smil.mil). [CJCSI 6212.01C, 2003, p. K-2]

As this model has been described in numerous technical reports, articles, and papers over the years, it will be summarized very briefly and references to more detailed summaries will be provided. Suffice it to say that LISI has been acknowledged as the most prominent interoperability measurement model within the Department of Defense over the past decade.

The LISI model is comprised of the LISI Assessment Basis and LISI Assessment Products. [C4ISR, 1998, p. 1-4] The Assessment Basis includes an Interoperability Maturity Model, a Reference Model, a Capabilities Model, and Implementation Options Tables. [Ibid] The Assessment Products include Interoperability Profiles, Interoperability Metrics, Interoperability Matrices, Comparison Tables, and Architecture Products.

LISI Assessment Basis. The LISI Interoperability Maturity Model is similar to LaVean's SoIM in that it describes levels of interoperability. Whereas LaVean had seven levels, LISI has five levels called maturity levels. Level 0 is Isolated, Level 1 is Connected, Level 2 is Functional, Level 3 is Domain, and Level 4 is Enterprise. [C4ISR, 1998, pp. 2-6 – 2.7] However, unlike LaVean's SoIM, LISI makes an improvement step by describing four attributes within each level which "encompass the full range of interoperability considerations." [Ibid] The four attributes are described by the acronym PAID—Procedures, Applications, Infrastructure, and Data. The LISI Reference Model puts the five levels on the rows of a matrix and the four attributes on the columns. The cells at the intersections describe the capabilities needed to achieve a specified level of interoperability for a certain attribute. [Ibid, p. 3-1] The LISI Capabilities Model is a "decomposition" of the reference model which describes specific capabilities required to achieve a specified level of interoperability for a certain attribute. [Ibid, p. 3-12] The LISI Implementation Options Tables are used to in building a systems' Interoperability Profile—one of the LISI Assessment Products. [Ibid, pp 3-17]

LISI Assessment Products. The first LISI product created during the LISI interoperability assessment process is the system Interoperability Profile. This document is created by answering a web-based questionnaire which gathers information about a system for all four interoperability attributes. [Ibid] Once the questionnaire is complete, an Interoperability Metric can be obtained. This metric is a triplet of metric type (Generic, Expected, & Specific), Level (0…4), and Sub-level (a…z). The metric quantitatively describes the level of interoperability for one system (generic) or a pair of systems (expected and specific). [Ibid, p. 4-4] The generic metric is the highest level of interoperability a single system is capable of whereas the expected metric describes the highest common level of interoperability between two systems. The specific metric describes the highest common level of interoperability between two information systems across all PAID attributes. [Ibid] The Interoperability Matrix takes the Interoperability Metrics for multiple systems and arrays them on a grid in which systems are labeled on the rows and columns and the intersections contain the interoperability level for that system pair. The color of the intersections indicates whether the specific interoperability for the system pairs exceeds, equals, or is less than the expected level for the pair. [Ibid, p. 4-10] Thus, the matrix can be used to visualize the interoperability of a group of systems. Comparison Tables can be used to "provide a comparison of interoperability implementation information between systems in terms of PAID," and are flexible in that they can be used for a specific attribute, or more generically for a group of attributes. [Ibid, p. 4-11] Finally, various architecture products can be created using LISI assessment data. For example, LISI generic metrics for individual systems can be overlaid upon a system interface description, thus giving not only a visualization of the connectivity of systems, but of the quality of connectivity of those systems. [Ibid, p. 4-16]

LISI has been reviewed and critiqued by many other researchers since its publication. Several recent reviews have been done by Brownsword, et al., Carney & Oberndorf , Clark & Jones, Clark & Moon, Kasunic & Anderson, Morris, et al., Tolk, and others. [Brownsword, et al., 2004], [Carney & Oberndorf, 2004], [Clark & Jones, 1999], [Clark & Moon, 2001], [Kasunic & Anderson, 2004], [Morris, et al., 2004], [Tolk, 2003]

Interoperability Assessment Methodology (IAM)

The Interoperability Assessment Methodology (we call it IAM) was published in the proceedings 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, Michael Leite, of SIM, Inc. was aware of the LISI effort, however, of the fourteen models surveyed, he was only author to reference the Mensh, Kite, and Darby Quantification of Interoperability Model (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, p. 1] Mr. Leite identified nine components (vice QoIM's seven) which are requirements, standards, data elements, node connectivity, protocols, information flow, latency, interpretation, and information utilization. [Ibid, p. 3] Each of the nine components has either a "yes/no" answer or a mathematical equation associated with it [Ibid, p. 22]. Mr. Leite also defines "degrees of interconnection" which are connectivity, availability, interpretation, understanding, utility, execution, and feedback. [Leite, pp. 3-8] He summarizes his Interoperability Assessment process in the form of a flowchart and applies the process to the Navy's Tactical Ballistic Missile Defense Program as an example. Mr. Leite's methodology also does not appear to have been institutionalized, but was referenced by Kasunic and Anderson in their 2004 Tech Note in which they graphically show that a "Mission Slice" can include a color-coded version of LISI metrics for systems supporting the slice and they further state that Mr. Leite's interoperability "quality attributes" can be used to extend the LISI model at this mission slice level. [Kasunic & Anderson, 2004, p. 26]

Organisational Interoperability Maturity Model for C2 (OIM)

In 1998, the Australian Defense Science and Technology Organisation (DSTO) completed a Command and Control Support (C2S) study. [Clark & Jones, 1999, p. 1] In this study, they described five layers of C2 Support (Telecommunications, Info Technology, Info Management, C2 Process, and C2 Framework), but they also determined that the just published LISI model could not easily map onto their model for three main reasons, 1) LISI is strongly technological, 2) LISI focuses on system and technical compatibility, and 3) LISI does not address higher layers of C2 support. [Ibid, p. 4] As a result, Clark and Jones determined to create an extension to LISI to "cover the organizational aspects of interoperability." [Ibid] The results 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, then revised in 2003 at the same conference by Fewell and Clark. [Ibid], [Fewell & Clark, 2003]

The OIM model was used to "identify problems and evaluate interoperability in a coalition operation." [Ibid, 2003, p. 3] It was specifically designed as an extension to LISI. [Clark & Jones, 1999, p. 4] Just as LISI defined five levels of interoperability, so did OIM (independent, cooperative, collaborative, combined, and unified). [Ibid, p. 6], [Fewell & Clark, 2003, p. 3] Whereas LISI defined four attributes of interoperability described by the PAID acronym, Clark and Jones defined four attributes of organizational interoperability. These are 1) preparation, 2) understanding, 3) command and coordination, and 4) ethos (Socio-Cultural factors). [Ibid, p. 8, 10] Fewell and 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 three scenarios: 1) the multi-national force participating in the Australian led, 1999-2000 International Force East Timor (INTERFET) operation, 2) an AS-US interoperability review, and 3) the Multinational Limited Objective Experiment 2 (MNLOE2) held in February 2003. [Ibid, pp. 4-14] These applications of the OIM showed that the model is used in the same fashion as LISI, and indeed extends the LISI model in an appropriate and useful fashion. It is our opinion that the combined LISI-OIM model is a most valuable tool for performing basic, high-level interoperability analysis of information systems used by operational forces in a specific scenario. The OIM model was reviewed by several researchers since its initial introduction in 1999. Some examples are: Briscombe, et al., Brownsword, et al., Clark & Jones, Clark & Moon, Fewell, et al., Kasunic & Anderson, and Morris, et al. [Briscombe, et al. 2006], [Brownsword, et al., 2004], [Clark & Jones, 1999], [Clark & Moon, 2001], [Fewell, et al., 2004], [Kasunic & Anderson, 2004], [Morris, et al., 2004] Additionally, another researcher, Anthony Dekker, has also published a modification to the model which he uses a modification of the OIM model to analyze the Black Hawk Down incident in Mogadishu in 1993. [Dekker, 2005] It is unknown whether the OIM model has been institutionalized by the Australian Department of Defence.

Stoplight

In 2002, Hamilton, Rosen, and Summers published an Interoperability Roadmap for C4ISR Legacy Systems which included a very uncomplicated interoperability measurement model which they simply called a Stoplight model. [Hamilton, Rosen & Summers, 2002, p. 17, 21] The creators of the Stoplight model state that "interoperability is notoriously difficult to measure," yet still propose a "simplified model" to measure it. [Ibid, pp. 20-21] Their model turns out to be quite useful (in its restricted sphere of applicability) as a starting point for interoperability analysis in spite of its simplicity. The model's purpose is to help decision makers understand whether or not their legacy systems meet operational and acquisition interoperability requirements. [Ibid, p. 21] The model 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. [Ibid] The intersections of the matrix are colored red, yellow, orange, and green depending on how well the specific type of requirement is met. [Ibid] Definitions of the color scheme are provided in Hamilton, Rosen, and Summers' paper. [Ibid, p. 22] The authors' also give an example of how a time-line with the color-coding overlaid can be created to show the plan to achieve improved interoperability in the future. [Ibid, p. 23] We have found no evidence that this model was institutionalized within the Department of Defense.

Levels of Conceptual Interoperability Model (LCIM)

The Levels of Conceptual Interoperability Model (LCIM) was published by Andreas Tolk and James 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, 2003, p. 1] Additionally, Tolk & Muguira 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] Tolk & Muguira focus their model on the world of modeling and simulation, and similar to LISI and OIM, proffer five levels of interoperability geared specifically toward conceptual interoperability. They are Level 0—System Specific Data, Level 1—Documented Data, Level 2—Aligned Static Data, Level 3—Aligned Dynamic Data, and Level 4—Harmonized Data. [Ibid, pp. 2-3] The number of levels was eventually extended to seven, and the names were changed as well due to "new research at VMASC and as the response to critique by the scientific community." [Turnitsa & Tolk, 2006, p. 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. [Turnitsa & Tolk, 2006, p. 2] LCIM is flexible enough to allow a developer to define metrics appropriate to the level of alignment needed between two or more models, and Tolk & Muguira aptly make the point that different models require different levels of interoperability—in other words, level 4 is not the goal for all situations. [Tolk & Muguira, p. 5] Tolk & Muguira's model makes clear that "meaningful interoperability of simulation systems on the implementation level…requires composability of the underlying conceptual models." [Ibid, p. 9] LCIM seems to be receiving considerable attention within the modeling and simulation community and has been widely cited. Others who have reviewed LCIM include Brownsword, et al., Kasunic & Anderson, and Morris, et al. [Brownsword, et al., 2004], [Kasunic & Anderson, 2004], [Morris, et al., 2004]

Layers of Coalition Interoperability (LCI)

In 2003, the same Andreas Tolk who introduced the LCIM model also introduced a different, but similarly acronymed, Layers of Coalition Interoperability (LCI) model. While he states that this model is "in its infancy," he hopes that it will become a "hub for future work." [Tolk, 2003, p. 21] LCI defines nine layers of interoperability, and shows through his reference model that there is a continuum between technical interoperability and operational interoperability rather than a distinct breakpoint between the two. [Ibid, p. 18] While others have described separate models for technical and operational interoperability, Dr. Tolk demonstrates that the interface between technical and operational interoperability is made at the knowledge/awareness layer. [Ibid] The nine layers in Dr. Tolk's LCI model 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." [Ibid, p. 12] Dr. Tolk proposes possible metrics for his model as those contained in the NATO Code of Best Practice for C2, Code of Best Practice for Experimentation, and Network Centric Warfare Metrics Framework. [NATO, 2002], [Alberts, et al., 2002], [Alberts, Garstka, & Stein, 2000] Interestingly, LISI and NMI were referenced by Dr. Tolk, but OIM (which was published four years earlier, also in the ICCRTS) was not. Dr. Tolk states in his paper 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, p. 17] LCI has been cited and briefly reviewed by one other group that we know of, Morris, et al. [Morris, et al., 2004]

NATO C3 Technical Architecture Reference Model for Interoperability (NMI)

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. 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 were: 1) unstructured data exchange, 2) structured data exchange, 3) seamless sharing of data, and 4) seamless sharing of information. These degrees (including degree 0) map directly to LISI's five levels of interoperability. NMI was overviewed by Brownsword, et al., Kasunic & Anderson, Morris, et al., Tolk & Muguira, and Tolk. [Brownsword, et al., 2004], [Kasunic & Anderson, 2004], [Morris, et al, 2004], [Tolk & Muguira, 2003], [Tolk 2003]

System-of-Systems Interoperability (SoSI) Model

This simple model was published in 2004 by the Carnegie-Mellon University Software Engineering Institute (CMU-SEI) by Morris, et al. According to the CMU-SEI on-line Interoperability Guide, SoSI was developed to enable CMU-SEI researchers to more effectively pursue system-of-systems interoperability research. [CMU-SEI] The SoSI model is founded upon three types of interoperability (operational, constructional, and programmatic) and the activities associated with each. [Ibid] While it appears to be a useful way of developing and integrating systems-of-systems, SoSI lacks metrics to specifically measure interoperability within a system-of-system. For this reason, we considered not including it in this survey, but in the end decided to include it because it provides a framework in which an analyst can use his/her own metrics to measure system-of-systems interoperability. The technical report in which SoSI is introduced contains a summary of LISI, OIM, NMI, LCIM, LCI, and SoSI. Morris, et al., also include in their paper a useful listing of various DoD interoperability initiatives. We found no evidence that SoSI has been institutionalized within the DoD or further referenced outside of CMU-SEI.

Non-Technical Interoperability (NTI) Framework

Stewart, et al., introduced the Non-Technical Interoperability (NTI) framework in 2004 for the purpose of developing a "valid framework describing the factors that underpin NTI" which would allow the United Kingdom's Ministry of Defence "to understand these aspects of interoperability better and to mitigate potential frictional factors in multinational forces." [Stewart, et al., 2004] Stewart, et al. felt that the DSTO OIM model was a "useful top-level framework" for the data they captured in their own research. [Stewart, et al., 2004, p. 6] But they also recognized that using the term operational interoperability left out other factors such as "social, personnel, and process factors," so they decided to use the term non-technical interoperability in order to be more comprehensive. [Ibid] They did not, however, reference any of the other non-technical interoperability models already published such as LCI. The four enabling attributes (preparedness, understanding, command style, and ethos) originally proposed by Clark and Jones in their OIM model form the core of the NTI framework and the research performed by Stewart, et al. provided a more detailed breakdown of these attributes. [Clark & Jones, 1999, p. 8], [Stewart, et al., 2004, p. 6] While a complete set of metrics was not provided by Stewart, et al., they did propose a Multinational Forces Co-operability Index which provides a score of 1, 2, 4, 8, 12, or 16 for two (preparedness and understanding) of the four attributes. [Ibid, pp. 8-9] For this reason we included NTI as an interoperability measurement model in our survey. While 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 the framework is undergoing further refinement or has yet to have been institutionalized within the UK Ministry of Defence. [Stewart, et al, 2004, pp. 5-6]

Organisational Interoperability Agility Model (OIAM)

Kingston, Fewell, and Richer of the Australian Defence Science and Technology organization (DSTO) published the Organisational Interoperability Agility Model (OIAM) in 2005. According to its authors, 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, Fewell, and Richer, 2005, p. 2] Organizational agility is defined by Kingston, Fewell, and Richer as "a single organisation's potential to have agile interfaces to other organizations in future coalition operations" and "assesses an organisation's ability to adapt to changing circumstances." [Ibid, p. 3] OIAM began with the idea of creating a maturity model similar to OIM and decided to use five levels of organizational agility in order to more closely align with OIM. Additionally, OIAM makes use of the four OIM attributes, only combines preparation and understanding. Therefore, the five levels are: Level 0—Static, Level 1—Amenable, Level 2—Accomodating, Level 3—Open, and Level 4—Dynamic. The three attributes are 1) Preparation + Understanding, 2) Command and coordination, and 3) Ethos. [Ibid, pp. 12-15] Specific definitions of these levels and attributes are provided by Kingston, Fewell, and Richer in order to help the analyst properly rate an organization's agility. [Ibid] Although no specific metrics are mentioned, we believe the model's levels themselves are metrics and can be used to form generic, specific, and expected metrics similar to those in LISI and OIM. The model's developers indicate that 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. [Ibid, p.16] As a new model, it has not yet been institutionalized by the Australian

Department of Defence. OIAM does not yet appear to have been referenced by any other published works.

The Layered Interoperability Score (*i-Score*)

The Layered Interoperability Score (*i-Score*) is a new methodology created by the same authors who have written this survey on interoperability measurement. It has been submitted and accepted for publication in the Proceedings of the 2007 Conference on Systems Engineering Research (CSER 2007). [Ford, Colombi, Graham, & Jacques, 2007, p. 1] *i-Score* is a mathematical method of measuring the interoperability of all types of systems (technological, biological, organizational, and environmental). [Ibid] It is easily computed, based upon an operational thread, makes use of existing architecture data, can be used in scenarios where more than one type of interoperability is included, and provides a means of quantitatively measuring the interoperability of the systems supporting an operational thread. [Ibid, p. 2] Unique to the *i-Score* methodology is a means of determining a realistic theoretical upper limit on interoperability for the systems supporting the operational thread. [Ibid] The methodology can quickly determine ways to close the “interoperability gap” between the as-is *i-Score* and the theoretical optimum *i-Score*. [Ibid, p. 6] The *i-Score* interoperability measurement methodology is also unique in that it can make use of custom layers (matrices) which allow the analyst to compensate the *i-Score* measurement for any number of interoperability-related factors such as bandwidth, protocols, mission capability rate, probability of connection, atmospheric effects, etc. It is even possible to create cost, schedule, reliability, and performance layers to measure the impact of various programmatic changes on the interoperability of the thread. [Ibid, p. 4] Since the methodology is entirely mathematical, it is possible to embed custom functions of interoperability-related variables so that optimization can be performed to determine the best “settings” for maximum interoperability. The methodology can be used to make non-traditional interoperability measurements such as organizational or policy interoperability measurements.

The *i-Score* interoperability measurement methodology is a six-step process. [Ibid, pp. 3-6] The six steps of the methodology are described below.

Step 1—Diagram the operational thread (e.g., time-critical-targeting) using an IDEF0, BPML, or UML activity diagram and define the ordered set T of systems supporting each activity in the thread. Step 2—Create an interoperability matrix $M=\left[c_{ij}s_{ij}\right]_{n\times n}$ where n is the number of systems supporting the thread, $C=[c_{ij}]_{n\times n}$ is a multiplicity matrix which describes the number of times a system is used in the thread, and $S=[s_{ij}]_{n\times n}$ is a spin matrix where $s_{ij}\in\{-1,0,1\}$ is a variable indicating no human or machine translation needed for a system pair (+1), machine translation required (0), or human translation required (-1). M can be augmented by multiplying additional matrices (layers) such as normalized bandwidth, probability of connection between system pairs, mission capable rate for systems, normalized cost, system reliability, etc.

Step 3—Calculate the *i-Score* $I=\sum_{i=1}^{n}\sum_{j=1}^{n}m_{ij}$.

Step 4—Calculate the optimum *i-Score* $I_{opt}=\sum_{i=1}^{n}\sum_{j=1}^{n}m_{ij}\Big|_{M_{opt}}$ where $M_{opt}=\left[c_{ij}s_{ij}\Big|_{s_{ij}=\max\{s_{ij}\}}\right]$ is the maximally upgraded interoperability matrix (i.e., upgrade all spins that can be upgraded in light of physical, fiscal, and operational constraints).

Step 5—Calculate the Interoperability Gap $I_{gap}=I_{opt}-I$.

Step 6—Perform interoperability analysis to 1) determine ways of closing the interoperability gap through spin upgrades or using common systems, 2) determine average interoperability spin, 3) compare operational threads through a normalized *i-Score*, or 4) visualize the interoperability of a thread by graphing it on an Interoperability Terrain graph.

While *i-Score* is new, and has not yet withstood wide academic debate, its authors naturally feel it has promise due to its ability 1) to represent different types of interoperability, 2) to provide not only an as-is measurement of interoperability but also a realistic theoretical optimum interoperability measurement, 3) to provide a mathematical means of measuring interoperability enabling a variety of optimization techniques to be used to improve networks of systems, 4) to provide a means of measuring interoperability for homogeneous and heterogeneous networks of systems, and 5) to provide a flexible and customizable model in which layers of different interoperability-related parameters can be analyzed.

Interoperability Measurement Model Summary

In order to more easily visualize the types, strengths, and weaknesses of the fourteen models surveyed in this paper as well as to help the analyst choose the model appropriate for his/her application, the fourteen models described above are summarized in two tables in the appendix. The first table is a list of the formats of the interoperability measures. The second table is a more comprehensive table which more fully categorizes the interoperability measures and models. The categorization of the models in the second table is based upon the published, descriptive statements by the model's creator. For example, if the author of a model did not state specifically that mathematical operations (e.g., optimization techniques) could be performed on the measurement associated with the model, then we did not indicate that on the table unless it was readily apparent (e.g., IAM).

The Mathematics of Interoperability Measurement

An inspection of the interoperability measurement model summary table in the appendix indicates that most authors of the interoperability measurement models were not focused on applying mathematical methods such as optimization theory, probability theory, or complexity theory to their model or having an analyst apply mathematics to their specific instance of the model. Only one of the fourteen models (*i-Score*) was designed specifically for this purpose, three are capable of having some mathematics applied (QoIM, MCISI, and IAM), and only seven have a numeric or partial numeric measurement (SoIM, QoIM, MCISI, IAM, LCI, LCIM, NTI, and *i-Score*). We believe that although a qualitative framework is useful as a starting point, the true power of interoperability measurement is in post-measurement analysis founded upon strong mathematical principles. Many large networks of systems are already in existence, but a qualitative approach cannot optimize these already functioning networks. The past decade has seen numerous improvements in linear programming techniques which can be applied to small or extremely large networks. Probability theory can be applied to our networks which already interoperate to more accurately measure their true interoperability compensating for real-world degradations. Finally, techniques related to complexity theory should be capitalized upon in order to measure the interoperability of either self-emergent networks, self-synchronizing systems, large scale-free, or time-varying networks.

Institutionalization of Interoperability Measurement Models

It is interesting to note from the interoperability measurement summary table in the appendix that only two models (LISI and NMI) appear to have been institutionalized by large organizations. Even then, LISI has recently been de-institutionalized within the Department of Defense. We believe there are many explanations for this. First, many interoperability measurements that are being performed may be focused on system-to-system measurements examining individual protocols, applications, or physical links. This type of measurement falls into the category of interoperability testing and is done at a very low level on the spectrum of interoperability defined by some of the models reviewed in this paper. Nearly all of the interoperability measurement models reviewed in this paper are more suited towards higher-level characteristics (e.g., social, organizational, or procedural) vice lower-level technical ones. Second, in spite of the interest interoperability has received over the past three decades, interoperability measurement appears not to have been used as often as it could be. Much attention has been placed upon standards, technical reference models, and common protocols, but we still have networks of systems which are using those accepted standards and protocols which are not fully interoperable. We've measured the interoperability of two systems, but have not measured their interoperability in a real-world network. We also have not measured their ability to interoperate in self-formed, emergent, or ad hoc networks. Third, it may be that such initiatives as the Net-Ready Key Performance Parameter (NR-KPP) and Joint Interoperability Test Center (JITC) Certification have focused attention on system-to-system interoperability, adherence to standards, and interoperability of applications within an as-is network. While these initiatives are beneficial, they may be partially deflecting attention and money away from some of the other useful types of measurements described by the models summarized in this paper such as operational interoperability, operational interoperability agility, conceptual model interoperability, and system-of-systems interoperability. Finally, several authors stated that their models were in their infancy, or were starting points for further research. Indeed, this indicates that further refinement of the current set of models is required before widespread use.

Conclusions and Areas for Future Work

To our knowledge, no other researcher or group of researcher has compiled as extensive of a summary of the past thirty years of interoperability measurement research as can be found in this paper. However, many very well written papers, reports, and notes have reviewed and critiqued sub-sets of the fourteen models presented in this summary document and have been cited throughout this paper. We encourage them to be read side-by-side with our document. Our study of all the materials cited in this research paper lead us to the following conclusions and recommendations for areas which merit further work.

Refine the Field of Interoperability Measurement Research. We agree with Morris, et al. in stating that there is a need for the community to work together to compile "a complete and consistent set of interoperability models." [Morris, et al., 2004, p. 47] We believe it might be useful to form a working group (possibly under the auspices of the ICCRTS or INCOSE) in which interoperability measurement as a science can be refined and promoted.

Pursue Mathematical Methods for Interoperability Measurement. As described earlier in this paper, the mathematics of interoperability measurement have largely been ignored in favor of qualitative measures of interoperability. We believe that, while qualitative measures are useful, quantitative methods such as linear programming and/or non-linear optimization, probability theory, graph theory, complexity theory, and others are required in the evolution of interoperability measurement. The measurement of interoperability of advanced and complex networks of systems of technology, people, and organizations is a critical step towards the realization of truly interoperable systems.

Develop a Method of Modeling and Measuring Interoperability of Heterogeneous Self-Forming Networks. An abbreviated search indicates that more and more researchers are beginning to pay attention to self-forming networks. Although much research seems to emphasize homogeneous networks, a framework for describing and a method for measuring interoperability of heterogeneous self-forming networks seems to be a useful field of study. The somewhat recently published OIAM could be an ideal non-technical starting point as it measures the ability of an operational network of forces to adapt and interoperate with other forces. [Kingston, Fewell, and Richer, 2005]

Perform Applied Research on Extant Models. The authors of the models described in this paper, also provided one or two case studies, military operations, or other examples of the application of their model. Many of those applications were limited in scale and the authors of at least five (QoIM, LISI, OIM, Stoplight, and OIAM) of the models stated a need for further application of their model in order to validate it or to find its strengths and weaknesses. [Mensh, Kite, & Darby, 1989, p. 259], [C4ISR AWG, 1998, p. 8-1], [Clark & Jones, 1999, p. 11], [Hamilton, Rosen, & summers, 2002, p. 29], [Kingston, Fewell, & Richer, 2005, p. 17] For this reason, we believe that more research showing the application of these models would be useful.

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John Colombi is an Assistant Professor of Electrical Engineering at the Air Force Institute of Technology. He teaches graduate courses and leads sponsored research in support of the Systems Engineering program. Before joining the faculty, Dr. Colombi led various Air Force C4ISR systems integration activities including the C2 Constellation. He served as Chief of Systems Engineering for U.S. AWACS. He has served at NSA developing information security and ran communications networking research at the Air Force Research Laboratory.

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David Jacques is an Assistant Professor of Aeronautical Engineering and joined the faculty of the Air Force Institute of Technology in the summer of 1999. Prior military assignments included tactical missile intelligence analysis, ballistic missile test and evaluation, and research and development for advanced munition concepts. In the winter of 2002-2003, LtCol Jacques led the activation of the new Air Force Center for Systems Engineering initiated by then Secretary of the Air Force Dr. James Roche. Dr. Jacques' research interests include multi-objective or constrained optimal design, and cooperative behavior and control of autonomous vehicles.

Appendix

Interoperability Definitions (in Chronological Order)

#	Origin	Definition	Source
1	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), (DoDD 2010.6, 1980, Encl. 2, p. 2), (Amanowicz, 1996, p. 280), (DoD 95), (DoD 98), (Leite, 1998, p. 3), (Curts 1999, p. 5.), (JV2020 (JP1-02), 2000, p. 15), (DoD 2001), (Clark 2001, p. 2), (Fewell, 2003, p. 2), (Kasunic, 2004, p. vii, 2, 32), (Morris, et al., 2004, p. 3, 7)
2	Other	The ability of one system to receive and process intelligible information of mutual interest transmitted by another system.	(Eldridge, 1978), (Kasunic & Anderson, 2004, p. 32)
3	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)
4	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)
5	Other	The effort required to couple one system with another.	(McCall, 1980), (Kasunic & Anderson, 2004, p. 32)
6	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, p. 1)
7	Standard	The ability of two or more systems or components to exchange information and to use the information that has been exchanged.	(IEEE, 1990), (Kasunic & Anderson, 2004, p. 32), (Kosanke, 2005, p. 2)
8	Other	Interoperability among components of large-scale, distributed systems is the ability to exchange services and data with one another.	(Heiler, 1995, p. 1)
9	Other	The ability to communicate with peer systems and access their functionality.	(Vernadat, 1996), (Kosanke, 2005, p. 2)
10	DoD	Operational Interoperability. The ability of systems, units, or forces to provide services to or access services from other systems, units, or forces, and to use the services to operate effectively together.	(DoD 96)
11	DoD	Technical Interoperability. Interoperability is the ability of systems to provide dynamic interactive information and data exchange among C4I nodes for planning, coordination, integration, and execution of Theater Air Missile Defense operations.	(JTAMDO 97)
12	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 98), (Leite, 1998, p. 3), (DoD, 2001), (Morris, et al., 2004, p. 7-8), (JP 1-2, 2004, p. 277)
13	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, p. 9)
14	Standard	The ability of two or more systems of elements to exchange information and to use the information that has been exchanged.	(IEEE 2000), (Morris, et al., 2004, p. 3)
15	Standard	The capability for units of equipment to work together to do useful functions.	(IEEE, 2000), (Morris, et al., 2004, p. 3)

16	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.	(IEEE, 2000), (Morris et al., 2004, p. 7)
17	Standard	The ability of two or more systems or components to exchange information in a heterogeneous network and use that information.	(IEEE 2000), (Morris, et al., 2004, p. 7)
18	DoD	The ability of systems to work together.	(DSP, 2001, p. B4-7)
19	Standard	The ability of different types of computers, networks, operating systems, and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner. There are three aspects of interoperability: semantic, structural, and syntactical.	(Dublin Core Metadata Glossary, 2001)
20	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.	(GIG, 2001), (Morris, et al., 2004, p. 4)
21	DoD	Programmatic Interoperability. Programmatic interoperability encompasses the activities related to the management of one program in the context of another program.	(Levine, 2003, p. 4)
22	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, 2003, p. 5)
23	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, 2003, p. 6)
24	DoD	The ability of systems to work together.	(Levine, 2003, p. 26)
25	DoD	The ability of systems to exchange and use services.	(Levine, 2003, p. 26)
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 2003, p. 26)
27	Standard	The ability to integrate data, functionality and processes with respect to their semantics.	(Berre, et al., 2004, p. 13)
28	DoD	Ability to achieve “cooperation” is generally termed “interoperability.”	(Carney, 2004, Slide #3)
29	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, p. 32)
30	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, p. 4)
31	Other	Interoperability is defined as the ability of two or more systems or components to exchange information and to use the information that has been exchanged.	(Blanc, 2005, p. 2)
32	Other	IDEAS Project defines interoperability as the ability of interaction between enterprise software applications. The interoperability is considered achieved if interactions can, at least, take place at three levels: data, application, and business process with the semantics defined in a business concept.	(Blanc, 2005, p. 2)
33	Other	Ability of two or more devices to work together in one or more applications.	(Kosanke, 2005, p. 4)
34	DoD	The ability to operate in synergy in the execution of assigned tasks.	(JP1-2, 2006, p. 277)

Interoperability Types

#	Interoperability Type	Source
1	Communications	(LaVean, 1980, p. 1448), (Kasunic & Anderson, 2004, p. 34)
2	Electronic	(DoDD 2010.6, 1980, Encl. 2, p. 2)
3	Logistics	(DoDD 2010.6, 1980, Encl. 2, p. 3)
4	Peacetime	(LaVean, 1980, p. 1450)
5	Systems	(LaVean, 1980, p. 1449), (Clothier, 1996, 1997), (Leite, 1998, p. 1), (Curts, 1999, p. 3), (GIG, 2001, p. 32), (Clark, 2001, p. 2), (Kasunic, 2004, p. 1)
6	Telecommunications	(LaVean, 1980, p. 1449)
7	Multidatabase	(Litwin & Abdellatif, 1986, p. 1)
8	Specification Level	(Wileden, et al., 1989, p. 1)
9	Object Oriented	(Konstantas, 1993, p. i)
10	High-Level	(Konstantas, 1993, p. 2)
11	Procedure Oriented	(Konstantas, 1993, p. 4)
12	Semantic	(Heiler, 1995, p. 1)
13	Process	(Clothier, 1996, 1997), (Clark, 2001, p. 2)
14	System-to-System	(Amanowicz, 1996, p. 280), (Kasunic & Anderson, 2004, p. 17)
15	Information	(Mathwick, 1997), (Curts, 1999, p. 4), (DSP, 2001, p. B4-7)
16	Isolated	(C4ISR, 1998), (Larsen, 2006, p. 2)
17	Connected	(C4ISR, 1998), (Larsen, 2006, p. 2)
18	Functional	(C4ISR, 1998), (GIG, 2001, p. 22), (Clark, 2001, p. 2), (Larsen, 2005, p. 2)
19	Domain	(C4ISR, 1998), (Larsen, 2006, p. 2)
20	Enterprise	(C4ISR, 1998), (Blanc, 2005, p. 3), (Kosanke, 2005, p. 8), (Larsen, 2006, p. 2)
21	Data	(ITSG, 1998), (Curts, 1999, p. 4), (GIG, 2001, p. 30), (Kasunic & Anderson, 2004, p. 4, 7, 34)
22	Joint	(Leite, 1998, p. 1), (GIG, 2001, p. 49), (DSP, 2001, p. B4-18), (Kasunic & Anderson, 2004, p. 13-14)
23	Architecture	(Curts, 1999, p. 10)
24	Organizational	(Clark, 1999, p. 1), (Clark, 2001, p. 1)
25	Technical	(Clark, 1999, p. 4), (GIG, 2001, p. 22), (Clark, 2001, p. 1), (Kinder, 2002, p. 25), (Carney, 2004, p. 16), (Kasunic & Anderson, 2004, p. 2)
26	Total	(Curts, 1999, p. 1)
27	Joint Information	(Nutwell, 2000)
28	Secure-Voice	(GIG, 2001, p. 33)
29	Non-GIG	(GIG, 2001, p. 29)
30	“Plug-and-Play”	(GIG, 2001, p. 47)
31	Coalition	(GIG, 2001, p. 48), (Fewell, 2003, p. 1)
32	Information Systems	(DSP, 2001, p. B4-iii)
33	Materiel	(DSP, 2001, p. B4-iii)
34	Doctrine	(DSP, 2001, p. B4-iii)
35	Domain-Centered	(DSP, 2001, p. B4-iii)
36	Mission-Centered	(DSP, 2001, p. B4-iii)
37	International	(DSP, 2001, p. B4-2)
38	Cultural	(Clark, 2001, p. 2)
39	Flexible	(Clark, 2001, p. 2)
40	Force	(Clark, 2001, p. 1)
41	Model	(Clark, 2001, p. 1)
42	Non-technological	(Clark, 2001, p. 1)
43	Planned	(Clark, 2001, p. 3)
44	Responsive	(Clark, 2001, p.2)
45	Cities	(Kinder, 2002, p. 18)
46	Horizontal	(Kinder, 2002, p. 27)
47	Intra-organisational	(Kinder, 2002, p. 23)
48	Public Administration	(Kinder, 2002, p. 6)
49	Public Service	(Kinder, 2002, p. 7)
50	Vertical	(Kinder, 2002, p. 27)
51	Constructive	(Levine, 2003, p. 5), (Carney, 2004, p. 19), (Morris, et al., 2004, p. 11)
52	Operational	(Levine, 2003, p. 6), (Carney, 2004, p. 19), (Kasunic & Anderson, 2004, p. 2), (Morris, et al., 2004, p. 11)
53	Transitive	(Morris, et al., 2004, p. 28)
54	Programmatic	(Levine, 2003, p. 4), (Carney, 2004, p. 19), (Morris, et al., 2004, p. 11)
55	System-of-Systems	(Morris et al., 2004, p. Cover)
56	Conceptual	(Carney, 2004, p. 18)
57	C4I	(Kasunic & Anderson, 2004, p. 9)
58	Lower-layer	(Kasunic & Anderson, 2004, p. 34)
59	Higher-layer	(Kasunic & Anderson, 2004, p. 34)
60	Application	(Kasunic & Anderson, 2004, p. 34), (Kosanke, 2005, p. 4)
61	Product-to-Product	(Kasunic & Anderson, 2004, p. 37)
62	Programmatic	(Morris, et al., 2004, p. 33)
63	Constructive	(Morris, et al., 2004, p. 35)
64	Coalition C2	(Larsen, 2006, p. 1)

Summary of 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
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)
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

Summary of Interoperability Measurement Models

	SoIM	QoIM	MCISI	LISI	IAM	OIM	Stoplight	LCI	LCIM	NMI	SoSI	NTI	OIAM	*i-Score*
Year	1980	1989	1996	1998	1998	1999, 2003	2002	2003	2003	2003	2004	2004	2005	2007
Authors	LaVean	Mensh, Kite, Darby	Amanowicz, Gajewski	Various	Leite	Clark, Jones, Fewell	Hamilton, Rosen, Summers	Tolk	Tolk, Muguira	Various	Morris, et al.	Stewart, et al.	Kingston, Fewell, Richer	Ford, et al.
Type of Interoperability Measured														
Operational Interoperability						X								
Technical Interoperability	X		X	X	X					X	X			
Operational Interoperability Agility													X	
Non-Technical Interoperability												X		
Coalition Interoperability								X						
Conceptual Interoperability									X					
Programmatic Interoperability							X				X			
Constructive Interoperability											X			
Multiple Types		X									X			X
Type of Measurement(s)											N/A			
Non-number			X	X	X	X	X		X	X		X	X	
Number	X		X		X			X	X			X		X
Aggregate (roll up to single measure?)			X				X							X
Non-aggregate or multiple measurement(s)		X	X	X	X	X	X	X	X	X		X	X	
Basis of Measurement											N/A			
System				X	X	X	X			X				
System Pair	X		X	X		X			X	X				X
More than two systems	X		X											X
Mission, scenario, thread, coalition, unit, etc.		X				X		X				X	X	X
Math Operations Possible on Measurement(s)?														
Yes														X
No	X			X		X	X	X	X	X	X	X	X	
Maybe, or only on part of model		X	X		X									
Institutionalization														
Government				X						X				
Industry														
Standards Organization														
Other or unknown	X	X	X		X	X	X	X	X		X	X	X	X