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***Review:***

# A review of interoperability assessment models*

Reza REZAEI, Thiam-kian CHIEW, Sai-peck LEE

(*Faculty of Computer Science & Information Technology, University of Malaya, Kuala Lumpur 50603, Malaysia*)

E-mail: rezarezaei@siswa.um.edu.my; {tkchiew, saipeck}@um.edu.my

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**Abstract:** Interoperability is the ability of systems to provide services to and accept services from other systems, and to use the services exchanged so as to operate together in a more effective manner. The fact that interoperability can be improved means that the metrics for measuring interoperability can be defined. For the purpose of measuring the interoperability between systems, an interoperability assessment model is required. This paper deals with the existing interoperability assessment models. A comparative analysis among these models is provided to evaluate the similarities and differences in their philosophy and implementation. The analysis yields a set of recommendations for any party that is open to the idea of creating or improving an interoperability assessment model.

**Key words:** Interoperability, Assessment, Measurement

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## 1 Introduction

Interoperability is a broad and complex subject. A common perception is that interoperability is synonymous with connectivity (Kosanke, 2006). However, it is actually much more than mere connectivity. It is also relevant to diverse operational and procedural concepts (Chairman Joint Chiefs of Staff, 2004; 2008). For this reason, developing and implementing an assessment and measurement solution in an area of such complexity is extremely problematic (DoD Directive, 1980).

Interoperability is often considered to be a desirable but unattainable goal, rather than a condition that can be quantified (Morris *et al.*, 2004a). Despite the current serious interoperability deficits, accurately and visually assessing, measuring, and reporting interoperability are inevitable for determining the priorities of systems (Stewart, 2004).

As Presson (1983) noted, "interoperability will never be an analytically useful field of study until it is defined in a quantitative way". Unfortunately all the attempts to develop a comprehensive interoperability assessment and measurement method acting on a systematic basis have been in vain (DoD, 1999).

First, we review the definitions and present conditions of interoperability concepts. The levels of the system interoperability model, which to some extent provides a structured and systematic approach for assessing and measuring the interoperability, is then described. Finally, a summary of other models and the best practices for interoperability measurement and assessment is presented.

## 2 Interoperability definitions

Numerous definitions have been given for interoperability. For instance, the following four definitions of interoperability have been given by IEEE (Radatz *et al.*, 1990; Breitfelder and Messina, 2000): (1) "The ability of two or more systems or elements to exchange information and to use the information that has been exchanged"; (2) "The capability for units of equipment to work efficiently together to provide useful functions"; (3) "The capability—promoted but

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not guaranteed—achieved through joint conformance with a given set of standards, that enables heterogeneous equipments, generally built by various vendors, to work together in a network environment"; (4) "The ability of two or more systems or components to exchange and use the exchanged information in a heterogeneous network" (Geraci *et al.*, 1991).

The US Department of Defense has also introduced multiple definitions of interoperability, some of which incorporate the IEEE definitions: (1) "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" (DoD, 2001b). (2) "The condition achieved among communications-electronics systems or items of communications-electronics systems 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, 2001a). (3) "(a) Ability of information systems to communicate with each other and exchange information; (b) Conditions, achieved in varying levels, when information systems and/or their components can exchange information directly and satisfactorily between them; (c) The ability to operate software and exchange information in a heterogeneous network (i.e., one large network composed of several different local area networks); (d) Systems or programs capable of exchanging information and operating together effectively" (United States Joint Forces Command, 2001).

## 3 Interoperability levels

Attaining interoperability requires resolution at several distinct levels. According to Heiler (1995), Munk (2002), Levine *et al*. (2003), Kasunic and Anderson (2004), Carney and Oberndorf (2004), Morris *et al.* (2004b), and Chen (2006), there are four levels of interoperability: technical, syntactic, semantic, and organizational interoperability.

1. Technical interoperability is achieved among communications-electronics systems or items of communications-electronics equipment when services or information can be exchanged directly and satisfactorily between them and their users (Novakouski and Lewis, 2012). In referring to specific cases, the interoperability degree must be defined (Kinder, 2003; Kosanke, 2006). Technical interoperability is typically associated with hardware/software components, systems, and platforms that enable machine-to-machine communication. This type of interoperability often focuses on communication protocols and the infrastructure required for the protocols to function (van der Veer and Wiles, 2008).

2. Syntactic interoperability is defined as the ability to exchange data. Syntactic interoperability is generally associated with data formats. The messages transferred by communication protocols should possess a well-defined syntax and encoding, even if only in the form of bit-tables (van der Veer and Wiles, 2008).

3. Semantic interoperability is defined as the ability to operate on the data according to the agreed-upon semantics (Lewis and Wrage, 2006). Semantic interoperability is normally related to the definition of content, and deals with the human, rather than machine, interpretation of this content. Thus, interoperability at this level denotes that a common understanding exists between people regarding the definition of the content (information) being exchanged (Hall and Koukoulas, 2008; van der Veer and Wiles, 2008; Guijarro, 2009).

4. Organizational interoperability pertains to the capability of organizations to effectively communicate and transfer meaningful data (information), despite the use of a variety of information systems over significantly different types of infrastructure, possibly across various geographic regions and cultures. Organizational interoperability relies on the successful interoperability of the technical, syntactic, and semantic aspects (van der Veer and Wiles, 2008).

## 4 Interoperability assessment models

Extensive research has been conducted on interoperability assessment models (Clark and Moon, 2001). This section provides a review on all of the existing assessment models for interoperability produced since 1980. The assessment models were identified through a search of relevant articles published between 1980 and 2012 available in the Web of Science database. Google Scholar was adopted as a tool to complement the search. Keywords such as ‘interoperability’ and ‘assessment model’ were used to define the search.

### 4.1 Levels of information systems interoperability

The Levels of Information Systems Interoperability (LISI) project was developed in 1998 by the US Department of Defense C4ISR Working Group (DoD, 1998). LISI is a reference model that provides a standard process for assessment of the information systems’ interoperability. In other words, it is a procedure for defining, measuring, assessing, and certifying the degree of interoperability required or achieved by and between organizations or systems (Kasunic, 2001).

LISI evaluates the level of interoperability attained between systems. A representation of the levels of the LISI model has been given in Fig. 1 (DoD, 1998).

The LISI model focuses on enhancing the interoperability levels of complexity within the systems (DoD, 1998; Kasunic, 2003). In this model five interoperability levels (0–4) are defined and each interoperability level exists in a specific environment.

Level 0 (isolated interoperability): in a manual environment. The level includes a wide range of standalone, or isolated systems. No connection is directly allowable within these systems, and their interface is manual. The level contains manual data integration and extraction between multiple systems.

Level 1 (connected interoperability): in a peer-to-peer environment. It depends on the electronic connection between systems with some form of simple electronic data exchange. At this level, shared data types are homogeneous, such as simple text email, graphics, and voice, and the capacity for information fusing is limited for the decision makers.

Level 2 (functional interoperability): in a distributed environment. At this level, systems are located in local network areas that permit data transfer from one system to another. Increasingly sophisticated media exchanges are provided at this level, and systems share logical data models with each other. At the level, heterogeneous data contained in a simple information format is combined, and the fused information is shared between functions and systems.

Level 3 (domain-based interoperability): in an integrated environment. At this level, the connection between systems is via wide area networks (WANs) that permit several users to access data. At this level, independent applications exchange information with each other using agreed-upon domain data models. Systems at this level support group collaboration in information combination, and are permitted to implement business rules and processes to facilitate direct database-to-database interactions.

Level 4 (enterprise-based interoperability): in a universal environment. At this level, systems are allowed to use a distributed global information space across multiple domains. At this level, complex data can be accessed by multiple users simultaneously, and applications and data are shared totally and can be distributed to support fused information. In addition, it is possible to have advanced forms of collaboration at this level. Common data interpretation is applied across the entire enterprise regardless of the format.

The LISI reference model is the foundation of the LISI process. Five LISI interoperability levels are illustrated in rows, and four columns, demonstrating that the attributes of the LISI reference model contain procedures, applications, infrastructure, and data (PAID). The broad classification of level/attribute intersections facilitates addressing the required specific capabilities. Consequently, in LISI, interoperability aspects are categorized into four unified attributes:

1. Procedure attributes include numerous forms of operational controls and documented guidance that influence all aspects of system integration, development, and operational functionality. The procedure attributes address the architecture guidance and standards, policies and procedures, and doctrine that enable information exchanges between systems.

2. Application attributes include the system mission, which is the fundamental purpose of system building and functional requirements of the system. These attributes indicate applications that permit processing, exchange, and manipulation.

3. Infrastructure attributes in which the establishment and use of a connection among applications or systems is supported. These attributes include the environments enabling the interaction such as system services, networks, and hardware.

4. Data attributes focus on information processes of the system, and contain both data format (syntax) and its content or meaning (semantics). These data attributes of interoperability include protocols and formats enabling information and data interchanges.

<table>
<tr><th colspan="3" rowspan="2">LEVEL<br>(environment)</th><th colspan="5">Interoperability attributes</th></tr>
<tr><th colspan="2">Procedures</th><th>Applications</th><th>Infrastructure</th><th>Data</th></tr>
<tr><td rowspan="3">Enterprise level (universal)</td><td rowspan="3">4</td><td>c</td><td colspan="2">Multi-national enterprises</td><td rowspan="2">Interactive (cross applications)</td><td rowspan="3">Multi-dimentional topologies</td><td rowspan="2">Cross-enterprise models</td></tr>
<tr><td>b</td><td colspan="2">Cross government enterprise</td></tr>
<tr><td>a</td><td colspan="2">DoD enterprise</td><td>Full object cut & paste</td><td>Enterprise model</td></tr>
<tr><td rowspan="3">Domain level (integrated)</td><td rowspan="3">3</td><td>c</td><td colspan="2" rowspan="3">Domain service/agency doctrine, procedures, training, etc.</td><td>Shared data (situation displays direct DB exchanges)</td><td rowspan="3">WAN</td><td>DBMS</td></tr>
<tr><td>b</td><td>Group collaboration (white boards, VTC)</td><td rowspan="2">Domain models</td></tr>
<tr><td>a</td><td>Full text cut & paste</td></tr>
<tr><td rowspan="3">Functional level (distributed)</td><td rowspan="3">2</td><td>c</td><td colspan="2" rowspan="2">Common operating environment (DII-COE level 5) compliance</td><td>Web browser</td><td rowspan="2">LAN</td><td rowspan="3">Program models & advanced data formats</td></tr>
<tr><td>b</td><td>Basic operations (documents, maps, briefings, pictures, spreadsheets, data)</td></tr>
<tr><td>a</td><td colspan="2">Program standard procedures, training, etc.</td><td>Adv. messaging (parsers, e-mail+)</td><td>Network</td></tr>
<tr><td rowspan="4">Connected level (peer-to-peer)</td><td rowspan="4">1</td><td>d</td><td colspan="2" rowspan="2">Standards complaint (JTA, IEEE)</td><td>Basic messaging (plain text, e-mail w/o attachments)</td><td rowspan="3">Two way</td><td rowspan="4">Basic data formats</td></tr>
<tr><td>c</td><td>Data file transfer</td></tr>
<tr><td>b</td><td colspan="2" rowspan="2">Security profile</td><td rowspan="2">Simple interaction (text chatter, voice, fax, remote, access, telemetry)</td></tr>
<tr><td>a</td><td>One way</td></tr>
<tr><td rowspan="5">Isolated level (manual)</td><td rowspan="5">0</td><td>d</td><td colspan="2">Media exchange procedures</td><td rowspan="4">N/A</td><td>Removable media</td><td>Media formats</td></tr>
<tr><td>c</td><td rowspan="3">Manual access controls</td><td>NATO level 3</td><td rowspan="3">Manual re-entry</td><td rowspan="3">Private data</td></tr>
<tr><td>b</td><td>NATO level 2</td></tr>
<tr><td>a</td><td>NATO level 1</td></tr>
<tr><td>0</td><td colspan="5">NO KNOWN INTEROPERABILITY</td></tr>
</table>

**Fig. 1 The Levels of Information Systems Interoperability (LISI) model**

The most important aspect of utilizing the LISI model for assessment of interoperability lies in its valuable feature of expressing the results in the interoperability metric form. The LISI metric quantitatively represents the 'interoperability degree' obtained from the systems. The required tool that helps in determining the degree of interoperability is an interoperability questionnaire acting as the data accumulation source and the LISI capabilities model that operates as a template for measurements (DoD, 1998).

By using LISI measurements, the aim of capturing the possibility of interactions amongst the systems is followed. In other words, such measurement clearly determines the outcome of a comparison between the systems with regards to the capability of interoperability incorporated within each individual system (Amanowicz and Gajewski, 1996).

Various styles of metric exist for the LISI model interoperability based on the nature, goal, and strategy they use for performing the comparison and displaying the results. Fig. 2 shows a typical configuration of various options available for the explanation of LISI metrics.

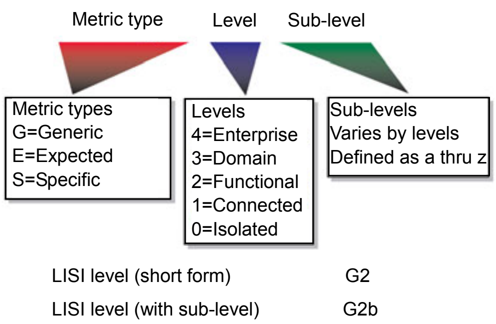


**Fig. 2 Interoperability metrics of the LISI model**

The LISI metric provides a shorthand definition of the particular form of interoperability as expressed in the LISI model.

As described in Fig. 2, there are three types of LISI metrics based on three kinds of relationships being measured. The main distinction between these three types is the comparison of a single system against the LISI model (generic) and the two different cases where two systems are compared to each other (expected and specific). The three metric types are addressed below:

1. Genetic level of interoperability: This level is calculated for single systems and expressed as a mathematically calculated value by making a comparison between a single system on the one hand and the LISI capabilities model on the other hand (Stewart *et al.*, 2004). The overall set of abilities across PAID is represented by a system that in practice determines the generic level. The interoperability generic level of any given system is determined by the highest level in the LISI capabilities model where all the PAID capabilities are implemented (without dependency to any certain implementation alternatives) (Fig. 3). This entails the necessity for a system to have implementations for each individual capability across the PAID attributes.

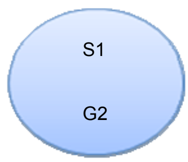


**Fig. 3 Generic level of interoperability**

2. Expected level of interoperability: It is assessed for a pair of systems and is the level that is anticipated using the LISI model as a reference, but without performing an implementation by implementation comparison between the two systems (Kingston, 2005). The interoperability expected level between one system and another is defined as the lowest generic level of both systems, that is, the level where the interoperability of both systems with each other is expected (Clark and Jones, 1999). This expected level is specified on the basis that any two systems must be capable of interoperating at a certain level in case each of them possesses the set of generic capabilities necessary for achieving the information exchange types of that level (Fig. 4).

3. Specific level of interoperability: It has been defined as the metric value calculated among the two systems resulting from the comparison among the implementation alternatives that each of the systems has used concerning the registered PAID abilities. The specific level is the highest level at which two systems perform documented interoperable implementations throughout the PAID aspects. It may differ from the expected level due to adding items to the LISI options tables and/or different criteria considerations of technical implementation (Fig. 5).

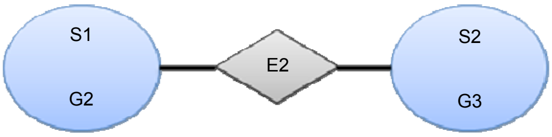


**Fig. 4 Expected level of interoperability**

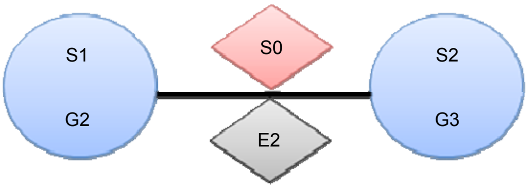


**Fig. 5 Specific level of interoperability**

The most important LISI products are addressed in detail. These are the products that are used, constructed, or analyzed directly in interoperability assessment of the systems (DoD Directive, 1980).

Interoperability data collection tool: for gathering relevant information necessary for assessing the interoperability of information systems, the LISI model makes use of an interoperability questionnaire.

Interoperability profiles: data collected by the LISI questionnaire is mapped to the template of the LISI capabilities model using the interoperability profiles (Levine *et al.*, 2003).

The implementation choices are therefore captured by the profiles for each of the PAID capabilities existing in the system(s) which is(are) under assessment, of course in a format that is able to facilitate the required comparison at system-to-levels as well as system-to-system scales (Schade, 2005).

System metrics are derived from profiles. The interoperability profile of a system has been depicted in Fig. 6 as a notional example. In Fig. 6, S1 (system 1) has a generic interoperability level of '2' while S3 (system 3) has a generic interoperability level of '3'.

A potential interoperability matrix can be generated for a group of systems based on the generic interoperability level of each system and the specific interoperability level for each system pair within the group. For a group of systems, a potential interoperability matrix is generated on the basis of the generic interoperability level of each individual system, and for the system pairs within the group, based on the specific interoperability level.

For example, in Fig. 7, systems are represented as S1, S2, etc. The shaded row and column next to the system name contain the generic interoperability level for each system. The intersections throughout the matrix contain the specific interoperability level between each pair of systems identified on the two axes. For example, the specific interoperability level between systems S1 and S2 is shown as '2' and the specific interoperability level between systems S2 and S4 is '1'. Different legends are used to highlight whether the specific interoperability level is less than, equal to, or greater than the expected interoperability level.

If the specific interoperability level equals the expected level, the system pairs have consistent implementation options for the group of capabilities that determine the interoperability level they have achieved.

If the specific interoperability level is less than the expected level, it means that one of the two systems is using at least one implementation of some important capability differing from the other, making it impossible for the two systems to maintain interoperability at the expected level (USA and Australia, 2004).

If the specific interoperability level is greater than the expected level, it means that both systems possibly use dedicated interfaces or some other shared implementations making them capable of interacting at an upper level than the expected level (Meyers and Smith, 2007).

### 4.2 Spectrum of the interoperability model

LaVean (1980) stated that the interoperability among systems was weak because of a "lack of a measure of interoperability by which to state goals for specific systems". To overcome this deficiency, he developed a spectrum of interoperability model. He developed two critical measures of interoperability assigned levels, namely the technical possibility and management/control possibility (Table 1), which state that "by combining these two measures, it is possible to derive a spectrum of interoperability that permits cost-versus-benefits tradeoffs". LaVean (1980)'s recognition of the possibility of differences among interoperability levels of each specific service that the two systems provide for each other, led him to devise a visualization method (interoperability matrix) able to list the services on the matrix rows and interoperability levels on the columns. Furthermore, for the purpose of showing the evolution of the

| LEVEL (environment) | | | Interoperability attributes: Procedures | Applications | Infrastructure | Data |
|---|---|---|---|---|---|---|
| Enterprise level (universal) | 4 | c | | | | |
| | | b | | | | |
| | | a | | | | |
| Domain level (integrated) | 3 | c | Service-approved MNS & ORD, WAN addressing scheme | | TCP/IP WAN, NFS, SNMP, ISDN card | MIDB, SQL |
| | | b | | | | |
| | | a | | | | |
| Level 2c | | | | | | |
| Functional level (distributed) | 2 | c | DII COE complaint, windows-std file name extensions | IE 4.0 | IP LAN NES, NTP, X.500 | NIFT, 2 USMTF, x.400, wks, xls, DTED, DBDB, .ppt, .doc, RPF, CGM, JBIG, JPEG, HTML, VPF |
| | | b | | MS office, access CMTK, SD, MPEG viewer | | |
| | | a | On-line documentation | Eudora | TIBS, LINK 16 & 22 | |
| Connected level (peer-to-peer) | 1 | d | Windows interface design guide (JTA) | | HF data modem, Kermit, STU III, GSM cellular | MPEG1.2 GKS, .wmf |
| | | c | | FTP | | |
| | | b | ITU-T Rec X.509. Mil Std 2045-28500 security labels | Chat 2.0, Win32 API, PPS | | |
| | | a | | | GBS | |
| Isolated level (manual) | 0 | d | Login procedures | | | |
| | | c | | | | |
| | | b | | | | |
| | | a | | | | |
| | | 0 | NO KNOWN INTEROPERABILITY | | | |

**Fig. 6 The interoperability profile of a sample system**

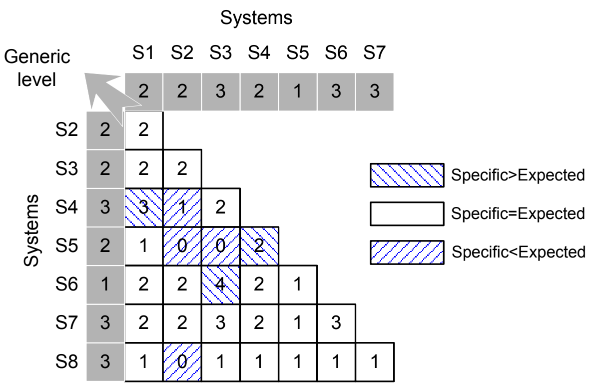


**Fig. 7 Potential interoperability matrix**

**Table 1 Spectrum of the interoperability model**

| 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 |

interoperability of the systems across time, he introduced a view of the interoperability matrix (Dimario, 2006). The intention behind developing the spectrum of interoperability model was to provide a convenient tool for system managers to evaluate their systems' current status, define the interoperability goals for the future, and visually control the present status in relation to the future (LaVean, 1980).

### 4.3 Quantification of interoperability methodology

Mensh *et al*. (1989) introduced a method called the 'quantification of interoperability', which forms the foundation for the LISI model. Their method was unique in that they incorporated the interoperability measurement with a measurement of effectiveness (MOE). Their goal was to assess interoperability issues for three mission areas: wide area surveillance, over-the-horizon targeting, and electronic warfare. They stated that "interoperability of systems, units, or forces can be factored into a set of components that can quantify interoperability" and identified the seven necessary components as languages, standards, environment, procedures, requirements, human factors, and media. For each component they allocated an MOE logic function and used it for creating a truth table that was filled with the simulation of discrete events. They stated that "our methodology for quantifying interoperability is being pursued"; however, they emphasized that "additional exercises will be required and are currently in the planning stages".

### 4.4 Military communications and information systems interoperability

Amanowicz and Gajewski (1996) introduced a model for measuring interoperability called 'Military Communications and Information Systems Interoperability' (MCISI) to mathematically model the interoperability of the Communications and Information Systems (CIS). Given the fact that interoperability modeling incorporates operational requirements, standards, CIS data, interfaces, and modeling facilities, they used a colored cube for visualizing the MCISI model. One axis of the cube represented the command level; the second indicated the CIS services and the third represented the transmission medium. The intersections had their own colors: red that represented none, yellow that meant partial, and green that indicated full interoperability of a specific service via a specific medium at a specified level of command. Furthermore, they explained that a number of points represent a set of systems within a multi-dimensional environment, while the features of the systems constitute the coordinates of the points. They then defined a normalized 'distance' between each two points as $d(A, B)$, and stated that in cases where $d(A, B)=0$, the systems $A$ and $B$ acquired full interoperability, and if $d(A, B)>1$, the two systems' interoperability was reduced. Through considering a dendrite (broken line connecting all points in a set) arrangement of systems, they covered a set of systems, maintaining that the most suitable arrangement is the one in which the dendrite has the shortest length.

### 4.5 Interoperability assessment methodology

The interoperability assessment methodology was published initially in the Proceedings of the 66th Military Operations Research Society (MORS) Symposium, three months after the publication of the LISI model; further revisions of the model were published in 1999 and 2003. It is not known whether the author knew about the LISI effort, but in his paper he made reference to Mensh *et al*.'s 'quantification of interoperability'. The interoperability assessment methodology like the quantification of interoperability, is based on the idea of 'measurement and quantification of a set of interoperability system components' (Leite, 1998). The interoperability assessment methodology model introduced nine components (contrary to the quantification of interoperability in which seven are used), which are requirements, node connectivity, data elements, protocols, information flow, information utilization, interpretation, latency, and standards. Each of the nine components included either a 'yes/no' response or a mathematical equation. Leite (1998) further defined 'degrees of interconnection' which includes the availability, connectivity, understanding, interpretation, utility, feedback, and execution. He described the interoperability assessment methodology using a flowchart and applied the process to the Navy's Tactical Ballistic Missile Defense Program.

The interoperability assessment methodology components identified by Leite (1998) are described as follows:

1. Requirements: Any system or components thereof, for which the interoperability is considered, must have requirements in common. Without such requirements, system developers and acquisition managers have no obligation to deliver interoperable systems.

2. Standards: The interoperability norms have defined the transmitting and receiving nodes, the message content, and the media used for carrying the data (data link) between the nodes (Meyers *et al.*, 2005).

The systems must achieve a common implementation of the standards to be interoperable.

3. Data elements: The standards and requirements have been thoroughly examined. If the assessments in those areas (the requirements and standards) are positive, we can claim that the flow of information among the nodes is established via a common format with suitable data rates. However, the interoperability is not yet sure. Next, what is important is assessing the data stream content.

4. Node connectivity: As node connectivity is a variable depending on time (both discrete and continuous time intervals), it can be said that it is a troublesome element to measure the interoperability amongst others. In simple terms, connectivity is the ability to send and receive data at any time. This implies that the transmitter and receiver are both up and that the link is available. For any interoperable system the operator has control of the medium and equipment; the environment represents those items which are outside the operator's direct control.

For a communication system, an index called the connectivity index is calculated, showing the relationship between the number of nodes in the system and the paths available between them. The following equation is used for defining the connectivity index:

$$C_{\mathrm{i}}=\frac{k}{n(n-1)}, \tag{1}$$

where $C_{\mathrm{i}}$ is the connectivity index, $k$ the number of connections (paths between nodes), and $n$ the number of nodes (participating units).

Measuring connectivity is directly affected by counting the total number of messages initially launched by all the units participating in communication and the number of messages received by the network or data communication link. As long as the link is working, the exemplified connectivity represents the network connectivity. Should the network operate intermittently, the sample needs to be carefully selected and tested, so that achieving the necessary confidence level is assured. The following shows the general relationship that is used for measuring the connectivity:

$$C=\frac{1}{n_{\mathrm{r}}}\sum_{y=1}^{n_{\mathrm{r}}}(M_{\mathrm{r}})_y \bigg/ \sum_{x=1}^{n_{\mathrm{t}}}(M_{\mathrm{t}})_x, \tag{2}$$

where $C$ is the node connectivity (during the measurement period), $n_{\mathrm{r}}$ the number of receiving nodes, $n_{\mathrm{t}}$ the number of transmitting nodes, $M_{\mathrm{t}}$ the messages transmitted by a node, and $M_{\mathrm{r}}$ the messages received by a node.

5. Protocols: Protocols facilitate access to the data stream. On the transmitting side, the protocol initiates the polling sequences, time allocations of transmittance, and the data that can be transmitted.

The protocols on the receiving side determine the data filtered out or sent to the user. The foundation on which the protocols are based is the data exchange requirements, data volume, and the available capacity of datalink/processor.

6. Information flow: Data volume is normally a function of the operations' tempo and the area of interest (AOI), which is determined by the operational commander. The operations' tempo is event-driven, but the estimations can still be performed on historical and exercise results.

Capacity is determined by the number of data links available. Practically multiple numbers of links or paths are available. For combat systems and war instruments, primary and back up paths are required. The data flow redundancy restricts the total capacity to a value lower than the sum of each individual system.

In connection with the system performance there are several items to be measured or calculated, including capacity, data latency, and system overload. The following relationships are used for these measurements:

Capacity: A system's capacity is the rate of data passage over time. The maximum data rate, given the involved operating parameters, will be calculated for a system or a group of systems. The following relationship is used for this purpose:

$$Q_{\mathrm{eff}}=(Q_{\mathrm{max}}-Q_{\mathrm{oh}})(t_{\mathrm{f}}-t_{\mathrm{p}}), \tag{3}$$

where $Q_{\mathrm{eff}}$ is the effective system capacity (data rate), $Q_{\mathrm{max}}$ the maximum data rate, $Q_{\mathrm{oh}}$ the system overhead data rate, $t_{\mathrm{f}}$ the time slot duration (unit transmission), and $t_{\mathrm{p}}$ the unit propagation time.

System overload: A system overload occurs when more data must be exchanged than the system is able to transmit. Typically, the overload is placed in a queue and then transmitted when capacity is available.

Therefore, the measure of system overload is the sum of the messages remaining in queues after their assigned transmission period for all system nodes.

$$M_{\mathrm{OL}} = n_{\mathrm{t}} \sum_{y=1}^{n_{\mathrm{r}}} (M_{\mathrm{q}})_y, \tag{4}$$

where $M_{\mathrm{OL}}$ is the system message overload, and $M_{\mathrm{q}}$ the messages in queue to be transmitted by a node.

Underutilization: When the data rate/message load of the system is lower than the full capacity while messages are in queues waiting for transmission, we are faced with an underutilization situation. In other words, this occurs if the transmission allocation to a number of selected nodes is lower than what is required to empty the queue by termination of the transmission period. Moreover, other nodes cannot use their allocated time span.

$$Q_{\mathrm{uu}} = \begin{cases} M_{\mathrm{OL}}, & M_{\mathrm{OL}} \le Q_{\mathrm{eff}} - Q, \quad (5) \\ Q_{\mathrm{eff}} - Q, & M_{\mathrm{OL}} > Q_{\mathrm{eff}} - Q, \quad (6) \end{cases}$$

where $Q_{\mathrm{uu}}$ is the system underutilization (data rate), and $Q$ the measured/observed data rate.

Undercapacity: When messages waiting in queues and data rate of the system reach maximum, undercapacity occurs.

$$Q_{\mathrm{uc}} = (Q + M_{\mathrm{OL}}) - Q_{\mathrm{eff}} \text{ (must be >0)}, \tag{7}$$

where $Q_{\mathrm{uc}}$ is the system undercapacity (data rate).

7. Data latency: It is the time span consumed from the event time to the time of receiving the message by the user, that is, the tactical data processor. The latency is usually divided into smaller segments for analytical objectives. Some of the common time periods are: (1) the event time to time of observation; (2) time of observation to processing completion time; (3) time of completion of processing to the receipt time of the tactical data processor.

This division can be useful in situations where a remote sensor and intermediary processing for reducing the data to an exploitable form (track message) occur before passing them to the user. The relevant relationships are as follows:

$$\overline{\Delta t} = t_{\mathrm{r}} - t_{\mathrm{e}}, \tag{8}$$

$$\overline{\Delta t}_{\mathrm{o}} = t_{\mathrm{o}} - t_{\mathrm{e}}, \tag{9}$$

$$\overline{\Delta t}_{\mathrm{m}} = t_{\mathrm{m}} - t_{\mathrm{o}}, \tag{10}$$

$$\overline{\Delta t}_{\mathrm{r}} = t_{\mathrm{r}} - t_{\mathrm{m}}. \tag{11}$$

Rewrite Eq. (8) as

$$\overline{\Delta t} = \overline{\Delta t}_{\mathrm{o}} + \overline{\Delta t_{\mathrm{m}}} + \overline{\Delta t}_{\mathrm{r}}, \tag{12}$$

where $\Delta t$ is the time latency, $\Delta t_{\mathrm{o}}$, $\Delta t_{\mathrm{m}}$, and $\Delta t_{\mathrm{r}}$ are the latencies of observation, measurement/processing, and transmission/receipt, respectively, and $t_{\mathrm{e}}$, $t_{\mathrm{o}}$, $t_{\mathrm{m}}$, and $t_{\mathrm{r}}$ are the time of event, observation, completion of processing, and receipt, respectively.

8. Interpretation: After the consistency of the transmitted data set is ensured, the interpretation of the data by each individual processor must be investigated.

9. Information utilization: Having passed the data and correctly interpreted it, the next step would be to verify that the proper action is taken. Verification of the action taken involves a review of the logic associated with every possible option in response to a message or operator action. These deal with questions of interoperability and not with the difficult, higher-level topic of measuring mission effectiveness. These data would be qualitative in nature, perhaps binary (i.e., successful vs. failed). Some suggested measures in this area include: (1) percentage of initial transmission messages received correctly by shooters; (2) percentage of consistency/disparity of redundant data sources; (3) number of attempts needed to establish connections; (4) delay in sending critical command messages and time to receive and acknowledge messages.

Now that every part of the interoperability puzzle has been reviewed, it is possible to develop an assessment process for objective assessing of the system interoperability. Many steps of the assessment process must be replied by a ‘yes/no’ or ‘go/no go’ answer. The negative answer represents no interoperability. With regards to the elements for which making calculations is necessary, results with lower than optimum values show the possibility of interoperability, but with degraded quality. Degraded interoperability can be considered as systems functioning with an imperfect data set. Most of the time, it is the outcome of reduced connectivity or sometimes, system overload.

The interoperability assessment process is shown in Fig. 8. Testing must be considered as an integral component of the definition of the requirements, as well as system development. Thus, testing must be essentially continuous, and 'stability' is a state that is never reached in any meaningful sense. Without continuous feedback, primary execution of the processes and systems may result in satisfactory interoperation at first, but not at a later time.

Results of this study show that interoperability must be considered for systems at the design stage, especially when the system requirements are defined. Developers can assign a number of components or characteristics that all together provide an objective interoperability assessment. Analysis of such characteristics is then transformed into a process or applicable flow chart by the analyst for determining the system interoperability (Leite, 1998).

### 4.6 Stoplight

Hamilton *et al.* (2002) introduced a very simple model for interoperability measurement called the Stoplight model. They maintained that "interoperability is notoriously difficult to measure"; still, they introduced a model for measuring it. This model is aimed at helping the decision makers determine whether or not the legacy system they use can meet the operational and acquisition interoperability requirements. As a matrix, it has been designed in a way that "meets operational requirements (yes/no)" is shown in rows and "meets acquisition requirements (yes/no)" appears in the matrix columns. The matrix intersections are in red, yellow, orange, and green. Assigning this hierarchical set of colors depends on how well each specific requirement is fulfilled. An example of a color coding that can be adapted on a timeline to represent the future improvements of the plan interoperability was introduced by Hamilton *et al.* (2002), though it was not institutionalized in the Department of Defense. The above two methods help to develop a four-colored system of interoperability assessment as shown in Tables 2 and 3 (Hamilton *et al.*, 2002).

### 4.7 Layered interoperability score

As a method of interoperability measurement for all kinds of systems, the layered interoperability score (i-Score) is used in an operational process context (Ford *et al.*, 2007a; 2008). This method uses the current architecture data and can involve more than one interoperability type. What distinguishes the i-Score method is the mechanism it uses for determining an empirical upper limit of interoperability for those systems that support the operational process. The i-Score method can accept custom layers allowing the analyst to offset the i-Score measurement for an unlimited number of performance factors related to interoperability. This set of factors can include bandwidth, mission capability rate, protocols, atmospheric effects, or probability of connection, amongst others.

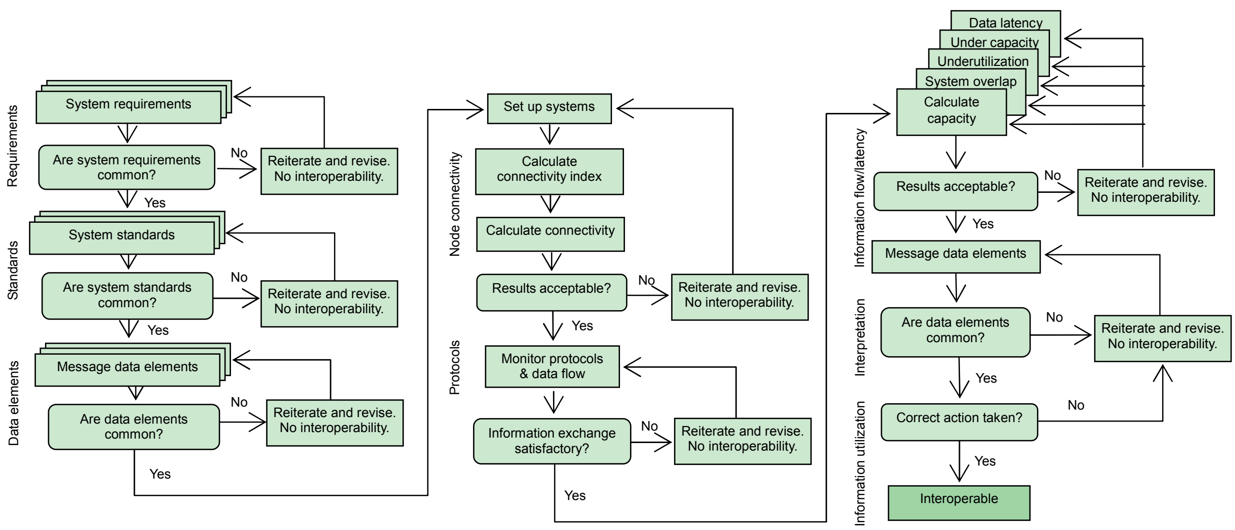


**Fig. 8 Interoperability assessment process**

**Table 2 Stoplight model**

| Meets operational requirements? | Meets acquisition requirements? | |
|---|---|---|
| | Yes | No |
| Yes | Green | Yellow |
| No | Orange | Red |

**Table 3 Stoplight color definitions and implications**

| Color | Definition | Implication |
|---|---|---|
| Green | The system meets its interoperability requirement set and has no known interoperability problems | Fielded system without known issues that meets all documented requirements |
| Yellow | The system does not meet its interoperability requirement set, but has no known interoperability problems | Documented requirements do not reflect operational use of the system |
| Red | The system does not meet its interoperability requirement set, but has no known interoperability problems | Improvement, migration and/or action plans needs to be put in place |
| Orange | The system meets its interoperability requirement set, but has known interoperability problems | Revisit requirements and determine if requirements are adequate |

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.

Other possible layers are reliability, cost, schedule, and performance which are used for measuring the impact(s) of diverse programmatic changes on the interoperability process. This method is useful for non-traditional measuring of interoperability like policy or organizational interoperability measurements.

### 4.8 A new approach for measuring the enterprise interoperability

The primary objective of this model was to introduce a new approach of measuring the enterprise interoperability (Chen *et al.*, 2008). This approach developed within frameworks of two major European IST projects, INTEROP NoE and ATHENA IP (Ruggaber, 2005; Berre *et al.*, 2007), were implemented in this field.

Considering the basic concepts of enterprise interoperability, the author(s) presented three varieties of measurement methods for enterprise interoperability: potentiality of interoperability, compatibility of interoperability, and performance of interoperability (Chen, 2006).

#### 4.8.1 Measuring the potentiality of interoperability

The interoperability potentiality is concerned with a set of characteristics that have impact on the ability to interoperate with a third partner. The objective of this measure is to evaluate the potential of a system to accommodate dynamically to overcome possible barriers when interacting with a partner.

By definition, potentiality is the fact that every enterprise features some inherent attributes relative to the interoperability, making it capable of conveniently interoperating with other enterprises, if the possibility for a partnership exists. To put it another way, potentiality means an intra-enterprise assessment of interoperability without the need to know the interoperating partner.

The proposed enterprise interoperability potentiality model concerns the evaluation of an enterprise according to three categories of barriers (conceptual, organizational, technological) that impact the development of interoperability, and the four areas of concern where interoperability occurs, i.e., business, processes, services, and data. For each category of barriers and each concern, five levels are defined to characterize the potentiality:

Isolated: total incapacity of interoperation;

Initial: interoperability may require great efforts, affecting the partnership;

Executable: possibility of interoperability exists but the risk of facing with problems is high;

Connectable: easy interoperability, despite the problems that may appear in distant partnership;

Interoperable: evolution of interoperability levels in the enterprise, with low risk of encountering problems.

Table 4 demonstrates the interoperability maturity model represented at the business level.

#### 4.8.2 Interoperability compatibility measure

The measurement of interoperability compatibility must be carried out during the engineering phase to incorporate interoperability within the

**Table 4 Enterprise interoperability potentiality model at the business level**

| Category of barriers | Potentiality |
|---|---|
| Conceptual | Isolated, initial, executable, connectable, interoperable |
| Organizational | Isolated, initial, executable, connectable, interoperable |
| Technological | Isolated, initial, executable, connectable, interoperable |

systems. The interoperability compatibility measure can be performed only when the two systems or two partners of the interoperation are known. The measurement is performed considering the identified obstacles to interoperability. The highest compatibility denotes no obstacle in the way of interoperability and the lowest compatibility means the weakest compatibility for interoperation.

Fig. 9 shows an exemplary illustration of obstacles identified when the two companies (*A* and *B*) wished to establish interoperability amongst themselves.

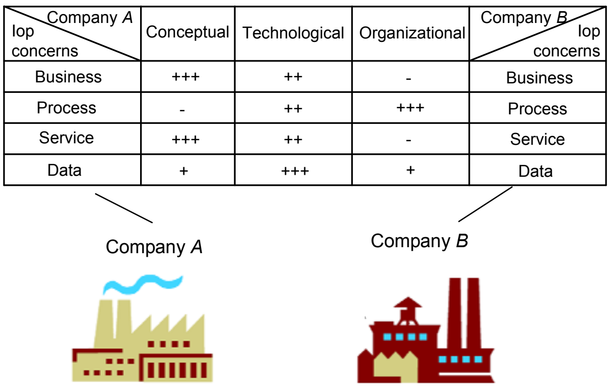


**Fig. 9 An example of the compatibility measure matrix**
'+++' means existence of a major barrier between the two enterprises, '+' means a weaker barrier, '++' means that interoperability is established despite the poor barriers, and '–'represents the inexistence of any hindering barrier

Identifying the interoperability obstacles is meant to determine those 'things' that need to be exchanged or shared between the two systems/enterprises; thus, interoperability needs a common basis for such elements. Practically, however, not all of the information controlled by the two systems are exchanged or shared. Consequently, interoperability requires the determination of the shared elements, as well as the possible obstacles that may appear between the two systems.

The compatibility measure can be performed with the help of a questionnaire. For example, regarding the three categories of interoperability barriers, the following questions can be asked:

(Conceptual compatibility) Syntactic: Has a common syntax been used for expressing the exchanged information between the two systems? Semantic: Is the meaning of the exchanged information identical between the two systems?

(Organizational compatibility) Persons: Have both sides clearly defined the authorities/responsibilities for each other? Organization: How about the structures compatibility of the parties?

(Technological compatibility) Platform: Are the technologies of the IT platforms used in both sides compatible? Communications: Are the partners using identical exchange protocols?

Evaluation of the measurement is also possible. Should an incompatibility be found, the coefficient 1 is allocated to the relevant concern of interoperability and the obstacle under examination, whereas the coefficient 0 will be assigned when no incompatibilities are found. Based on these rules, the following compatibility matrix can be made (Table 5).

**Table 5 The compatibility measurement evaluation matrix**

| Concern | Conceptual | | Organizational | | Technological | |
|---|---|---|---|---|---|---|
| | Syn | Sem | AR | O | P | C |
| Business | 1 | 1 | 0 | 1 | 0 | 0 |
| Process | 1 | 1 | 1 | 1 | 1 | 1 |
| Service | 1 | 0 | 0 | 0 | 1 | 0 |
| Data | 0 | 0 | 0 | 1 | 1 | 1 |

Syn: syntactic; Sem: semantic; AR: authorities responsibilities; O: organization: P: platform; C: communication

### 4.8.3 Interoperability performance measure

Measurement of the interoperation performance must be effected during the operation or test phase of the two interoperating enterprises (Jochem, 2010). For operational performance measurement, a number of criteria including the cost, quality, and delay can be considered. Also, the evaluation of each type of measurement can be performed using local coefficients to acquire a global coefficient with a range from 'good interoperability' to 'poor interoperability'.

Time of interoperation: The interoperation time corresponds to the time span between the information request time and the information utilization time. The interoperation time is decomposable into several time ranges. Fig. 10 shows a sample of interoperation time decomposition, which is adapted from Kasunic and Anderson (2004).

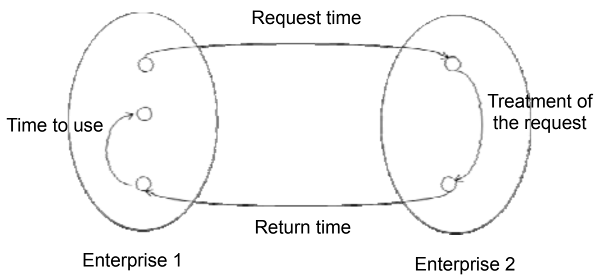


**Fig. 10 Decomposition of the time of interoperation**

The request time is the time span between the date on which the request was sent by a party and the date on which the request was received by the other party. The request treatment time relates to the time necessary for treating the request. The return time is the time span between the date on which the requested information was sent back and the date on which it was received. 'Time to use' indicates the time span between the date on which the information was received and the date on which it was exploited.

The actual value of the interoperation time can be calculated as the sum of the durations that compose this interoperation. Thus, the real value calculation formula is shown as

$$t_{\text{ineff}} = \Delta t_{\text{req}} + \Delta t_{\text{treat}} + \Delta t_{\text{ret}} + t_{\text{use}}, \qquad (13)$$

where $t_{\text{ineff}}$ is the real value of interoperation time, $\Delta t_{\text{req}}$ the request time, $\Delta t_{\text{treat}}$ the time of treatment of the request, $\Delta t_{\text{ret}}$ the return time, and $t_{\text{use}}$ the time to use.

Assessing the interoperation time corresponds to a comparison between the actual value of interoperation time and the interoperation time expected by the partners. If the measured time is longer than the expected time, it can be concluded that a deficiency produced a significant impact with respect to the time of interoperation.

Interoperation quality: Three kinds of quality are meant by interoperation quality: (1) exchange quality, (2) usage quality, and (3) conformity quality.

If the information exchange is performed correctly (that is, the information is sent successfully to the partner), then a quality interoperation has occurred. The usage quality corresponds to the amount of information that has been received by the partner, compared with the amount of requested information. If the amount of received information is higher (difficulty in treating all the information) or lower than the amount of requested information (lack of information), this situation denotes the existence of a deficiency.

The information quality relates to information exploitation, that is, whether the received information is exploitable or not.

Thus, the interoperation quality is defined as the sum of the three quality types, calculable through the following relationship:

$$q_{\text{in}} = \Delta q_{\text{ex}} + |\Delta q_{\text{ut}}| + \Delta q_{\text{conf}}, \qquad (14)$$

where $q_{\text{in}}$ is the quality of interoperation, $\Delta q_{\text{ex}}$ the quality of exchange, $|\Delta q_{\text{ut}}|$ the absolute value of use, and $\Delta q_{\text{conf}}$ the quality of conformity.

The interoperation quality assessment relates to the comparison between the interoperation quality real value and the quality that the parties expect; any difference denotes existence of a deficiency as to interoperation quality.

Interoperation cost: Interoperation costs can be defined as the costs inflicted by removing the obstacles and system modifications to obtain a satisfactory time and interoperation quality. The relationship can be denoted as follows:

$$C_{\text{in}} = C_{\text{ex}} + C_{\text{ut}}, \qquad (15)$$

where $C_{\text{in}}$ is the cost of interoperation, $C_{\text{ex}}$ the cost of exchange (i.e., the cost to exchange information), and $C_{\text{ut}}$ the cost needed to make the information exchanged usable.

The interoperation cost assessment entails a comparison between the interoperation costs' real value and costs that the partners expect. In cases where the costs calculated are more than the costs expected by the parties, it can be inferred that a deficiency in terms of interoperation costs exists.

## 5 Comparative analysis of the interoperability assessment models

In this section, the existing interoperability assessment models are discussed and compared. Table 6 illustrates each of the introduced interoperability assessment models including the main contributions they provide.

Table 7 shows the required amount of interoperability levels that each interoperability assessment model covers.

Table 8 presents the assessing formats of interoperability that are defined in each of the assessment models, and the structure offered for them. Most of the interoperability assessment models cover the technical assessing formats of interoperability, and a few of them support the assessing formats of syntactic, semantic, and organizational interoperability.

## 6 Discussion

In this section, the strengths and weaknesses of the existing interoperability assessment models are presented.

Levels of information systems interoperability: The LISI approach is intriguing because it provides a detailed interoperability model with mapping between the model and implementation technologies. In addition, the LISI approach intends to measure interoperability. It is required to categorize systems and indicate if they are capable of being interoperated (DoD, 1998; Morris *et al.*, 2004b).

The LISI approach consists of processes and a maturity model in order to determine the interoperability requirements. Also, it evaluates the information systems' ability to meet the requirements. The LISI approach creates a common structure and language

**Table 6 Main contributions of interoperability assessment models**

| Interoperability assessment model | Main contribution |
|---|---|
| Levels of information systems interoperability | Information systems' interoperability attributes |
| Spectrum of interoperability model | Measurement of interoperability is possible in terms of levels |
| Quantification of interoperability methodology | Effectiveness measurements are correlated to interoperability |
| Military communications and information systems interoperability | The spatial distance between the points in the modeled system corresponds to their interoperability |
| Interoperability assessment methodology | The interoperability attributes |
| Stoplight | Acquisition & operations require a number of interoperability requirements |
| The layered interoperability score | Measuring the interoperability is an operational process attribute which is limited to a maximum value |
| An approach for enterprise interoperability measurement | This model presents basic concepts and approaches of enterprise interoperability measurement. This model also contributes to establishing a science based enterprise interoperability considered as the roadmap for enterprise interoperability by the European Commission |

**Table 7 Levels of interoperability**

| Interoperability assessment model | Interoperability level | | | |
|---|---|---|---|---|
| | Technical | Syntactic | Semantic | Organizational |
| Levels of information systems interoperability | √ | | | |
| Spectrum of interoperability model | √ | | | |
| Quantification of interoperability methodology | √ | | | |
| Military communications and information systems interoperability | √ | | | |
| Interoperability assessment methodology | √ | | | |
| Stoplight | √ | | | √ |
| The layered interoperability score | √ | | | |
| An approach for enterprise interoperability measurement | √ | √ | √ | √ |

**Table 8 Assessing formats of interoperability**

| Interoperability assessment model | Assessment format |
|---|---|
| Levels of information systems interoperability | $X_{ny}$ per info system where $X\in$ {General, Specific, Expected}, $n\in\{0, 1, 2, 3, 4\}$, $y\in\{a, b, \ldots, z\}$ |
| Spectrum of interoperability model | 1, 2, …, 7 per a pair of systems |
| Quantification of interoperability methodology | $x/y$ ratio for each one of the seven components where $x$, $y$ are positive integers |
| Military communications and information systems interoperability | Positive integer per a pair of systems |
| Interoperability assessment methodology | Different number & non-number measures per attribute |
| Stoplight | Red, Yellow, Orange or Green per the legacy system |
| The layered interoperability score | Actual number per system, mission, operational thread, or network |
| An approach for enterprise interoperability measurement | This model focuses on presenting three kinds of enterprise interoperability measurements: interoperability potentiality, interoperability compatibility, and interoperability performance |

for interoperability between organizational information systems. This creates a transition plan and practical solutions to achieve higher interoperability levels (DoD, 1998).

In the LISI approach, there are two major concerns. Firstly, the LISI model reflects a set of standards and interoperability expectations aligned with the US Department of Defense at the time of its creation. The levels of information systems interoperability model contains risks in becoming out-dated and the interoperability options tables are required to be updated to reflect new technology and approaches. However, the levels of information systems reference model includes certain technological assumptions that reflect a specific technology bias (DoD, 1998; Morris *et al.*, 2004b).

The second concern, which is more significant, is that two or more systems will not necessarily be highly interoperable with a highly shared interoperability profile. This occurs since the differences in service qualities, the intention of using systems, how data is used, or other factors might render two systems non-interoperable, or even if the systems technical underpinnings are identical (Morris *et al.*, 2004b).

The LISI model focuses on technical interoperability and the interoperation's complexity between systems. This model does not address the organizational and environmental issues that contribute to the maintenance and construction of interoperable systems (Morris *et al.*, 2004b).

Spectrum of interoperability model: Although the spectrum of interoperability model was revolutionary and was the newest method for measuring the interoperability, no further mention of this model has been found since it was first published and it is not clear whether or not the program managers have used it to improve the interoperability among the systems (Ford *et al.*, 2007b).

Quantification of interoperability methodology: Apart from a citation made by Leite (1998) no other mention or usage of the specification can be found (Ford *et al.*, 2007b).

Military communications and information systems interoperability: The MCISI was not immediately accepted for institutionalization after publication (Ford *et al.*, 2007b).

Interoperability assessment methodology: Although interoperability assessment methodology is not institutionalized, it is referred that the interoperability assessment methodology attributes could be utilized for extending the LISI model at the mission slice level (Kasunic and Anderson, 2004; Ford *et al.*, 2007b).

The layered interoperability score: This method has not been institutionalized in the Department of Defense (Ford *et al.*, 2007b).

An approach for enterprise interoperability measurement: The three kinds of enterprise interoperability measurements allow for the consideration of the three aspects of interoperability evaluation, including measuring the set of intrinsic properties of the system for interoperability (potentiality measure), detecting barriers between two particular enterprises (compatibility measure), and performance evaluation during the operational phase (performance measure). The three measurements are complementary and consistent with respect to enterprise interoperability concepts.

Concerning interoperability potentiality measurement, the approach presented mainly focused on the maturity measure. Other system properties that have impact on interoperability (such as openness, flexibility to change and to adapt, and configurability) need to be investigated and explicitly considered.

Relating to compatibility measurement, it should be noted that the measurement can be used in an interoperability engineering project to evaluate both the degree of existing interoperability at the beginning of the project and the achieved degree at the end of the project, in order to assess the improvement of interoperability.

For interoperability performance measurement, the measures proposed at this stage of research are rather straightforward and need to be tested in more industrial cases for refinement and validation. It is also worthwhile to note that the criteria used (time, quality, and cost) are also used in other approaches to evaluate an industrial system's performance in general.

From a researcher's perspective, generally the strengths of the existing interoperability assessment models could be classified as follows: (1) All of the existing interoperability assessment models cover the technical interoperability level; (2) Few of the existing interoperability assessment models contain the organizational interoperability level.

Also, in general, the weaknesses of the existing interoperability assessment models can be described as follows: (1) From the existing interoperability assessment models, only the enterprise interoperability measurement supports the syntactic and semantic interoperability level; (2) In each of the existing interoperability assessment models, different sets of interoperability attributes have been defined. There is no unique set of interoperability attributes defined in the existing interoperability assessment models.

## 7 Conclusions

This paper deals with an overview of the development of interoperability assessment models. Measuring interoperability allows a company to know the strengths and weaknesses to interoperate and to prioritize actions to improve the interoperability. In order to measure interoperability, a number of attempts have been made to develop interoperability assessment models. With regards to the strengths of the existing interoperability assessment models, all of the existing models cover the technical interoperability level. As for the weaknesses of the existing interoperability assessment models, few of the existing interoperability assessment models contain the syntactic, semantic, or organizational interoperability level. Furthermore, in each of these interoperability assessment models, different sets of interoperability attributes have been defined. Most of the interoperability assessment models cover the relevant attributes of the technical and organizational interoperability, and only a few of them support the relevant attributes of organizational interoperability.

The realizations gained from the study of the aforementioned interoperability assessment models can be summarized as follows:

In terms of interoperability levels, an interoperability assessment model cannot be realized by addressing only the technical interoperability level. A bottom-up approach beginning with technical interoperability is necessary. In this context, syntactic, semantic, and organizational interoperability issues deserve greater priority and effort than the technical interoperability level. An interoperability assessment model addresses all the attributes relevant to different levels of technical, syntactic, semantic, and organizational interoperability.

Regarding the completeness of the interoperability assessment models examined, an approach for enterprise interoperability measurement seems to have a more complete set of specifications on interoperability assessment models.

Finally, an approach for enterprise interoperability measurement is often cited as one of the foundational documents when interoperability is discussed. It has been used as the basis for the definition of interoperability assessment models and for providing guidance to business managers and interoperability officers.

For future research and development, the interoperability assessment model must be defined based on the standard concepts and definitions of interoperability. Lessons learnt from research on interoperability assessment models can be summarized as follows: (1) A comprehensive interoperability assessment model must cover all aspects of interoperability, such as interoperability levels and interoperability attributes. In addition, metrics and properties shall be identified to improve the development of interoperability between systems. (2) An interoperability assessment model should be simple and easy to understand for the convenience of the developers.

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