Measuring Tool Chain Interoperability in Cyber-physical Systems

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***Abstract*—Cyber-Physical Systems are developed through complex engineering projects that include many stakeholders and a variety of tools and processes from different engineering backgrounds. Interoperability in these development tool chains is an important aspect for well-integrated systems. Furthermore, since full tool chain interoperability is neither possible nor necessarily desired, measuring interoperability in development environments is essential for setting the right priorities. This systematic literature review gives an overview of the literature about interoperability assessment methods. A survey was conducted through digital libraries and a total of 42 papers were read. Out of these papers, 24 different interoperability assessment models were identified and analyzed. A striking find of this study is that no proof of industrial adaptation of these models was found. In this paper, we analyze the reasons for this lack of validation in the context of CPS development.**

Keywords—interoperability measurement; interoperability assessment; interoperability maturity models; cyber-physical systems

I. Introduction

Tool support for Cyber-Physical System (CPS) development is becoming significant due to the requirement for cost-effective development. Furthermore, CPS development needs seamless integration of development, business, and manufacturing tools. Regardless, even though *tool integration* is an active research field, the associated classification schemes and context descriptions remain high-level and vague [1]. At the same time, several of the most important non-functional properties of tool integration, such as *flexibility*, *scalability*, and *evolvability* [1], would benefit directly from metrics for quantifying integration.

Kasunic and Anderson [2] made the following comments about interoperability measurement:

> *Developing and applying precise measurements in an area as multidimensional and complex as interoperability is difficult. However, measurement, assessment and reporting of interoperability results in a visible way are essential to continued focus and to setting the right priorities.*

Interoperability measurement methods, models, and metrics have been under research for many years with the goal of increasing communication between different tools for a more integrated environment. There are several studies on interoperability that investigate interoperability challenges [3–5]. However, so far none of these efforts are adequate to solve interoperability issues. Even though there are case-by-case efforts on interoperability assessment, there is still no comprehensive or systematic approach.

Carney and Oberndorf [6] underline the importance of interoperability assessment by saying *"Interoperability must be quantifiable to be achievable"*. However, one of the difficult challenges experienced by researchers is to identify quantifiable attributes that characterize the interoperability. Thus, developing an approach to measure interoperability is an important challenge.

CPSs and interoperability research are disparate and originate from different communities. Therefore, the purpose of this study is to review the current status of interoperability assessment approaches and to understand their importance, applicability, achievements, and missing aspects with regard to CPS development.

The aim of this paper is to give an overview of the existing models, methodologies, or techniques for measuring interoperability from a CPS perspective. Section II focuses on the literature review process and findings. In Section III, we present a detailed analysis of the survey results. Section IV concludes the study and provides a short outlook regarding future work.

II. Literature Review

A substantial amount of research effort has been spent on interoperability research, but measuring interoperability is difficult. One of the reasons behind this is the vagueness of the definition of interoperability. Ford et al. listed 34 distinct interoperability definitions dating from 1977 to 2006 in their extensive survey [7]. After an extensive survey of research papers, standards, and other government documents, the authors [7] found 64 different interoperability types.

In this paper, due to the highly heterogeneous nature of CPS development, which involves many stakeholders, tools, and disciplines, we adopt the IEEE definition of interoperability, that is:

> *The ability of two or more systems or components to exchange and use the exchanged information in a heterogeneous network* [8].

Although a comprehensive survey on a topic as broad as interoperability is not possible, our survey intended to focus on the interoperability measurement or assessment aspects. Throughout the literature review we focused on how interoperability can be measured and how we can benefit from literature to find the best practice to measure tool chain interoperability for CPS development environments. We have read 42 academic papers, theses, and reports.

Kitchenham's [9] procedure for conducting a systematic review was adopted for this survey. As a selection method for the literature survey, we chose to conduct a digital library search of different sources. In addition, systematic searches of journal papers, conference proceedings, reports, and workshop papers were used to judge the literature. The digital libraries that we used to find relevant papers are listed in Table I.

TABLE I. SEARCHED DIGITAL LIBRARIES AND NUMBER OF ARTICLES FOUND IN EACH.

Source	Number of Articles
ACM Digital Library	3
Google Scholar	9
IEEE Xplore Digital Library	8
JSTOR	1
Science Direct	5
Scopus	3
Springer Link	2

The search strategy when selecting literature was to start with a systematic search of relevant digital libraries using "interoperability measurement", "interoperability assessment", and "integration measurement" as keywords. We reviewed the abstract of each article found through this search, or the entire article if there was no abstract, to determine how it related to our inclusion/exclusion criteria:

Inclusion criteria: Articles referred to the most relevant interoperability types, that is, systems, technical, enterprise, domain, organizational, conceptual, functional, programmatic, operational, process, and data interoperability.

Exclusion criteria: Articles were not in English or did not deal explicitly with interoperability assessment. No articles were excluded based on date of publication.

Fig. 1 shows the domain distribution of the articles. Here we can easily see that most of the literature is from either the enterprise or the defence/military domain. On the other hand, the domains of information systems, software, business and command, control, communication, and management information systems have less research on interoperability measurement. This shows us that interoperability assessment is not the focus of all related domains. Furthermore, it is not surprising that both the enterprise and the defence domain are quite aware of the interoperability issues and work intensively on the measurement phase to improve interoperability. This enforces the need for interoperability assessment for Cyber-Physical Systems, given the comparable size and complexity of the systems these domains deal with.

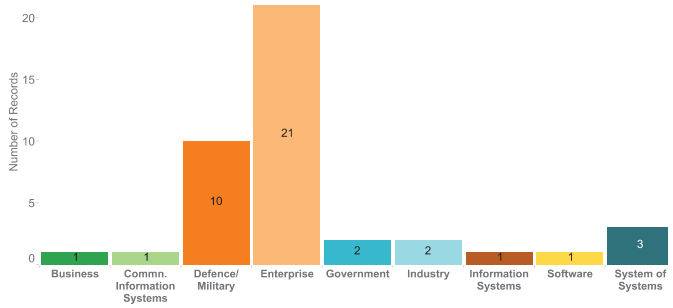

Fig. 1. Domain distribution of the literature review.

We also classified the read articles based on their subject. The subjects can be listed as assessment, case studies, challenges/opportunities, frameworks, measurement, methods, methodologies, models, and surveys.

Most of the papers we read that were relevant for interoperability measurement research focused on assessment models, methods, or methodologies. Another main research subject was surveys about interoperability assessment. Out of 42 papers, ten papers defined, explained, or used assessment models. Also, eight of the papers were about surveys and offered analyses of such models. To validate these models there are only 2 case studies contucted. Fig. 2 illustrates the number of records for each subject.

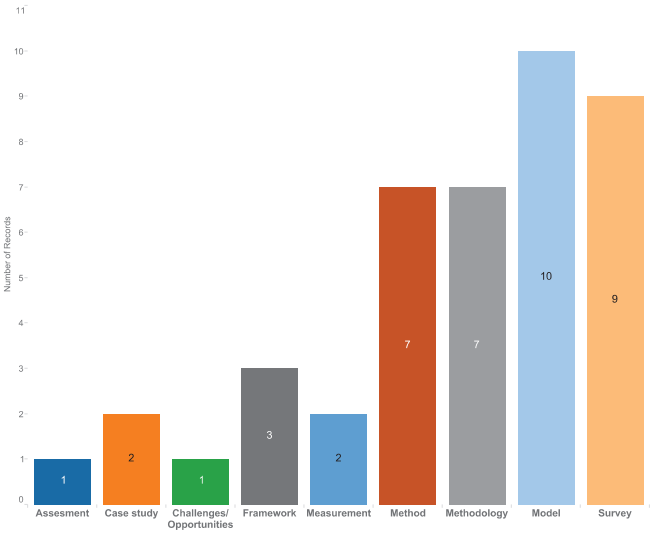

Fig. 2. Number of records according to subject.

The dense reliance on models in the interoperability assessment comes into prominence in the systematic literature review. Irrespective of the subject of the paper, nearly all of the papers that we read mentioned assessment models in their research. Even if not all of the articles *focused* on models, nearly all of them *mentioned* such models in their research. Therefore, we decided to take a closer look at the interoperability assessment models that were mentioned. In

total, we found 26 different models in the reviewed articles. Fig. 3 lists these models in the order of how many times they have been cited by the literature we have read. We called popularity as the amount of publications by which they are referenced out of 42.

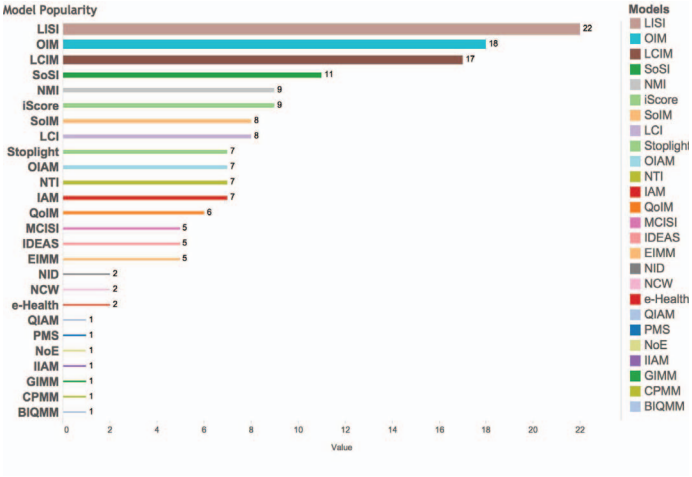

Fig. 3. Popularity of the models according to the literature.

Each model has a precise focus and some are more comprehensive than others. Some models have been widely cited, while others are rarely mentioned. In the next section, we concentrate on the analysis of the fourteen models that are located on top of the list.

III. Detailed Analysis

The details about the most popular models are listed in Table II. The interoperability assessment models are formed according to different methods. While earlier methods adopted spectra [10], mission-based [11], or taxonomies [12], others emphasize either maturity models or general levelling methods [13–17].

The majority of models are concentrated on technical interoperability, such as SoIM, MCISI, LISI, IAM, NMI, and SoSI, whereas OIM is the only model that aims to measure operational interoperability and OIAM concentrates upon the agility of operational interoperability. Models predominantly study the assessment of only one type of interoperability. For instance, NTI is about non-technical interoperability while LCI mainly works on coalition interoperability. However, SoSI studies technical, programmatic, and constructive interoperability together.

In many models, researchers defined the stakeholders, such as the business, as well as the application, data, and technical. In particular, LISI lists some attributes as procedures, applications, infrastructure, and data. Models like SoIM, LISI, OIM, LCIM, NMI, and QIAM refer to levels. These levels are alternately physical, technical, organizational, empiric, syntactic, semantic, pragmatic, and social. For instance, LISI names levels, IAM refers to components, and EIMM considers areas of concern and maturity levels.

TABLE II. Assessment Models in Chronological Order.

Title	Acronym	Year	Author
Spectrum of Interoperability Model	SoIM [10]	1980	LaVean
Quantification of Interoperability Model	QoIM [11]	1989	Mensh et al.
Military Communications and Information Systems Interoperability	MCISI [12]	1996	Amanowicz and Gajewski
Levels of Information Systems Interoperability	LISI [13]	1998	C4ISR Interoperability Working Group
Interoperability Assessment Methodology	IAM [20]	1998	Leite
Organizational Interoperability Maturity	OIM [14]	1999	Clark and Jones
Stoplight	Stoplight [21]	2002	Hamilton et el.
Levels of Conceptual Interoperability Model	LCIM	2003	Tolk and Muguira
Layers of Coalition Interoperability	LCI [15]	2003	Tolk
NATO C3 Technical Architecture Reference Model for Interoperability	NMI [16]	2003	ADatP-34
Non-Technical Interoperability	NTI [17]	2004	Stewart et al.
Organizational Interoperability Agility Model	OIAM [18]	2004	Kingston et al.
System of Systems Interoperability	SoSI [19]	2004	CMU-SEI
Interoperability Score	i-Score [22]	2007	Ford and Colombi

A striking observation from this study concerned the lack of usage and validation of these interoperability assessment models. Although the listed models are vastly cited, we could not find any publications that evaluated the SoIM model. In addition, QoIM is also not used in any of the case studies in the literature. LISI is cited by many researchers; however there is only one case study [23] that examines the applicability of the model. There is no information about whether NTI was ever institutionalized by the UK Ministry of Defence or OIAM by the Australian Department of Defence, and iScore has not yet been adapted by the DoD.

The studied models use either complex metrics, separate levels, or combinations of these to differentiate between different states of interoperability. This is problematic for the usability, and therefore the impact, of these models. To begin with, complex metrics make quantification of interoperability difficult. Perhaps when one analyses a rather stable system this is not necessarily a problem. However, CPS development is not stable (technological solutions, for instance, are replaced every few years) and is typically carried out in very different contexts.

It is also observed that most models concentrate primarily on selected aspects of interoperability. For instance, they mostly study the assessment of only one type of interoperability, as discussed earlier. In CPS development, there are many relationships between entities that need to be handled, such as those between organizations, individuals, engineering disciplines, tools, and so on.

Last but not least, all models are created for modelling and reasoning about the current structure and content of a system. However, if the overall goal is, for example, flexibility, scalability, and evolvability [1], then the research focuses on identification of the problems. To be usable in the day-to-day operations of CPS development, these models should ideally include guidelines and support for identifying weaknesses or even faults and which parts or aspects of the system would gain most from improvements for one reason or another.

IV. Conclusion

This paper presents a systematic literature review of interoperability assessment methods that can be valuable for use in the context of tool chain interoperability in CPS development.

We found that interoperability assessment models have received a considerable amount of attention in academia but have not been widely adopted in industry. Furthermore, we identified three main problems with the investigated models that might explain this lack of impact:

1) The models use either complex metrics, separate levels, or combinations of them without tool support.
2) The models mainly concentrate on selective aspects of interoperability.
3) The models focus on structure and content, providing little guidance on how to deal with interoperability improvements.

Future work will be to include survey to cellect user needs for interoperability on CPS development and harmonizing these needs with our literature survey results in a case study.

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