Chapter 2

Smart Systems-of-Information Systems: Foundations and an Assessment Model for Research Development

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Abstract

Software-Intensive Information Systems (IS) have supported many application domains. Recently, they have been connected to form synergistic arrangements of IS known as Systems-of-Information Systems (SoIS). Each IS cooperates with its own capability to compose more complex functionalities that could not be delivered separately. However, SoIS have sometimes been conceived from a static perspective, with a low degree of flexibility in their architecture and with high costs to support a proper interoperability of their constituents. The main contribution of this chapter is to step forward, proposing a new type of SoIS named Smart SoIS, i.e. an SoIS that presents a dynamic architecture and full interoperability. Dynamic architecture guarantees that the architectures of SoIS can change over time, rearranging themselves (adding, changing, or eliminating constituents) to keep the SoIS in operation. Full interoperability supports transparent interoperability, which can be achieved spontaneously and instantaneously, exploiting capabilities of the constituents to accomplish missions assigned to the Smart SoIS. We also present foundations for Smart SoIS, and a model to assess the evolution of the research and technology for Smart SoIS over the next few years.

2.1. Introduction

Information Systems (IS) have been the cornerstone of several business endeavors. They are often software-intensive systems in the sense that software is a dominant feature that intensively impacts the entire system development life cycle and the delivered results [ISO 2011]. IS have supported a great diversity of application domains, such as business, health, and crisis response [Goldschmidt 2005, Procaci et al. 2014, Santos et al. 2014; 2015]. Currently, IS have been under pressure to offer more complex functionalities. In turn, they have been constructed to be domain-specific with a set of increasingly narrowed functionalities. As a result, the engineering of complex functionalities has shifted to a perspective in which multiple IS have been combined to interoperate, achieving results that add value to the client [Boehm 2006]. These types of systems are termed Systems-of-Information Systems (SoIS[1]) [Carlsson and Stankiewicz 1991, Breschi and Malerba 1997, Saleh and Abel 2015, Majd et al. 2015]. SoIS are a specific type of Systems-of-Systems (SoS) that poses new challenges for IS development and research. SoIS exploit individual functionalities offered by their constituent IS to build complex functionalities that cannot be delivered by any of these IS separately. Significant investment has gone into subsidizing SoIS engineering. For instance, Saudi Arabia is investing 70 billion dollars in smarter cities and, in South Africa, a 7.4 billion dollars smart city project has been conducted [Cerrudo 2015]. However, their smooth operation is of paramount interest as faults can have a significant impact. Hence, it is important to investigate how to construct SoIS for them to be trustworthy, i.e. SoIS that are able to keep operating despite failures or threats. Constituents will be required to form a SoIS spontaneously in response to new SoIS missions, an ability termed as *full interoperability* [Maciel et al. 2016]. Moreover, to maintain operation despite occasional changes, dynamic architectures will be required as well. These new SoIS must be *smarter* in the sense that they must comply with such requirements.

This set of essential characteristics gives rise to a novel class of SoIS termed *Smart SoIS*. This is a special type of SoIS that, besides the essential characteristics of a SoS [Maier 1998], accomplishes two additional dimensions: full interoperability and dynamic architecture. In this scenario, research directions must be established to support a deeper investigation of this new context, eliciting the main challenges that must be addressed to comply with these requirements. In this chapter, we establish foundations for Smart SoIS, a forthcoming and distinguished class of SoIS that exhibits a particular set of characteristics that should be addressed by the scientific community of IS in the next few years. We briefly outline the foundations of SoIS in Section 2.2, firstly explaining what an SoS is, and after advancing the discussion for SoIS and Smart SoIS. In Section 2.3, we establish characteristics that must be accomplished by Smart SoIS. In Section 2.4, we establish a model to assess the level of development and research in Smart SoIS over the next few years. Finally, we present our concluding remarks and perspectives for future work in Section 2.5.

2.2. SoIS: Systems-of-Information Systems

Systems-of-Systems (SoS) are based on a set of independent systems, so-called constituents, available and predisposed to accomplish a given set of missions by means of interoperability among them [Maier 1998]. Functionalities offered by constituents are often referred to as capabilities [Boardman and Sauser 2006, Dahmann et al. 2008]. SoS share important characteristics [Maier 1998]: (i) managerial independence, i.e. constituents are owned and managed by distinct organizations and stakeholders (ii) operational independence, i.e. constituents perform their own activities, even when they are not accomplishing one of the SoS missions (iii) distribution, i.e. constituents are dispersed requiring connectivity to communicate (iv) evolutionary development, i.e. SoS evolve due to the evolution of their constituents,

1 For sake of simplicity, SoIS will be used interchangeably to express singular and plural.

environment, and/or missions and (v) emergent behavior, i.e. complex functionalities emerge from the interoperability among constituents. Remarkable examples of SoS include smart cities, smart grids, smart buildings, and a range of smart-* systems [Fitzgerald et al. 2013].

A SoS is called *smart* when it presents self-* characteristics (self-adaptation, self-healing, and self-management) [Giese et al. 2015]. The five characteristics assigned by Maier make SoS have a dynamic (or evolutionary) architecture, i.e. the constituents of a Smart SoS can be changed according to the operation of the SoS. Dynamic architecture has been considered a necessary characteristic for SoS [Boardman and Sauser 2006, Fitzgerald et al. 2012, Andrews et al. 2013, Weyns and Andersson 2013, Batista 2013, Romay et al. 2013, Graciano Neto et al. 2014, Nakagawa et al. 2014, Nielsen et al. 2015, Oquendo 2016]. Constituents can be added, for example, to improve the performance of a capability that is provided; other constituents can fail and be substituted; and some of them can leave the SoS spontaneously, requiring a reorganization of the remaining constituents to keep the SoS in operation and the missions being accomplished. However, self-* abilities and dynamic architecture have not been considered as intrinsic characteristic of SoS in broadly accepted definitions.

In particular, when a set of interoperable IS exhibits all SoS characteristics, they can be considered an SoIS. The term SoIS first appeared in the 1990's [Carlsson and Stankiewicz 1991, Breschi and Malerba 1997], and has recently emerged again [Saleh and Abel 2015, Majd et al. 2015]. From this perspective, SoIS exhibit a strong business nature. These authors claim that SoIS should (i) be concerned with the flow of information and knowledge among different IS (ii) address the impact of the interrelationships between different SoIS (SoIS as constituents themselves) (iii) be responsible for generating information from emergent SoIS (iv) tackle information interoperability as a key issue. SoIS are made up of several IS that combine their capabilities. Virtual Organizations are a potential instance of business supported by SoIS. They comprise several distinct organizations that spontaneously get together, working cooperatively (including their systems) in the context of a specific project for a well-defined period of time, such as six months or two years, leaving the SoIS after that. Movements such as Clean Web in which social network software and information technology are articulated to solve issues related to natural resource constraints also represent trends in SoIS.

Interconnection of IS to achieve more complex functionality is not a recent topic [Wiederhold 1992, Carlsson and Stankiewicz 1991, Breschi and Malerba 1997]. In fact, these arrangements of IS have been constructed over the last decades with differing names and distinct purposes. Complex Systems [France and Rumpe 2007], Ultra-Large Systems [Feiler et al. 2006], and Federated Information Systems [Tu et al. 2011, Graciano Neto et al. 2014] are some examples that have emerged to represent classes of software-intensive systems made up of a set of IS. The main difference between a SoIS and these other types of systems is the level of independence of their constituent systems. Constituent IS still exhibit independent operation when not contributing to the accomplishment of global missions [Falkner et al. 2016], whilst Federated IS and other classes that combine IS often have IS exclusively dedicated to the purposes of the larger systems.

SoIS that inherit the peculiarities of SoS are supposed to be not only a permanent structure but also a phenomenon triggered by some stimulus. Other types of systems assembled with pre-existing systems are specifically designed to be part of a new complex system or they are engineered/refactored to be a permanent part of a much larger system. Constituents are not necessarily designed to be part of an SoIS, and they also have an independent existence. There are distinct requirements that must be fulfilled regarding constituents: they must be engineered to interoperate among them (as other similar large systems do), but they also need to have an independent existence. Nevertheless, SoIS must be as trustworthy as SoS. They are required to deal with the dynamics of the architecture, requiring another constituent to work when one fails, and self-adapting their structure to keep to the accomplishment of a mission even when external events threaten the stability of the SoIS. To deal with these requirements, new characteristics are added to SoIS, giving rise to a new class of systems named Smart SoIS, as we discuss in the next section.

2.3. Towards Smart SoIS

Besides the five inherent SoS characteristics, Smart SoIS also have two novel dimensions: (i) evolutionary or dynamic architecture, and (ii) full interoperability. We discuss each one of the characteristics and their particularities for Smart SoIS below:

Independence (decoupling) of constituents. Constituents in a Smart SoIS are decoupled IS, which have an independent existence, operation, and purposes, but that occasionally offer their capabilities to contribute to the accomplishment of a mission of a Smart SoIS. Constituents can be enterprise information systems, decision support systems, social networks, or any other type of IS.

Managerial independence of constituents. Multiple organizations and stakeholders can hold and contribute with their IS to form a Smart SoIS.

Evolutionary development. IS inherently evolve the Smart SoIS, which changes according to new requirements, new IS joining and leaving the SoIS, with evolving missions, and evolving their own architecture.

Emergent behavior. Such behaviors are a holistic phenomenon manifested as results of the interoperability among constituents that produce a global result that cannot be delivered by any one of them in isolation. It is worth highlighting that emergence can be deliberately and intentionally designed [Boardman and Sauser 2006], i.e. SoIS engineers are the major players for creatively exploiting functionalities delivered by the constituents, assembling them for innovative purposes. In Smart SoIS, other types of emergent behaviors can be found, such as information-intensive capabilities that form emergent behaviors that add value to business, positively impacting users being supported by these systems.

Distribution. To achieve the required interoperability and to address emergent behaviors, a strategy must be established to support communication and data exchange among IS of a Smart SoIS. Shared databases, mediators, middleware, and an enterprise service bus are some classic examples of means to support it.

Evolutionary (dynamic) architecture. A Smart SoIS remains in operation by adapting its own architecture during the accomplishment of a mission. If we consider an SoIS made up of several

IS, some of them may stop working for some reason (due to cyber-attacks, for example). A Smart SoIS must be able to explore capabilities available in a set of constituents still in operation, rearranging them to maintain the mission accomplishment in progress. As a consequence, the constituent IS and connections are not stable (from an architectural perspective). It is necessary to investigate how to provide this type of ability in the context of Smart SoIS by designing mechanisms to support rearrangement of their dynamic architectures and self-adaptability abilities required for such purposes.

Full interoperability. It is a more complex and broader concept, which comprises the spontaneity of forming a Smart SoIS according to needs that emerge, in a transparent manner for the user, abstracting issues, such as middleware, network, data exchange (representation and transport), and communication support details. To achieve this, the IS must support instantaneous interoperability with any other type of IS which is available, exchanging information among themselves, and being able to contribute to the accomplishment of missions. Moreover, they must be capable of arbitrarily forming a Smart SoIS under a new demand. This characteristic is itself a challenge [Maciel et al. 2016].

Hence, the main challenge that we face for the next 10 years is *to conceive Smart SoIS that comply with the aforementioned characteristics*. When we achieve this milestone, Smart SoIS will become feasible and trustworthy, being conceived fast and on demand, with the IS being selected at runtime according to pre-established restrictions. To aid in the assessment of the evolution of the research in Smart SoIS over the next few years, we propose an assessment model, discussed in the following section.

2.4. An Assessment Model to Evaluate the Progress of Research into Smart SoIS

We established an assessment model named SoISAM (Smart SoIS Assessment Model) as a reference to classify the level of development of the research in Smart SoIS over the next few years. We adapted it from technology assessment standards, such as Technology Readiness Levels (TRL) [Shishko et al. 2004, Mankins 2009] and SOA Maturity Model [OMG 2005]. The former corresponds to a method proposed by NASA and the Department of Defense (DoD) of the United States to assess the maturity level of a particular technology. The latter provides guidance to measure progress and the adoption of SOA.

In our model, a *level of research development* is assigned to the state of the art in Smart SoIS according to the nature and maturity of the evidence and results towards real Smart SoIS. We established nine research development levels. SoISAM 0 is the lowest and SoISAM 8 is the highest. Associated to them, we defined metrics to support the assignment of a level to given research in Smart SoIS, and the type of evidence that is expected for each level of maturity. Additionally, a SoISAM level is considered achieved when metrics show that the respective type of evaluation and expected deliverables, e.g. publications, prototypes, patents, and tools, are available in the state of the art and practice.

Each one of the maturity levels has specific characteristics. These are discussed considering the force of the evidence that supports results being reported by publications or products. The SoISAM levels are:

- **SoISAM 0 -** This is the lowest level of maturity. It establishes foundations for Smart SoIS. Results reported are mostly based on position studies. Background and principles are raised to construct a consistent theory for Smart SoIS. Studies propose perspectives of research and challenges. There is no empirical validation.
- **SoISAM 1** – When research achieves this level, toy examples and proofs-of-concept are implemented. Characteristics of a Smart SoIS are tackled separately. Preliminary research starts to communicate the existence of prototypes that address one or more characteristics of a Smart SoIS. Methods, techniques, and tools are planned, and parts of them are implemented.
- **SoISAM 2** – Prototypes of tools, models, and methods already support the carrying out of case studies. Case studies are designed and conducted. State of the art covers prototypes of Smart SoIS with preliminary results on supporting dynamic architecture and full interoperability, besides the other five inherent characteristics of SoS. Exploratory research is carried out.
- **SoISAM 3 –** Preliminary experiments are performed and prototypes of Smart SoIS exhibit all the characteristics required. Prototypes of tools, models, and methods are used to validate and verify predicted functionalities of Smart SoIS in the laboratory (*in-virtuo*). Simulations are conducted to evaluate the software and hardware aspects of Smart SoIS. Reference architectures for Smart SoIS are established.
- **SoISAM 4 –** Prototypes of Smart SoIS are constructed and tested in representative environment. Since a simulation is performed in level 3, at this level, a real prototype is constructed and tested. Tests are still laboratory-based, in a controlled environment and on a small or medium scale.
- **SoISAM 5 –** Real Smart SoIS are conceived and tested in the environment. After validation of the expected results in the laboratory, tests are carried out en masse in a real operational environment.
- **SoISAM 6 –** The results of research are transferred to industry. Patent filing is required, methods, techniques, and tools are well-established, and companies start the production of Smart SoIS on an industrial scale.
- **SoISAM 7 –** Industry is already producing IS with full support for the spontaneously creation of Smart SoIS on demand. Smart SoIS are accessible to the population as public services, entertainment products (e.g. toys and games), or personal products.
- **SoISAM 8 –** Smart SoIS are already part of everyday life. Even non-programmers are able to form small-scale Smart SoIS using a set of interoperable IS, and public entities construct reliable Smart SoIS applications to improve the quality of human life. Smart SoIS are everywhere, becoming pervasive and well-adopted, fostering, for instance, sustainability and health. Many options of technologies are available and new business models come into existence which rely on Smart SoIS.

Table 2.1. Metrics associated to maturity levels for SoISAM

Maturity Level	Type of Evidence	Supporting Metric
SoISAM 0	Publications as position studies proposing models based on Smart SoIS concept.	Number of publications that introduce or adopt the concept of Smart SoIS.
SoISAM 1	Toy examples and proofs-of-concept	Number of publications that communicate first essays on providing operational examples and simple Smart SoIS.
SoISAM 2	Case studies	Number of publications that report results of case studies carried out to measure specific parameters, comparing them to predictions or real cases, establishing a relationship between what is expected from Smart SoIS and what is achieved in that point of research.
SoISAM 3	Experiments *in-virtuo*	Number of publications that report experiments with computer-based models. In these experiments, the behavior of the environment with which the Smart SoIS interact is described as a model and represented by a simulation.
SoISAM 4	Experiments *in-vitro*	Number of publications and number of operational prototypes of Smart SoIS created in the laboratory.
SoISAM 5	Experiments *in-vivo*	Number of publications and academic tools available, supported by the results of experiments carried in the laboratory, under well-defined restrictions, and with operational prototypes that cover all the characteristics of a Smart SoIS, and that are tested in a real environment. This level of development can be demonstrated by real Smart SoIS in operation.
SoISAM 6	Transfer of research results to industry	Number of initiatives, projects, patents, and publications that report the beginning of the production of Smart SoIS in industry.
SoISAM 7	Industrial large-scale production	Number of commercial tools available to support the construction of Smart SoIS.

SoISAM 8	Smart SoIS pervasiveness	Number of publications, technical reports, and data delivered by such publications that communicate Smart SoIS being formed spontaneously and number of IS being sold that achieve full interoperability.

Table 2.1 summarizes the research development levels of SoISAM. Each level has a specific type of empirical evidence that must be reported to support the level achieved. In parallel, specific metrics are established for each level. Each metric details the elements that will be assessed. The elements, e.g. publications, patents, and tools, are used as parameters to classify the type of evidence that is available and being reported, such as case studies, experiments, or large-scale production.

2.5. Final Remarks

We presented an overview of the research challenges to be addressed by the IS community over the next few years. We propose a new type of SoIS named Smart SoIS that, besides having the inherent characteristics of SoS, also exhibits other two important features: dynamic architecture and full interoperability. Under this reality, software-intensive IS should be able to voluntarily form new Smart SoIS, according to new demands. Our proposal is in alignment with START (SofTware ARchitecture Team) research group of ICMC/USP (Instituto de Ciências Matemáticas e de Computação/Universidade de São Paulo) together with ArchWare, a French multidisciplinary scientific research group that integrates IRISA (Institut de Recherche en Informatique et Systèmes Aléatoires) working on the development of SoS in remarkable application domains, such as health and emergency response and crisis management. Additionally, our proposal is in alignment with another Big Challenge for IS: Full Interoperability [Maciel et al. 2016].

Smart SoIS will become substantially more relevant for society. Flood monitoring [Horita et al. 2015], healthcare systems [Rodríguez et al. 2015], smart cities [Lytra et al. 2015], and crowdsourcing systems for emergencies and crisis situations [Santos et al. 2014; 2015] are some instances that show the pervasive, multidisciplinary, and crosscutting impact of them in the forthcoming future. We must research, synthesize results, and elaborate new theories and technologies to support the efficient development of these new SoIS appropriately. It is necessary to deal with issues related to modeling, design, and simulation of Smart SoIS architectures, definition, elaboration, and specification of missions, and design of mechanisms to deal with emergent behaviors. We must comprehend how we can develop Smart SoIS to address the phenomenon of spontaneously joining IS on demand, contributing to the missions to be accomplished by SoIS.

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