Annual Reviews in Control 39 (2015) 128–143

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Sustaining interoperability of networked liquid-sensing enterprises: A complex systems perspective

Carlos Agostinho [a,*], Ricardo Jardim-Goncalves [a,b]

[a] Centre of Technology and Systems, CTS, UNINOVA, 2829-516 Caparica, Portugal
[b] Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal

ARTICLE INFO

Article history:
Received 10 January 2015
Accepted 7 March 2015
Available online 11 April 2015

ABSTRACT

The emerging Liquid-Sensing Enterprise (LSE) concept provides manufacturing industrial networks with the required enablers to seamless interoperate and sustain its interoperability along the operational life cycle. Actually, the actual domain of enterprise information systems interoperability prospects the need for a new paradigm able to manage the network dynamics, facilitating adaptation along the lifecycle of an enterprise and the LSE network. The theory of complex systems provides a set of heuristics that can be applied to support the formalization of the LSE industrial network and its dynamics, demonstrating how they can be enabled and at the same time controlled to keep the overall level of interoperability stable. Hence, today there is technology suitable to implement such systems, capable to realize the LSE real, digital and virtual worlds. However, isolated, this technology cannot deliver the requirements for a self-sustainable LSE network. The authors propose a novel metaphor from complexity as a framework to model and implement the mechanism for sustaining interoperability in such networked environments. They identify the motivations for sustaining interoperability of networked liquid-sensing enterprises, having complex and adaptive systems as a vehicle to model and understand the relationships between enterprises and enterprise information systems in networked environments. Then, existing technology such as model-driven interoperability, agent-based or service oriented architectures, and knowledge management, is proposed to detail the conceptual solution for the sustainability of interoperability. An instantiation of the concept proposed is presented, which details the prototypal application elaborated in a real manufacturing scenario, implemented and validated during the European Project Factories of the Future IMAGINE.

1. Introduction

The manufacturing domain has been associated with the transformation of raw material and assemblage of components into final products that would fit the needs of many and could be sold worldwide. As a consequence, past research and development (R&D) has targeted the acceleration and mass-replication of more or less static production processes, construction of production machinery and the development of software to control such systems. However, the last decade has demonstrated clear signs that industry cannot proceed practicing ‘business as usual’. As identified by the European Commission’s Future Internet Enterprise Systems cluster (FInES) roadmap in 2012, a change of paradigm is required to maintain and improve the current standard of life (FInES Research Roadmap Task Force, 2012).

Producing goods is becoming a smaller part of manufacturing activities. Indeed, nowadays, manufacturing enterprises provide a huge spectrum of highly customized services, from pre and after sales, to design and marketing. As demonstrated by the “smiley curve” identified in the Observatory on Europe 2014 (Ambrosetti, 2014), the highest share of value added is currently embedded in pre-production (related to R&D and design), and in post-production (in activities like marketing and pre-sales of after-sales services). Also, as production stages and technologies have become more mobile, a single final manufactured product is often processed in many companies, countries, and crossing several information systems (IS) with sequential tasks in the value chain. Hence, the growing servitisation (Baines, Lightfoot, Benedettini, & Kay, 2009; Thoben, Eschenbächer, & Jagdev, 2001), and enterprises participation in global and dynamic value chains, addresses by Papakostas, Efthymiou, Georgoulias, and Chryssolouris (2012), are shaping today’s manufacturing sector.

Therefore, the survival of enterprises in the near and long term future will depend on the ability to see their own role within the

* Corresponding author.
E-mail addresses: ca@uninova.pt (C. Agostinho), rg@uninova.pt (R. Jardim-Goncalves).

http://dx.doi.org/10.1016/j.arcontrol.2015.03.012
1367-5788/

physical and social environment and to become flexible to changes in paradigm that could give them a competitive advantage. Complexity has risen in parallel with flexibility and mobility, which represents an immense opportunity for Future Internet (FI) technologies to make an impact, including the Internet of Things (IoT). Supported by smart components providing global and physical awareness to the business systems, FI will enhance overall context awareness and the opportunity to make better decisions.

1.1. Networked liquid-sensing enterprises

Santucci, Martinez, and Vlad-câlcic (2012) analyzed our digital society, redefining the Enterprise in a context where "*the network is the business*". Indeed, the concept of networked collaboration is of high interest both in the business-to-business (B2B) and business-to consumer (B2C) industry (Mathew, 2002). In B2B, collaborative development processes or value chain interactions, involving people, processes and technologies across multiple organizations working in the same domain is becoming the industry standard. In the latter, customer service manufacturers and providers may try to develop their collaborative skills to better reach out to their customers and to maintain constant contact with them.

To potentiate that, the Sensing and Liquid Enterprise concepts envisioned in the FInES 2025 roadmap can complete the digital transformation and provide manufacturing networks the required enablers to connect, customizing FI components and technology to address customer experience, operational processes and business models alignment (FInES Research Roadmap Task Force, 2012). However, although smart business systems can be described as an evolution of the IoT, the evolution of traditional enterprises into digital liquid and sensing enterprises represents a fundamental change in the business models and information systems that is not immediate, and should be supported by methods and tool that do not harness existing partner relations. Each one should be able to evolve at its on pace.

Sensing Enterprise (SE): The concept was created in the advent of the Augmented Internet, as an attempt to reconcile traditional non-native "Internet-friendly" organizations with the tremendous possibilities offered by the cyber worlds. Acknowledging the fact enterprises need to change paradigm applying innovative ideas to adapt and remain competitive, SE envisions the enterprise as a smart complex entity capable of sensing and reacting to stimuli, by integrating decentralised intelligence, context awareness, dynamic configurability and sensorial technology into its decision-making process (Danila et al., 2013). It also refers to an enterprise anticipating future decisions by using multi-dimensional information captured through physical and virtual objects (Santucci et al., 2012).

Liquid Enterprise (LE): The designation of "liquid" or "fluid" is often proposed to accommodate all that is located within the fuzzy borders of a specific domain. In terms of the enterprise, and within the context of global value chains, collaboration and outsourcing, the LE is an enterprise having fuzzy boundaries, in terms of human resources, markets, products and processes. In such setting, more and more, it is not easy to distinguish the 'inside' and the 'outside', the employees and the partners, the competitors and the collaborators (FInES Research Roadmap Task Force, 2012).

The mix of concepts in the form of **Liquid-Sensing Enterprise (LSE)** has the goal to harmonize developments from both the IoT and FInES "worlds". IoT is enabling objects in our environment to become active systems, sharing information with many IS, and gaining the skills for recognizing events in their networked surroundings, to which they are acting and reacting autonomously (IERC, 2011). In LSE, each IoT object or system has therefore a physical presence in the Real World (RW), a model in the Digital World (DW) specifying predefined pattern or behavior, and an image in the Virtual World (VW) to project hypothetical what-if scenarios ruled by some laws and policies. Events could be generated in any of the three worlds and they should be propagated to the other two worlds by interaction and negotiation in the LSE network (Agostinho, Sesana, Jardim-Goncalves, & Gusmeroli, 2015; Spirito et al., 2014, chapt. 7).

1.2. Self-sustainable interoperability in LSE networks

An enterprise is a complex artifact and the LSE is making it even more intricate. As pointed by ISO TC184/SC5 (2000), the enterprise anatomy is composed of different passive elements, and active systems such as the Human or artificial ICT components. However, with the appearance of networked systems such as the LSE, one must face the idea that humans should (will) no longer have a complete control over all the operations. This is true also for IS, which need appropriate mechanisms to maintain stability and remain dynamic following the demands of such a changing environment.

Interoperability is a key requirement in the implementation and maintenance of enterprise information systems (e.g. ERP, CRM, etc.), and it is an essential property for any enterprise development and growth. Actually, to reduce the costs of poor interoperability (White, O'Connor, & Rowe, 2004), it is extremely important that systems compatibility is achieved as fast and soon as possible and in a sustainable form. Nowadays, Enterprise Interoperability (EI) can be in part solved by non-ambiguous description of the information systems. Indeed, EI research as reached a mature status, providing methods for seamless interoperation, as long as organizations keep their business objectives aligned, software applications communicating, and the knowledge and understanding of the domain harmonized (Berre et al., 2007; Jardim-Goncalves, Grilo, Agostinho, Lampathaki, & Charalabidis, 2013).

The current state of the art has proposed model transformation mechanisms to support multilevel interoperability. The first drawback is that it would be ideal to rely on dedicated knowledge models and international standards as information regulators among organizations, but interoperability, especially at the level of software, is typically obtained by point-to-point mappings, hardcoded to relate information models, services and terminology. Therefore, automated model transformations remain static, limited to certain categories of models, and a frequent problem concerns the interoperability of the new systems or components with already existing parts in the same collaboration network. Moreover, the reality imposes that systems, e.g. service systems as explored by Ducq, Chen, and Doumeingts (2012), are increasing their dynamism to respond and adapt to new requirements and sensed realities. In the scope of the networked LSE, dynamism is the new paradigm of interoperability and key to a **self-sustainable interoperability (SSI)**, defined by Agostinho and Jardim-Goncalves (2009) and Agostinho, Pinto, and Jardim-goncalves (2014) as the "*Interoperability that convenes the needs of the present without compromising the ability of future changes, meeting new system requirements, and performing adequate adaptation and suitable management of the transitory elements*".

As illustrated in Fig. 1, where global networks of enterprises are represented as "molecules" of information systems (nodes), sustainable interoperability offers enterprises the possibility of dealing with internal network dynamics (evolution) and of successfully facing interoperability disruptions, i.e. operative harmonization breaking. In the case exemplified, A evolves which breaks interoperability with its partners (B, C, and D). In this case, being LSE's and sensing the disruption, automated SSI methods on C and D readjusted relations from A to C and A to D. The loss of B to