# Novel strategies for global manufacturing systems interoperability

Jardim-Goncalves, R, Grilo, A & Popplewell, K

**Author post-print (accepted) deposited by Coventry University's Repository**

**Original citation & hyperlink:**
Jardim-Goncalves, R, Grilo, A & Popplewell, K 2014, 'Novel strategies for global manufacturing systems interoperability' Journal of Intelligent Manufacturing, vol 27, no. 1, pp. 1-9. DOI: 10.1007/s10845-014-0948-x
https://dx.doi.org/10.1007/s10845-014-0948-x

DOI 10.1007/s10845-014-0948-x
ISSN 0956-5515
ESSN 1572-8145

Publisher: Springer

***The final publication is available at Springer via http://dx.doi.org/10.1007/s10845-014-0948-x***

**Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.**

**This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.**

# Novel Strategies for Global Manufacturing Systems Interoperability

**Ricardo Jardim-Goncalves (1); Antonio Grilo (2); Keith Popplewell (3)**

(1) Faculdade de Ciências e Tecnologia da UNL, DEE-FCT, UNINOVA, Portugal, rg@uninova.pt

(2) Faculdade de Ciências e Tecnologia da UNL, UNIDEMI, Portugal, acbg@fct.unl.pt

(3) Faculty of Engineering and Computing, Coventry University, UK, k.popplewell@coventry.ac.uk

***Abstract***

*This paper reviews some of the most recently reported research into novel strategies for global manufacturing systems interoperability. Such research can be categorised as addressing four broad topic areas: the Sensing Manufacturing Enterprise; Semantics and Knowledge Management in Manufacturing; Service Orientation and the Need for Negotiation; and Business Interoperability. Thus we identify a spectrum of research from the management of hardware and virtual sensing devices, through the semantic interpretation of the data and information generated by these, and its utilisation to support the collaborative manufacturing network lifecycle through service oriented software, and ultimately the provision of effective business interoperability. This study includes conceptual, theoretical, empirical and technological contributions, illustrated by real examples and demonstrating the novelty in comparison with previously reported results. The paper concludes elaborating final considerations on novel strategies for global manufacturing systems interoperability.*

***Keywords*** *– Enterprise Interoperability, Global Manufacturing, Sensing Manufacturing Enterprise, Semantics and Knowledge Management in Manufacturing, Service Orientation, Negotiation, Value proposition, Business Interoperability*

## 1. INTRODUCTION

As manufacturing systems evolve and become more complex, the need for novel strategies for interoperable operations, automated data interchange and coordinated seamless knowledge and behaviour of large scale manufacturing systems becomes highly critical (Chen 2008). Global manufacturing depends on the interoperability of its systems and applications, and to achieve such a holistic, adaptive and seamless intelligent manufacturing environment there is a need to devise strategies that leverage applied research and technological developments on a more solid and rigorous science base (Jardim-Goncalves 2010).

Lack of interoperability disturbs creation of collaborative work and networked systems (Frankston 2009). Apart from being a technical issue, interoperability challenges also emerge at organisational and semantic levels, underlying the need for solutions that support the seamless cooperation among manufacturing systems, processes and methods, information and knowledge, organisational structures and people (Berre 2007)(Jardim-Goncalves 2010). Thus, intelligent methods and tools to support the interoperability and seamless integration of manufacturing systems have been recognised as a high-impact productivity factor, affecting the overall efficacy, efficiency, quality, yield time and cost of manufacturing transactions, design and operations or digital services (Grilo 2010a). However, up to now the principal tools for targeting the above challenges are grounded on the various standards that try to govern methodologies, manufacturing information systems, development and operations (Agostinho 2011). Standards are usually linked with specific sectors, application areas and technology trends, having a limited time span, a static nature and quite have often different interpretations by engineers, technology vendors, and users in general (INCOSE 2007)(FINES 2012).

Therefore Manufacturing Systems Interoperability suggests the seamless interoperation in manufacturing environments, fostering novel collaborative and networked culture, by transferring and applying the research results in industrial sectors, within the scientific domains of systems complexity, network science, artificial intelligence, information theory and web science, distributed systems, shared data and knowledge, evolving applications, dynamics and adaptation of networked organisations on a global scale (Jardim-Goncalves 2014). All are directly related with rapid evolution of technology and applications, plug and play instruments, self-monitoring capabilities, benchmarking and evaluation of degrading processing, automatic or on demand reprocessing, recompiling or fixing of components or processes (Ferreira 2013). Moreover, to achieve a steady, stable, interoperable environment on a global scale there is the need for intelligent supervision supported by embedded monitoring systems with learning capabilities (Ducq 2012)(Chen 2008).

This paper presents the analysis of several current works in the domain of interoperability for manufacturing systems, considering novel contributions from researchers and practitioners who are exploring the definition and applicability of Manufacturing Systems Interoperability in a global perspective towards Intelligent Manufacturing Systems. This study puts focus on novel strategies, methods and tools in a scientific-based standpoint, including conceptual, theoretical, empirical and technological contributions, illustrated by manufacturing examples and demonstrating noteworthy novelty in comparison with previously reported results. Our analysis considers four intertwined dimensions: the Sensing Manufacturing Enterprise; Semantics and Knowledge Management in Manufacturing; Service Orientation and the Need for Negotiation; and Business Interoperability (Grauer 2010)(Jardim-Goncalves 2014). These four dimensions cover much of the most relevant focus of current research in the Novel Strategies for Global Manufacturing Systems Interoperability.

## 2. THE SENSING MANUFACTURING ENTERPRISE

A major research trend in global manufacturing systems interoperability addresses redesigning enterprise assets, with the support of smart electronics and embedded systems that facilitate a constant knowledge gathering process able to enable context awareness of management information systems, in such way that it will provide enterprises with capabilities similar to human senses, i.e., the Sensing Manufacturing Enterprise (Santucci 2012). This will push enterprises to dynamically change the way they work, into a more sensitive and advanced world, where event processing, knowledge handling, contextualisation, decision-making, actuation, and business intelligence work together to provide a generation of new business models and processes, with the intent to help such manufacturing enterprises become more flexible, efficient, collaborative, productive and smart (Broll 2009)(Koussouris 2011)(Frankston 2013).

Zhiying Tu et al. (2014) propose a federated approach for developing manufacturing enterprise interoperability. They advocate that cooperating parties must accommodate and adjust “on the fly” to establish interoperability, where the entire model mapping needs to be done dynamically through “negotiation”. The federated approach has no common predefined format for all models and needs dynamic adjustment and accommodation. The framework for the High Level Architecture (HLA) based platform, accelerates the establishment of virtual enterprise collaboration, and also provide the “easy pass” service for adapting to different potential clients with heterogeneous cooperation purposes and modalities. It models reverse engineering and an HLA Evolved approach. The framework provides a five step process to generate models for simulation starting from conceptual enterprise models to be converted to MDA models and code to accelerate the rebuilding of legacy information systems for implementation of information system exchange facilities. The long-term experience in management, interoperability and synchronisation of data in distributed simulation is reused by applying the HLA standard for information exchange. Zhiying Tu et al. (2014) have been deploying an HLA Evolved approach with the open source RTI, portico, extended by a new component straddling between HLA federation LAN and WAN to fulfil HLA 1516-2010 standard requirements.

Moisescu and Sacala (2014) propose a sensing based approach to the design of Future Internet based manufacturing enterprise systems, supporting interoperability needs. They have identified two principles that have to be taken into consideration in the design of Sensing Systems as components. Their work considers three types of model for integrating sensing capabilities into enterprise systems: Sensing Objects Based Enterprise System; Process Based Sensing Enterprise System; and Global Enterprise Sensing Systems. In a Sensing Objects Based Enterprise System, the Interaction Layer must manage data from sensor networks. The sensing object will be part of an environment, acquire specific data about the real or virtual environment, and must be able to interact with the environment and with other objects. A Process Based Sensing Enterprise System is characterised by the ability of changes in certain parameters, monitored through sensors, to trigger predefined behaviours. The appropriate behaviour is selected by the behaviour selector and integrated in the existing business process, thus adapting to the changing environment. Global Enterprise Sensing Systems can implement a similar algorithm as the one previously described. The main difference is that the data acquisition and analysis model has to take into consideration a more complex set of parameters. A focus for this Enterprise Sensing System is the one related to human-human and human-enterprise interaction.

Moisescu and Sacala (2014) propose that the Enterprise Architecture should consider the elements measured inside and outside the boundaries of the Enterprise environment, having the Sensing Systems classified in two categories: External Sensing Systems, and Internal Sensing Systems. Internal Sensing Systems can be directly associated to active functions performed by Internal Actuating Systems. Internal Sensing Systems provide the Enterprise system with the capability of measuring enterprise parameters classified in two categories: Human Behaviour related parameters such as presence, execution time; and Performance Indicators related to core processes, management processes and infrastructure. External Sensing Systems monitor the environment parameters associated with exterior factors that may influence the enterprise. A set of Key Performance Indicators can be correlated with the direct impact of external factors and monitored.

Alix Vargas et al. (2014) propose an initial Framework for Inter-Sensing Enterprise Architecture (FISEA), which classifies, organises, stores and communicates, at the conceptual level, all the elements for inter-sensing enterprise architectures and their relationships, ensuring their consistency and integrity. The FISEA provides a description of the elements and views that create collaborative networks and their inter-relationships. The FISEA has a meta-model describing how the collaborative process in a collaborative network is performed through the life cycle phases (from creation until dismantling) and how the different views are integrated into each life cycle phase and with each other phases. For Alix Vargas et al. (2014), the collaboration process starts when two or more stakeholders in a supply chain decide to collaborate in order to create synergies that allow them to be more competitive. This phase is defined by the organisational structure of the collaborative network, the teams that are going to work together, and the members of each team as well as the roles of each member. When the negotiation process starts at a higher strategic level, the management teams think and design the joint business strategy and the sensor strategy that must be aligned with each other. During the negotiation, the information exchange plan has to be clear, as well as the exception handling and the compensation system. In the definition phase, the negotiation process is finished when all the stakeholders sign the contract that includes the objectives defined in the business strategy. The joint business strategy defines objectives that are measured through KPIs. Those objectives have associated re-engineering tasks that seeks to evaluate the current AS-IS process to be improved in a new TO-BE process with the support of the knowledge that each organisation can provide. The TO-BE processes need the data that sensors provide to keep the process running, and the sensor strategy defines the sensor ontology that incorporates the definition of the sensors and the relationships between each another, as well as their implementations. Once the collaboration operation starts in the tactical and operative levels, the process is monitored taking into account the KPIs defined in previous phases, so that the contract is confirmed as being fulfilled. At technological level, the sensors that have been installed generate a behaviour pattern that triggers the process operations that produce data and information. The collaboration process operation creates knowledge that is shared among enterprises. In the evolution phase, the performance assessment is executed, and if the results are in accordance with the objectives, the process continues in a normal way. Finally, the joint business and sensor strategies have to be double-checked and the contract will be modified as well as the processes and behaviour patterns.

Danila et al. (2014) present an organisation level context-aware architecture for supply chain management to achieve interoperability and collaboration between partners. Context sensing is done through sensors that can be represented by physical or virtual objects. Physical sensors are represented by hardware sensors that can capture almost any type of real data and virtual sensors can sense data from software applications or web services or even from the Internet. The sensed raw data is pushed to the Complex Event Processing (CEP) Engine. The CEP Engine analyses the data and detects if a modification of interest appeared in the environment. The proposed architecture has a Coordinator that receives updates concerning the sensed context through the publish/subscribe mechanism. Whenever a change appears in a topic to which the Coordinator has subscribed on one of the sensing objects, a notification is sent to it. The notification is processed and pushed to the Context Interpreter, whose tasks are: deriving high-level contexts from low-level contexts; querying context knowledge; maintaining the consistency of context knowledge and resolving context conflicts. The architecture is composed from a Context Reasoner and Context Knowledge Base components. The Context Reasoner's purpose is to provide deduced contexts based on direct contexts, detecting inconsistencies and conflicts in the Context Knowledge Base (CKB). The CKB contains context ontology in several sub-domains and its instances. The proposal of Danila et al. (2014) for addressing interoperability of sensing context-aware enterprises connected in a supply chain is addressed at all levels of interaction: data (exchange of XML based SOAP messages over HTTP); services and applications (WS-Notification standard, WS-Security and WS-Reliable Messaging); processes and knowledge (event notification mechanism); business, with semantics interoperability being achieved through the embedding of RDF (Resource Description Framework) data in the SOAP messages.

## 3. SEMANTICS AND KNOWLEDGE MANAGEMENT IN MANUFACTURING

The web technology has enabled firms to arrange information syntactically, though most information has to be interpreted by humans before use, rather than being processed automatically by machines (Sarraipa 2010). However, interoperability in global manufacturing networks must address knowledge management within a corporate environment and across enterprises, whilst enabling a machine-to-machine inter-organisational knowledge management and sharing (Charalabidis 2010).

Khilwani and Harding (2014) focus on semantic web concepts and tools that enable computers to automatically process and understand information. The primary benefit of this new vision is to represent web resources in formalisms that both machines and humans can understand. They devise a framework for corporate memory management on the semantic web. Their proposed approach gleans information from the documents, converts this into a semantic web resource using RDF and RDF Schema, and then identifies relations among them using a Latent Semantic Analysis (LSA) technique. The framework proposes the extraction of information from the web documents and population of a Bag-of-Phrases (BOP). The BOP is further converted into a semantic web resource using RDF and RDF schema. In the BOP, keywords represent unique entities such as the name of a person, organisation, place etc., whereas, terms and phrases are used to represent domain specific words and concepts. These terms and keywords often differ from domain to domain and vary according to the enterprise, which hampers the interoperability and sharability of information between machines, people and enterprises. Domain specific meaning will be added to the terms and keywords available in the document. The semantic documents created using the proposed framework can be used for tagging the terms and phrases present in documents with definitions of their meaning across manufacturing networks.

Khilwani and Harding (2014) advocate that the semantic annotations and relations can be used to represent text documents in formalisms that both machines and humans can understand, and perform intelligent search, querying and reasoning on them. The annotations added in the enterprise documents using local dictionary or published glossaries will create links among the manufacturing enterprises' documents. Document search can further be improved by glossaries built using an ontology that defines relations among the terms in the glossary. For example, SKOS (Simple Knowledge Organisation Schema), a semantic data model built upon semantic RDF and RDFS and used for sharing and linking knowledge organisation systems such as thesauri, classification schemes, taxonomies, and any other type of structured, controlled vocabularies.

Khalfallah et al. (2014) propose a sophisticated methodology for designing cross-organisational collaborative platforms addressing some of the most critical interoperability issues. They methodology combines usage of semantic web, service oriented, and cloud technologies. Data interoperability is addressed at *syntactic*, *structural* and *semantic* levels. In order to ensure semantic interoperability, the interoperability services use a common standards-based ontology converting the enterprise's proprietary data models into an OWL-based equivalent representation, which are then mapped to a reference OWL ontology that is built using the building blocks and concepts defined in prominent data exchange standards in the aerospace industry. Finally, when enterprises need to exchange information, the interoperability services use mappings previously established as one of the inputs for data transformation. As semantic web technologies do not address data transformation, the mapping is completed by conversion rules based on other technologies, in order to transform the exchanged data among communicating partners. The use of cloud technologies ensures availability of the collaborative platform as a ready to use scalable and flexible set of capabilities, easily useable without investing on creating dedicated infrastructure. The authors approach has been validated in aerospace manufacturing sector and provides a good demonstration for the use of semantics and knowledge management in a highly complex and rich content ecosystem, linking manufacturers, suppliers, and third parties.

Nevertheless, to respond to the prominent need of information systems to have an agile capability of handling knowledge, it is necessary that systems have a formal knowledge representation capability supported by specific and advanced reasoning features. Sarraipa et.al (2014) proposes a knowledge management approach with the purpose to gather, model and consume community knowledge for specific recommendation commitments. Such approach is accomplished by a semantic lexicon alignment between the various community knowledge assets, to facilitate collaborations establishment between people and systems in an interoperable fashion. Thus, it is proposed a knowledge base supported by a thesaurus able to represent all the metadata needed to represent and characterize the various community stakeholders' resources. The thesaurus represents the lexicon in the domain, which for example in the ALTER-NATIVA systems is mostly used to support the various e-Learning elements (e.g. courses) and users categorization, sustained by synchronization features to facilitate a constant update of its information. A set of services designed to recommend specific resources in relation to a determined profile of user is provided. Actually, this kind of knowledge enables context awareness abilities in the organisation's systems, demanding for effective knowledge transfer to enhance the delivery of skills and competences among the manufacturer's workers. Also, it contributes indirectly to an efficient training implementation, which training programmes in industrial setting would be related to the establishment of interoperable and collaborative technological solutions.

## 4. SERVICE ORIENTATION AND THE NEED FOR NEGOTIATION

Sensing manufacturing enterprises and knowledge management are two clearly strategic vectors of research on global manufacturing systems interoperability using service orientation, representing high-level architecture options for designing solutions. However the operationalization of these two dimensions requires further developments in order to sustain day-to-day activities in intra-organisational processes and inter-enterprise processes (Cretan 2012). For some years, Service-Oriented Architectures and Environments for systems interoperability have been deployed, and much research is still going on (Ducq 2012a). More recently, research on manufacturing service orientation and interoperability has been proposing service composition, orchestration and overall negotiation mechanisms in order to enable further levels of automation and withdraw human intervention regarding some of the configuration options (Wadhwa 2009).

Hsieh and Lin (2014) propose to use Holonic Multi-agent Systems (HMS) as a flexible and reconfigurable architecture to accommodate changes based on dynamic organisation and collaboration of autonomous agents in a global manufacturing ecosystem. They describe a methodology to design self-adaptive software systems based on the HMS architecture which enables formulation of a workflow adaptation problem (WAP) and an interaction mechanism based on contract net protocol (CNP) to find a solution to WAP to compose the services based on HMS. The interaction mechanism relies on a service publication and discovery scheme to find a set of task agents and a set of actor agents to compose the required services in HMS. Their approach sustains a viable self-adaptation scheme to reconfigure the agents and the composed services based on cooperation of agents in HMS to accommodate the changes in workflow and capabilities of actors. The Hsieh and Lin (2014) design methodology is broken down into five parts. Firstly, there are the task models and actor activity models in Petri nets using Petri Net Markup Language (PNML) editors. After, it is developed a service publication and discovery scheme based on Petri net models. The third part consists of an interaction mechanism based on CNP to form a holarchy that is composed of the best agents, and combines the PNML files of the task models and actor activity models of agents into a single PNML file to represent the complete Petri net model. Fourthly, there is the architecture to facilitate the generation of the list of actions for the actor agents in a given system state. Finally, a self-adaptation scheme is developed to respond to the process changes.

In a different approach, Jakjoud et al. (2014) address the need for optimisation of supply chain and manufacturing processes in the common situation of these processes being heterogeneous and poly-disciplinary, and to assure a general consistent model for all systems engineering concepts. The challenge here is in achieving an equilibrium covering all key concepts of systems engineering processes and providing a rich language to express the details of these concepts. Their proposed solution defines a system process engineering metamodel inspired from research advances on SPEM (Software Process Engineering Metamodel) and SysML (System Modelling Language). Their solution goes beyond the definition and description of processes by providing an orchestration mechanism based on aspect oriented programming, to animate the execution control and monitoring through non-intrusive mechanisms. SysPEM is a modelling language intended to describe systems engineering processes, and to provide orchestration there is a mechanism able to trigger activities and actions without putting it directly inside the meta-model. SysPEM's general architecture (Jakjoud et al. 2014) consists of defining Requirements, Products, Activities and Roles. They enrich SysPEM with an orchestration engine able to automate a control process. This is done through software component based on oriented programming that works as articulations between active entities (activities, actions and tests).

With a similar challenge, but taking a different approach, Karnok et al. (2014) address organisational heterogeneity in networks where new members may join at any time and that may require ongoing actions to maintain interoperability, and thus requiring automation on data model and dataflow design, as well as handling of data at run-time. Their approach on data type definition and manipulation, through a dataflow engine and type-related features, present, aside from an XML-based type system, type inference algorithms, which are employed both during design and flow execution. Building upon the ADVANCE framework that supports design and execution of data flows typically associated with processes in logistics networks, the authors present a possible XML-schema-based type definition system with associated type comparison operations, as well as type inference applicable to concrete, variable and parametric types. While being two cleanly separable areas, formal type definition and type handling algorithms rely on each other, hence their combined presentation in the paper. The data type specialisation approach selected for the application scenario required formal support for type definition with emphasis on structure, i.e. the XML-schema-based type definition system elaborated in the project that presented new results by providing such a solution that enables automatic type operations to be efficiently performed. Operating on types defined by the aforementioned means, type operation algorithms were elaborated, their added value being support of parametric types, and proper bootstrapping of the type graph processed by the algorithm, enabling fully automated operation with guaranteed results.

The wide adoption of services does still present some challenges, as for example service registry that does not support the Quality of Service (QoS) properties, the common web service description language (WSDL) that does not allow specification of the QoS properties, and where there is no common ontology structure to store services. Chhun et al. (2014) aim at overcoming this issue by proposing to enhance the representation of services to assist the service selection and composition process. They define a Web Service Ontology (WSOnto) and a service selection algorithm to validate the proposed WSOnto. WSOnto is defined to represent the semantic information of the existing available services and their service categories. This ontology is composed of two main parts, the first part stores the categories of services, and the second stores services' properties (functional and non-functional). The web service ontology is automatically generated, and the tModel values of UDDI are used to categorise the services into groups. In addition, each category group is associated with a list of keywords extracted from the category's name, category's description, service's name and service's description. Chhun et al. (2014) approach considers a service selection algorithm with multi-criteria as input, introduced to validate the proposed ontology structure. The multi criteria are domain context, service's functional properties, weight of QoS attributes and service's security. The service's security properties refer to the authentication information. The WSOnto and a service selection algorithm can be used to assist the re-engineering of business processes from users' designed business processes.

Service negotiation mechanisms are seen as fundamental to propose a service-base for advanced collaboration in enterprise networks, as a solution to improve the sustainability of interoperability within manufacturing enterprise inter-organisational information systems. Coutinho et al. (2014) proposes a Collaborative Framework offering mechanisms to support negotiations in a distributed environment. This includes a set of hierarchically layered and distributed components that implement the rules of the modelled negotiation and also handle the interoperability aspects of the negotiation. The framework's top layer (Negotiation Manager) is targeted to the Manager of each negotiation party. It handles all business decisions that need to be taken (e.g., proposal, acceptance of proposal, rejection of proposal, invite of another party to take part in the negotiation process) and analyses and manages the negotiated parameters, communicating with the lower layers using web-services. A second layer is dedicated to the Coordination Services (CS) which assist the negotiations at a global level (negotiations with different participants on different jobs) and at a specific level (negotiation on the same job with different participants) handling all issues regarding communication at this layer level, i.e. synchronisation among the CS of the several parties that are taking place in the negotiation. The CS also handles the on-going transactions and manages persistence of the status of the negotiation sequences. The middleware layer services provides support for performance of all aspects related with basic infrastructure, and handling the heterogeneity related with multiple negotiation players. It may also include publication of the job requirements and characteristics, in order to allow potential companies interested in participating to "subscribe" and be able to enter the negotiation. For Coutinho et al. (2014) each negotiation is organised in three main steps: initialisation; refinement of the job under negotiation; and closure. The initialisation step allows definition of what has to be negotiated (Negotiation Object) and how (Negotiation Framework). In the refinement step, participants exchange proposals on the negotiation object trying to satisfy their constraints, and in Closure it concludes the negotiation.

## 5. BUSINESS INTEROPERABILITY

Having revised the main lines of research in global manufacturing systems interoperability, there is still room to consider the business interoperability dimension of the challenge, something that is not common to see addressed but that has a major impact on the success of systems interoperability deployment (Grilo 2010)(EDE 2010).

Galasso et al. (2014) propose a method to select in a given context the most appropriate interoperability solution between two or more companies. In their approach, the first step is the modelling of the collaborative scenarios to understand the existing collaboration, the disruptions in the collaboration, and to have a diagnosis on the points to improve. Based on the expected collaboration scenarios, performance of each scenario is assessed through a discrete event simulation approach and an aggregated performance is calculated using a Causal Performance Measurement Model (CPMM) qualitative model. The accessibility of each scenario is evaluated based on four criteria: human resource, budget, risk and cultural gap. The comparison is done for several scenarios in a synthetic decision support matrix in order to select the best solution.

Behnamia and Ghomi (2014) reviewed a specific problem and challenge of business interoperability, namely the multi-factory scheduling problem and its many variants that have appeared since 1981. The survey classified the literature according to the shop environments, including single machine, parallel machines, flow shops, job shops and open shops. They proposed three groups of factors to be considered in terms of forthcoming research focus and regarding the business interoperability dimension, stressing the importance of a more realistic production network. Hence, they recommend that research should consider: Heterogeneous Factories, Virtual Production Networks, Self-interested Factories as production agents, Responsibility of factories to their region, Transportation among factories, Network with open shop, Parallel machine environment in factories, Production network with combined structures, and Network with dissimilar machines' environment in the factories.

Tibaut et al. (2014) reviews the state-of-the art of automated manufacturing systems in the architecture, engineering and construction (AEC) sector and the interoperability requirements for automated construction in context of the entire building lifecycle. Their work is based on experimental free-form clay building, designed with embedded simple HVAC components, and manufactured with additive layer technology. They define a new interoperability demand function according to the evolution of automated versus manual operations in manufacturing tasks: $I_d = A/M$, where *A* is a percentage of project's time completed in an automated manner (i.e. automated data exchange, automated manufacturing systems) and *M* is the percentage of project's time completed in traditional, manual way (i.e. manual data exchange, manual field work). The lower limit of $I_d$ (0) means that there is no need for automation because the percentage of manual work in a project is 100%, which in consequence means that there is no demand for digital interoperability. The case $I_d$ (0) is still present in simple construction projects and/or countries with less developed construction industry. The interoperability demand scale upper limit $I_d$ (100) is virtually impossible to reach in construction projects because today's technology is far away from 100% automated construction process. F demands (or necessity) for interoperability inherently grows as more and more automation technologies are introduced in the lifecycle of a construction project.

Tibaut et al. (2014) state that inefficiency is regarded as lack of interoperability within an individual phase and between the three phases of the life-cycle. The cost share of interoperability inefficiency in construction lifecycle is the highest in the operation and maintenance phase. This means that the phase has the greatest potential for interoperability improvement when compared to the cost share in the planning and design phase, and construction phase. Improved interoperability in the operation and maintenance phase would reduce the cost share in this phase. Reduced cost share of interoperability inefficiency in each single lifecycle phase would result in lower total (absolute) cost of a construction project. Automated manufacturing systems correspond to the construction phase (erection of the building). More automation in construction phase would increase interoperability demand in this phase.

## 6. Final Considerations on Novel Strategies for Global Manufacturing Systems Interoperability

Within each of the categories considered, we see strong common themes, as well as diversity of focus within the theme. In the first category, the sensing manufacturing enterprise, all the papers reviewed are concerned with the application of sensing devices, but the focus ranges from their integration with distributed discrete event simulation, and characterisation of sensing objects to deployment in negotiation and context reasoning. In semantics and knowledge management the use of semantic reasoning on web content in manufacturing collaborations, and other contexts, contrasts with the development of cross organisational semantic platforms to support interoperability. Service orientation and need for negotiation embraces agent based service selection, and enhanced representation of services to include description of, amongst other indicators, quality of service. This category also includes a systems engineering approach to supply chain process optimisation, the delivery of on-the-fly XML based services that can respond to frequent change in volatile production networks, and services to support negotiation in collaborative manufacturing. The final category, business interoperability, presents a collaboration performance measurement model based on the modelling of collaboration scenarios, and an advance in the established problem of multi-factory scheduling, as well as a state of the art review of interoperability requirements in the automated manufacturing systems in the architecture, engineering and construction (AEC) sector.

It is also possible to discern a spectrum of related research interests across the categories, in that the sensing enterprise category addresses issues relating to hardware or virtual sensing devices, whilst semantics and knowledge management address the semantic interpretation and modelling of knowledge generated from such devices. Service orientation and negotiation have the potential to deliver real benefit from the information and knowledge and reasoning abilities provided by the above, and in turn provide the capabilities needed to achieve business interoperability. All of the categories of research are yielding novel strategies for global manufacturing systems interoperability, though there is a clear need for ongoing research.

## Acknowledgement

The authors acknowledge the projects SEMANTIK, ISOFIN and PRODUTECH, co-financed by STEPVALUE and IAPMEI and the European Funds QREN COMPETE. Also, the European Commission for funding the projects IMAGINE nr 285132, (www.imagine-futurefactory.eu/), FITMAN nr 604674 (http://www.fitman-fi.eu), and OSMOSE nr 610905 (http://www.osmose-project.eu), and Fundação da Ciência e Tecnologia for funding our research units.

## REFERENCES


1. Agostinho, C., Sarraipa, J., Goncalves, D., Jardim-Goncalves, R. (2011). Tuple-based semantic and structural mapping for a sustainable interoperability. In Technological Innovation for Sustainability (pp. 45-56). Springer Berlin Heidelberg.

2. Behnamian, J., Ghomi, S. (2014) A survey of multi-factory scheduling, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1692)

3. Berre, A. et al., (2007), The ATHENA interoperability framework. In 3rd International Conference on Interoperability for Enterprise Software and Applications (I-ESA'07). Funchal, Madeira: Springer.

4. Broll, G., Rukzio, E., Paolucci, M., et al. (2009) Perci: Pervasive Service Interaction with the Internet of Things. Internet Computing, IEEE. 13(6):74-81. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5262929 [Accessed June 8, 2014].

5. Charalabidis, Y., Lampathaki, F., Kavalaki, A., Askounis, D. (2010) A Review of Interoperability Frameworks: Patterns and Challenges. International Journal of Electronic Governance (IJEG), 3 (2), pp. 189-221. Inderscience Publications

6. Chen, D., Doumeingts, G., Vernadat, F. (2008) Architectures for enterprise integration and interoperability: Past, present and future. Computers in Industry 59 (7), 647-659.

7. Chhun, S., Moalla, N., Ouzrut, Y. (2014) QoS Ontology for Service Selection and Reuse, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1893)

8. Coutinho, C., Cretan, A., Silva, C., Ghodous, P., Jardim-Goncalves, R. (2014) Service-based Negotiation for Advanced Collaboration in Enterprise Networks, Journal of Intelligent Manufacturing, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-2130)

9. Cretan, A., Coutinho, C., Bratu, B., Jardim-Goncalves, R., (2012), NEGOSEIO: A framework for negotiations toward Sustainable Enterprise Interoperability, Annual Reviews in Control, 36(2), (pp. 291-299), ISSN 1367-5788.

10. Danila, C., Stegaru, G., Stanescu, A., Serbanescu, C. (2014) Web-Service based Architecture to support SCM context-awareness and interoperability, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1881)

11. Ducq, Y., Chen, D., Alix, T., (2012), Principles of Servitization and Definition of an Architecture for Model Driven Service System Engineering. In 4th International IFIP Working Conference on Enterprise Interoperability (IWEI 2012). Harbin, China: Springer.

12. Ducq, Y., Chen, D., Doumeingts, G., (2012a), A contribution of system theory to sustainable enterprise interoperability science base. Computers in Industry, 63(8), pp.844–857.

13. EDE (2010), Envisioning Digital Europe 2030: Scenarios for ICT in Future Governance and Policy Modelling – JRC European Commission, 2010, http://ftp.jrc.es/EURdoc/JRC61593.pdf [Accessed June 8, 2014]

14. Ferreira, J. et al., (2013), Standard Blueprints for Interoperability in Factories of the Future (FoF). 7th IFAC Conference on Manufacturing Modelling, Management and Control, 2013. Russia, pp. 1322–1327.

15. FINES (2012), Future Internet Enterprise Systems (FInES) Research Roadmap 2025, 2012, http://cordis.europa.eu/fp7/ict/enet/documents/fines-research-roadmap-v30_en.pdf [Accessed June 8, 2014]

16. Frankston, B., (2009), Ambient Connectivity: An Introduction. Available at: http://frankston.com/public/?n=IAC [Accessed June 8, 2014].

17. Frankston, B., (2013), The Internet of Things Versus the Access Framing. IEEE Consumer Electronics Magazine, pp.56–57.

18. Galasso, F., Ducq, Y., Lauras, M., Gourc, D., Camara, M. (2014) A Method to Select a Successful Interoperability Solution through a Simulation Approach, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1904)

19. Grauer, M., Metz, D., Karadgi, S., Schafer, W., & Reichwald, J. (2010). Towards an IT-framework for digital enterprise integration. Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology (p. 1467–1482). Springer. http://www.springerlink.com/index/786x362p2316375u.pdf [Accessed June 8, 2014].

20. Grilo, A., Jardim-Goncalves, R., (2010), Challenging electronic procurement in the AEC sector: BIM-based integrated perspective, Journal Automation in Construction AUTOCON, 20(2), (pp. 107-114), ISSN 0926-5805

21. Grilo, A., Jardim-Goncalves, R., (2010a), Value proposition of interoperability on BIM and collaborative working environments, Journal Automation in Construction AUTOCON, 19(5), (pp. 522-530), ISSN 0926-5805, Elsevier

22. Hsieh, F., Lin, J. (2014) A Self-Adaptation Scheme for Workflow Management in Multi-Agent Systems, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1877)

23. INCOSE, (2007), Systems Engineering Vision 2020 (INCOSE-TP-2004-004-02), INCOSE. http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf [Accessed June 8, 2014]

24. Jakjoud, A., Zrikem, M., Baron, C., Ayadi, A. (2014) SysPEM: Toward a consistent and unified System Process Engineering Metamodel, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1879)

25. Jardim-Goncalves, R., & Grilo, A. (2010). Building information modeling and interoperability. Automation in Construction, 19(4), 387.

26. Jardim-Goncalves, R., Agostinho, C., Lamphataki, F., Chalarabidis, I., Grilo, A., (2014), Systematisation of Interoperability Body of Knowledge: The foundation for EI as a science, Enterprise Information Systems Journal, (pp. 7-32), 7(1)

27. Karnok, D., Kemeny, Z., Ilie-Zudor, E., Monostori, L. (2014) Data type definition and handling for supporting interoperability across organizational borders, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-D-13-02393)

28. Khalfallah,M., Figay, N., Silva, C., Ghodous, P. (2014) A Cloud-Based Platform to Ensure Interoperability in the Aerospace Industry, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1873)

29. Khilwani, N., Harding, J. (2014) Managing corporate memory on the semantic web, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1871)

30. Koussouris, S., Lampathaki, F., Mouzakitis, S., Charalabidis, Y., Psarras, J. (2011). Digging into the Real-Life Enterprise Interoperability Areas Definition and Overview of the Main Research Areas. In Proceedings of CENT 2011: Collaborative Enterprises 2011 – Platforms, Processes, and Practices Advancing the Enterprise 2.0, Orlando/FL, USA, July 19-22, 2011.

31. Moisescu, M., Sacala, I., (2014) Towards the Development of Interoperable Sensing Systems for the Future Enterprise, Journal of Intelligent Manufacturing, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1883)

32. Santucci, G., Martinez, C. & Vlad-câlcic, D. (2012), The Sensing Enterprise. In FInES Workshop at FIA 2012. Aalborg, Denmark. http://www.theinternetofthings.eu/sites/default/files/%5Buser-name%5D/Sensing-enterprise.pdf [Accessed June 8, 2014]

33. Sarraipa, J., Jardim-Goncalves, R., Steiger, A., (2010), MENTOR: An Enabler for Interoperable Intelligent Systems, International Journal of General Systems, 39(5), (pp. 557-573), ISSN: 0308-1079, Taylor and Francis

34. Sarraipa, J., Marques-Lucena, C., Baldiris, S., Fabregat, R., Aciar, S. (2014) The ALTER-NATIVA Knowledge Management Approach, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-D-14-00001)

35. Tibaut, A., Rebolj, D., Perc, M. (2014) Interoperability requirements for automated manufacturing systems in construction, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1976)

36. Tu, Z., Zacharewicz, G. (2014) A Federated Approach to develop Enterprise Interoperability, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1720)

37. Vargas, A., Cuenca, L., Boza, A., Sacala, I., Moisescu, M. (2014) Towards the development of the framework for inter sensing enterprise architecture, Vol X Num X, (pp XX-XX), Forthcoming (JIMS-1849)

38. Wadhwa, S., Mishra, M., & Chan, F. (2009). Organizing a virtual manufacturing enterprise: an analytic network process based approach for enterprise flexibility. International Journal of Production Research, 47(1), 163-186.