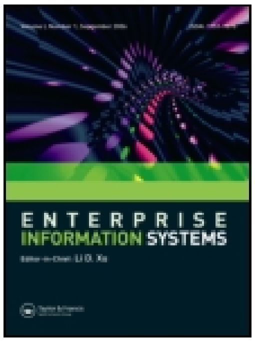

Enterprise Information Systems

ISSN: 1751-7575 (Print) 1751-7583 (Online) Journal homepage: http://www.tandfonline.com/loi/teis20

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To cite this article: Ricardo Jardim-Goncalves , Antonio Grilo , Carlos Agostinho , Fenareti Lampathaki & Yannis Charalabidis (2013) Systematisation of Interoperability Body of Knowledge: the foundation for Enterprise Interoperability as a science, Enterprise Information Systems, 7:1, 7-32, DOI: 10.1080/17517575.2012.684401

To link to this article: https://doi.org/10.1080/17517575.2012.684401

Enterprise Information Systems
Vol. 7, No. 1, February 2013, 7–32

Systematisation of Interoperability Body of Knowledge: the foundation for Enterprise Interoperability as a science

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(*Received 12 October 2011; final version received 9 April 2012*)

The recently posed challenge of developing an Enterprise Interoperability Science Foundation (EISF) prompted some academic agents to attempt a systematisation of the Interoperability Body of Knowledge (IBoK). Still in their embryonic stages, these efforts have sought to organise and aggregate information from very fragmented and disparate sources, and with different granularities of detail, distinct epistemology origins, separate academic fields, etc. This paper aims to distinguish between levels of specificity of the Interoperability academic work, which are often confused, by considering Models, Theories, and Frameworks. The paper revises these concepts within the context of the EISF's recent work. The results presented here, reflecting consultation with the expert community, provide the synthesis of the current state of play regarding the work developed by the Enterprise Interoperability (EI) at the European Commission's Future Internet Enterprise Systems (FInES) cluster.

Keywords: Enterprise Interoperability; Science Foundation; theory; model; frameworks

1. Introduction

Enterprise Interoperability (EI) is a well-established area of applied research that addresses the problems related with the lack of systems and applications' interoperability in organisations and proposes novel solutions for EI problems. However, in spite of research efforts to date, the proper scientific foundations for EI remain elusive. This lack has been preventing the generalisation and full reuse of the methods and tools that have been developed so far and is threatening the sustainability of EI as a domain for research.

Interoperability of Enterprise Systems and Applications has been a strong focus of research in the lasting recent years, by the industry and research community alike (Charalabidis 2010a, Popplewell 2011). Worldwide researchers have been working on main areas that have direct contribution in EI (Koussouris 2011): (1) Data Interoperability (Atzeni *et al.* 2006, Jardim-Goncalves *et al.* 2006a, Li and Yang

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ISSN 1751-7575 print/ISSN 1751-7583 online

http://dx.doi.org/10.1080/17517575.2012.684401
http://www.tandfonline.com

2008, Cao and Zhang 2009, Hammar and Tarasov 2010, Kabak and Dogac 2010); (2) Process Interoperability (Seng and Lin 2007, Burkhart *et al.* 2009, Carpenter *et al.* 2009, Zhao *et al.* 2009, Grangel *et al.* 2010, Agostinho *et al.* 2011, Grilo and Jardim-Goncalves 2011); (3) Rules Interoperability (Jouault and Kurtev 2007, Kutvonen *et al.* 2007, Del Fabro *et al.* 2009, Demey *et al.* 2010); (4) Objects Interoperability (Al-Salqan 1996, Broll *et al.* 2009, Welbourne *et al.* 2009); (5) Software Systems Interoperability (Allen and Garlan 1997, Bing-Hai *et al.* 2005, Chen *et al.* 2008, Demirkan *et al.* 2008, Chung and Lee 2010); (6) Cultural Interoperability (Lewis and George 2008, Moon *et al.* 2008, Recabarren *et al.* 2008); (7) Knowledge Interoperability (Berners-Lee *et al.* 2001, Bonifacio and Molani 2003, Bock *et al.* 2005, Ye *et al.* 2007, Yang and Chen 2008, Sarraipa *et al.* 2010, Jardim-Goncalves *et al.* 2011); (8) Service Interoperability (Benslimane 2008, Bertoli *et al.* 2010, Li *et al.* 2010, Schuster *et al.* 2011); (9) Social Networks Interoperability (Zhu *et al.* 2008, Abel *et al.* 2009, Facebook 2011); (10) Electronic Identity Interoperability (Palfrey and Gasser 2007, Halperin and Backhouse 2008, Backhouse and Halperin 2009); (11) Cloud Interoperability (Buyya *et al.* 2009, Rings *et al.* 2009, Brandic *et al.* 2010, Dillon *et al.* 2010, Hofmann and Woods 2010, Mell and Grance 2011) and (12) Ecosystems Interoperability (Aziz *et al.* 2005, Briscoe and Marinos 2009, Wadhwa *et al.* 2009, Grauer *et al.* 2010).

The effort was triggered by a significant increase in research funding by the European Commission that, in 2011 alone, has already distributed more than 30 million Euros to support research projects in this area and created a specific cluster of projects addressing the research field of Interoperability of Engineering Systems and Applications, towards the foundation of a science-base for EI (ENSEMBLE 2011). This cluster represents a community of more than 30 active research projects, bringing together more than 200 industrial and research organisations.

However, any scientific domain exists in an ecosystem of neighbouring scientific domains and must therefore recognise its relationship with these domains. This relationship will include at least:

(1) Boundaries between application fields, which may be fuzzy in the sense that there are some applications which could be addressed from the perspective of either domain. Formally, it may be appropriate to define membership functions to applications in order to recognise and resolve this overlap.
(2) Shared methodologies, techniques and tools that may be applicable to problems in more than one domain. Recognition of such sharing provides a unique opportunity for domains to advance by absorbing methodological and technical advances from their related disciplines.
(3) Conflicts in approaches may also exist and present possible barriers to interdisciplinary research or application. Formal documentation of such conflict areas will reduce risk of failure in projects arising out of the application of incompatible approaches.

The need for definition of an Enterprise Interoperability Science Base (EISB) was first documented in the EI Research Roadmap version 4 (EC 2006) published in 2006 by the European Commission. Here, the definition of an EISB was specified as one of four main Grand Challenges to be addressed by researchers in the domain. This challenge was recognised by the EI Cluster promoted by the European Commission, and in 2008, the Cluster formed a small task force to work on the EISB. This task force reported back to Cluster meetings through 2008 and 2009 and compiled part of the source material that is summarised in the following chapters. This work was published in Future Internet Enterprise Systems (FInES) (2010). In 2009, the European Commission sponsored an "Enterprise Interoperability Science Base Meeting" to which members of the FInES Cluster (previously the EI Cluster mentioned above) and international scientific experts were invited.

In this context, the purpose of the current paper is to contribute to the scientific foundations of the EI research domain, systematising the state of play in EI applied research by the Interoperability Body of Knowledge (IBoK), taking as a basis the reference work from main researchers in the area. The recent efforts developed by this community, and led by the authors of this paper, to develop an Enterprise Interoperability Science Foundation (EISF) within the IBoK, demonstrates a growing interest in developing the subject of Interoperability in a more systematic and scientific way. According to IBoK, given the need for multiple disciplines and levels of analysis involved in studying the configuration relationships amongst technologies, rules and relevant aspects of the world, the study of Interoperability can be developed depending on theoretical work undertaken at three levels of essential specificity, including frameworks, theories and models. Hence, the posed research question in this work is: *How can the systematisation of IBoK contribute for the foundations of EI as a science?*

Two guiding statements related to the research process followed have been laid down to address the research question, namely:

- Statement 1: The EISF should address IBoK at the levels of frameworks, theories and models (see Section 3) and make a gap analysis of where current academic scientific state-of-the-art is and where it needs to go to respond to the actual EI requirements.
- Statement 2: Analysis conducted at each IBoK level provides different degrees of specificity related to a particular Interoperability problem.

This paper is organised as follows: In Section 2, the paper revises the concepts of frameworks, theories and models within the context of the Enterprise Science Foundation's recent and ongoing work. In Section 3, the current state-of-the-art on Interoperability frameworks is addressed, and forthcoming developments towards science-based achievements are envisioned. Section 4 describes Interoperability Theories and pinpoints some potential developments, paths and theory systematisations. Section 5 analyses the most relevant interoperability models pertaining to EI as a science, grounded on the recent FInES Research Roadmap Challenges and Key Technologies. The paper closes with considerations on the major contributions of the paper towards EI as a science.

2. Methodology for the analysis of the EISB state of play

With the goal of outlining a set of up-to-date advancements that will be taken into account during the formulation of the EISB, the work carried out for this State of Play Analysis, focuses on two directions (Figure 1):

- **Axis I:** Definition of the contents and structure of the EISB considering the EI neighbouring scientific domains.

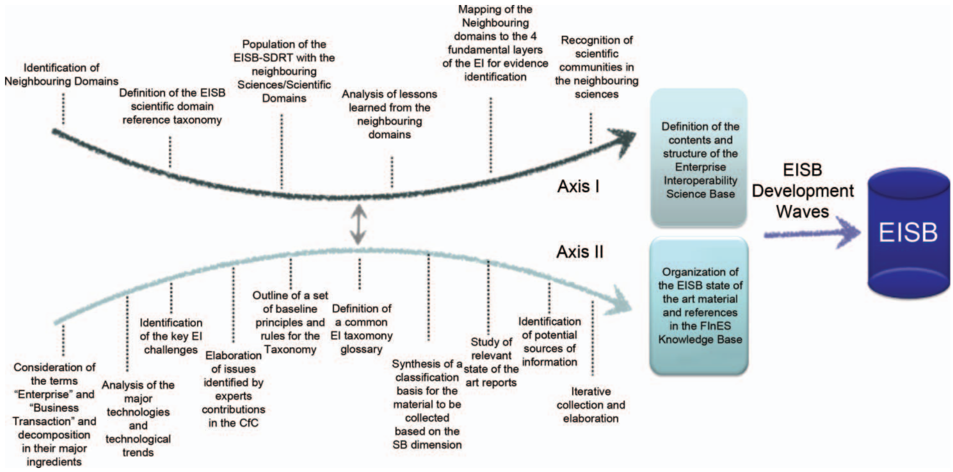

Figure 1. Methodological approach for EISB definition and state of play review.

- **Axis II:** Elaboration on the scientific areas that constitute the EI concept and contribute to characterising it as a self-standing research domain.

The methodology adopted consists of two parallel-running processes, under constant bi-lateral communication and coordination, in order to ensure their proper execution and alignment for the specifications of the areas and the contents that should be included in the EISB.

With regard to the definition of the Science Base, the following steps have been followed:

(1) Identification of well-established Sciences and underlying Scientific Domains that are related to EI and can be characterised as its Neighbouring Domains;
(2) Definition of the EISB scientific domain reference taxonomy (EISB-SDRT) with a three-level structure (Popplewell 2011);
(3) Population of the EISB-SDRT with the neighbouring Sciences/Scientific Domains;
(4) Analysis of lessons learned from those domains by matching their basic issues to EI;
(5) Mapping of the Neighbouring domains to the three fundamental levels of frameworks, theories and models;
(6) Recognition of scientific communities in the neighbouring sciences through notable scientific journals in which their work is published in order to facilitate knowledge extraction and identification of possible future joint research schemes;
(7) Definition of the scope and contents of the Science Base for the domain of EI.

In parallel, as far as Axis II is concerned, the driving principle is to collect all material related to EI and to classify it into Scientific Areas and the initial Science Base Structure. This axis includes the formulation of a reference taxonomy for the EI internal domains, analysis of the major technologies in adoption, elaboration of issues identified by experts' papers, study of relevant state-of-the-art reports from other related research projects funded (i.e. INTEROP, ATHENA, COIN, GENESIS, etc.) and identification of potential sources of information in order to cover various EI aspects (including Academic literature databases (SCOPUS, ISI Web of Knowledge, SpringerLink and Google Scholar), Social media (such as blogs, Twitter hashtags and delicious bookmarks tags) and Project websites).

The results presented in this paper report the current state of play regarding the work developed by the EI at European Commission Future of Internet Enterprise Systems cluster. The results studied emerge from the consultation and discussion from more than 70 past and ongoing research projects involving about 700 researchers. The research results summarised in this paper have been analysed and validated by a large community of EI experts, in workshops at the Samos 2011 Summit (Charalabidis *et al*. 2011) along with ex-post event off-line feedback over the documents produced and discussions in the meeting. The Samos 2011 Summit on Future Internet was an event where joint collaborative workshops were organised, including those on EI Research Roadmap and Enterprise Interoperability Scientific Formulation. About 100 participants including industry executives and engineers, administration officials and researchers and the Experts Scientific Committee members discussed ideas and concepts on interoperability of engineering systems and applications. The empirical results presented in this paper are grounded on relevant outputs resulting from this summit and have been validated by experts and research projects of the European Commission FInES cluster.

3. Conceptualising frameworks, theories, and models

The recent efforts to develop an EISF within the IBoK demonstrate a growing interest in advancing the subject of Interoperability in a more systematic and solid way. Nobel prize laureate Elinor Ostrom (2005) stresses the necessity of distinguishing between levels of specificity of academic work that are often confused. She attributes special importance to the clear consideration of Models, Theories and Frameworks. In the case of Interoperability and its Science Foundation, given the need for multiple disciplines (and therefore multiple disciplinary languages and the multiple levels of analysis involved in studying configurable relationships amongst technologies, rules and relevant aspects of the world), the study of Interoperability depends on theoretical work undertaken at three levels of specificity that are often confused with one another. These essential foundations include (1) frameworks, (2) theories and (3) models. Hence, it is defended in this paper that the Scientific Foundation of Interoperability should address the various levels and make a gap analysis of where current academic scientific state-of-the-art is and where it needs to go. The reason is that analyses conducted at each level provide different degrees of specificity related to a particular Interoperability problem.

Ostrom (2005) stresses that the development and use of a general framework helps to identify the elements and relationships among these elements that one needs to consider for analysis. Frameworks organise diagnostic and prescriptive research and inquiry. Hence, they provide the most general list of variables that should be used to analyse all types of interoperability research and development. Interoperability frameworks will provide a meta-theoretical language that is necessary when developing theories for Interoperability and that can be used to compare theories. They attempt to identify the universal Interoperability elements that any theory relevant to Interoperability would need to include. Many differences in surface reality can result from the way these variables combine or interact with one another. Thus, the elements contained in a framework help the analyst to generate the questions that need to be addressed when first conducting an analysis.

The development and use of theories enables the analyst to specify which elements of the framework are particularly relevant for certain kinds of questions and to make general working assumptions about these elements (Ostrom 2005). Thus, Interoperability theories will focus on a framework and make specific assumptions that are necessary for an analyst to diagnose a phenomenon, explain its processes and predict outcomes. Several theories are usually compatible with any framework.

Finally, models make precise assumptions about a limited set of parameters and variables (Ostrom 2005). Logic, mathematics, game theory, architectures, experimentation and simulation, and other means are used to explore the consequences of these assumptions systematically on a limited set of outcomes. Multiple models are compatible with most theories.

4. Interoperability frameworks

Interoperability Frameworks can be used in EI research to outline possible courses of action or to present a preferred approach to ideas. Interoperability frameworks shall attempt to connect to all aspects of inquiry (e.g. problem definition, purpose, literature review, methodology, data collection and analysis) and can act like maps that might give coherence to conceptual theory development and empirical inquiry.

In the context of Enterprise Systems and Applications, the Interoperability Framework development has been triggered on the Interoperability Developments for Enterprise Application and Software (IDEAS) project, a European Commission funded project under the European V Framework Program (FP5), which was completed in 2003 and aimed to create and manage a Working Group to elaborate a strategic roadmap in the domain of enterprise application and software interoperability (IDEAS 2005). It stated that in order to achieve meaningful interoperation between enterprises, interoperability must be achieved in all levels of an enterprise. This includes the business environment and business processes on the business level; the organisational roles, skills and competencies of employees and knowledge assets on the knowledge level and applications, data, and communication components on the ICT level. In addition, semantic descriptions can be used to create the necessary mutual understanding between enterprises that wish to collaborate.

The ATHENA Project was subsequently funded by the European Commission under the VI Framework Program (FP6) and aimed at adopting a holistic perspective on interoperability in order to analyse and understand the business needs and the technical requirements, and a multidisciplinary solution approach to solving the interoperability problems (ATHENA 2004).

In the wake of these projects, a number of initiatives have sought to systemise and classify the different interoperability aspects into comprehensive interoperability frameworks, amongst others the e-Government Interoperability Framework (e-GIF), the Levels of Information Systems Interoperability framework (LISI) and the European Interoperability Framework (EIF). Generally, the initiators of these frameworks have been practitioners or public administrations that are hoping to standardise across distributed organisations and avoid technology vendor lock-in (Charalabidis *et al.* 2009b, 2010a,b). The frameworks identified for EI are summarised in Table 1.

Table 1. Enterprise Interoperability Frameworks.

EI Framework	Identified levels
Levels of Information System Interoperability (LISI) C4ISR (1998)	Isolated Systems, Connected Systems, Distributed Systems, Domain Systems and Enterprise Systems, affecting four interoperability attributes: Procedures, Applications, Infrastructure and Data.
Organisational Interoperability Maturity Model (Clark and Jones 1999)	Independent, Ad hoc, Collaborative, Integrated and Unified.
NATO C3 Technical Architecture (NC3TA) Reference Model for Interoperability (NMI) (NATO 2003)	No Data Exchange, Unstructured Data Exchange, Structured Data Exchange, Seamless Sharing of Data and Seamless Sharing of Information.
IDEAS Interoperability Framework (IDEAS 2005)	• Business level focusing on business environment and processes. • Knowledge level focusing on organisational roles, skills and competencies of employees and knowledge assets. • ICT systems level focusing on applications, data and communication components. Semantic and Quality dimensions, cutting across the three identified levels, focusing on supporting mutual understanding on all levels.
CEN/ISSS eBusiness Roadmap (CEN/ISSS 2006)	• Technical interoperability, which consists of the common methods and shared services for the communication, storage, processing and presentation of data. • Semantic or business interoperability, which includes discovery and collaboration aspects, including workflow and decision-making transactions. This can require alignment. of business processes as well as operational synchronisation of collaboration data. • Organisational interoperability. Sector-specific issues can cut through the entire stack.
C4 Interoperability Framework (C4IF) (Peristeras and Tarabanis 2006)	Connection, Communication, Consolidation and Collaboration, containing three objects of integration: Channel, Information, Process.
ATHENA Interoperability Framework (Berre *et al.* 2007)	Conceptual integration, Applicative integration and Technical integration that include: • Interoperability at the enterprise/business level should be seen as the organisational and operational ability of an enterprise to factually cooperate with other, external organisations in spite of e.g. different working practices, legislations, cultures and commercial approaches. • Interoperability of processes aims to make various processes work together. A process defines the sequence of the services (functions) according to some specific needs of a company. In a networked enterprise, it is also necessary to study how

(*continued*)

Table 1. (*Continued*).

EI Framework	Identified levels
	to connect internal processes of two companies to create cross-organisational business process. • Interoperability of services is concerned with identifying, composing and executing various applications (designed and implemented independently). • Interoperability of information/data is related to the management, exchange and processing of different documents, messages and/or structures by different collaborating entities.
Panetto (2007)	Synchronic Interoperability, Model-driven Interoperability, Semantic-driven Interoperability, Vertical Interoperability, Horizontal Interoperability, Diachronic Interoperability
European Interoperability Framework draft v2.0 (IDABC 2008)	• Political Context: Cooperating partners having compatible visions and focus on the same things. • Legal Interoperability: The appropriate synchronisation of the legislation in the cooperating Member State (MS) so that electronic data originating in any given MS is accorded proper legal weight and recognition wherever it needs to be used in other MS. • Organisational Interoperability: The processes by which different organisations such as different public administrations collaborate to achieve their mutually beneficial and mutually agreed eGovernment service-related goals. • Semantic Interoperability: Ensuring that the precise meaning of exchanged information (concept, organisation, services, etc.) is preserved and well-understood. • Technical Interoperability: The technical issues involved in linking computer systems and services (open interfaces, interconnection services, data integration, middleware, data presentation and exchange, accessibility and security services).
Gottschalk (2009)	Computer interoperability, Process interoperability, Knowledge interoperability, Value interoperability and Goal interoperability.
Agostinho and Jardim-Goncalves (2009)	Slack Interoperability, Unregulated Interoperability, Standard-based Interoperability, Semantic Interoperability, Sustainable Interoperability.

(*continued*)

Table 1. (*Continued*).

EI Framework	Identified levels
Levels of Conceptual Interoperability (Wang *et al.* 2009)	• L6 (Conceptual) – Interoperating systems at this level are completely aware of each other's information, processes, contexts and modelling assumptions. • L5 (Dynamic) – Interoperating systems are able to re-orient information production and consumption based on understood changes to meaning, due to changing context as time increases. • L4 (Pragmatic) – Interoperating systems will be aware of the context (system states and processes) and meaning of information being exchanged. • L3 (Semantic) – Interoperating systems are exchanging a set of terms that they can semantically parse. • L2 (Syntactic) – Have an agreed protocol to exchange the right forms of data in the right order, but the meaning of data elements is not established. • L1 (Technical) – Have technical connection(s) and can exchange data between systems
Business Interoperability Parameters (Aneesh *et al.* 2011)	Business Strategy; Management of External Relationships; Collaboration Business Processes; Organisational Structures; Employees and Work Culture; IPR Management; Business Semantics; Information Systems.

These interoperability frameworks distinguish different levels of interoperability and describe artefacts or high-level standards for each of these levels. According to Charalabidis *et al.* (2010a,b), a generic Interoperability Framework should consider the following structure:

- Technical Interoperability, investigating problems and proposing solutions for the technical-level interconnection of ICT systems and the basic protocols, digital formats or even security and accessibility mechanisms.
- Semantic Interoperability, including methods and tools, usually in the form of ontologies or standardised data schemas to tackle issues of automated information sharing during the various process execution steps.
- Organisational Interoperability, relating to the problems and solutions relevant to business processes, functional organisation or cross-enterprise collaboration activities – usually involving various ICT systems and data sources.
- Policy Interoperability, referring to the alignment of higher enterprise functions or government policies, usually to be expressed in the form of legal elements, business rules, strategic goals or collaborative supply chain layouts.

In evolutionary terms, these frameworks started by distinguishing the infrastructure, data/message and functions/services levels (Charalabidis *et al.* 2010b). In addition, the EIF introduced policy and organisational aspects of interoperability, e.g. the definition of business goals and the modelling of business processes to enable different organisations to work together. Moreover, most frameworks introduce either explicitly or implicitly an evolutionary perspective and suggest a linear advancement from lower to higher levels of interoperability. Peristeras and Tarabanis (2006) relate existing interoperability frameworks to theoretical concepts from linguistics and semiotics and derive the Connection, Communication, Consolidation and Collaboration Interoperability Framework (C4IF) for information systems interoperability. A more holistic approach is taken by the Business Interoperability Framework suggested by Legner and Wende (2006), who explicitly introduced organisational and management-related levels. On the basis of contingency theory, the authors argue that the maximum level of interoperability is not necessarily the optimal one and identify organisational and environmental contingencies (e.g. industry dynamics, e-business maturity) impacting this optimal level of interoperability (Legner and Lebreton 2007).

Aneesh *et al.* (in press) has further refined these levels and designed the Business Interoperability Parameters (BIP). Although aimed at measuring and assessing the degree of interoperability between companies, along with selecting priorities for EI improvement, the BIP provides a finely detailed Interoperability Framework for developing sectoral frameworks.

From the analysis, it is possible to conclude that overall there is a great degree of maturity in the existing body of knowledge regarding EI frameworks, with most frameworks addressing similar levels and variables. Still, further refinement of the levels and variables will be useful to provide better confinement for theory development.

5. Interoperability theories

Theories have been advanced for explaining Interoperability problems, issues and challenges (Charalabidis *et al.* 2009a), including (i) intelligent reconfiguration of components in evolutionary networked systems; (ii) conformance testing and checking in complex systems; and (iii) harmonisation of ontological structures to support dynamic ecosystems.

Intelligent reconfiguration of components, for interoperability maintenance of evolutive networked systems, has the following theory drivers:

(a) Learning and adaptability: Upon identifying the need to solve an interoperability problem, the related systems typically include little pertaining to the requirements to have the overall system completely interoperable. A learning process should be designed to support the adaption of the several system network nodes involved and thus keep the global network interoperable.
(b) Automatised categorisation of ontological structures: Automatised development of ontologies from descriptive specifications in non-specialised language, e.g. queries described in natural language, supported by an engine with feedback for the user, with learning and reconfiguration capacities.
(c) Transient analysis: The overall interoperable network, as a complex integrated system, will face transients whenever an internal or external

"interference" occurs, e.g. update in one of its nodes. Thus, there will be a period of time in which the system's nodes need to react and readapt before the system becomes stable and interoperable again. The evolution and progressive adaptation of each network system node should be supported by a systematic study and analysis of the network transients, at single node, clusters and overall network.

Regarding conformance testing and interoperability checking for complex systems interoperability assessment, theory drivers are as follows:

(a) Discovery and Notification: When a new system node is integrated in the network or is updated, how can such updates be automatically identified and completely recognised by the network, and how should the network react in order to become interoperable, or keep its interoperability with the new node or update, through the automatic understanding of the intrinsic knowledge and behaviour of the node? Then, what such information can be processed and what adaptations are needed at the systems node to restore overall interoperability to the network?
(b) Conformance checking: The evolution of the network through the integration of a new node or updates in the existing ones will require checking for the conformance of data, models, knowledge and behaviours of the systems and applications. A proper methodology should be in place to assure such conformity in the advent of such dynamics.
(c) Interoperability checking: The overall network needs to be checked and assessed in order to assure the maintenance of the networked interoperable system. A proper methodology for monitoring, diagnosis and prognosis should be in place to assure the interoperability of the complex system in the advent of dynamics in the network.

Finally, concerning harmonisation of ontological structures to support the application dynamics and enable adaptability of users' semantic specifications, the theory drivers are as follows:

(a) Mutation of ontologies supported by stochastic methods: Mutation of ontologies using stochastic method to support the updates in the representation of concepts and its instances.
(b) Harmonisation of ontologies and semantic adaptability: Semantic harmonisation and adaptive mapping in dynamic environments, with mediation of semantic conflicts according to the interactions and evolution with the systems with which it interacts.
(c) Adaptive services for knowledge management: Knowledge is the basis for seamless interoperability of the integrated overall network. Adaptive services for knowledge management will assure the accuracy of the information and behaviour of the complex system at each node and in the integrated network. They support the dynamics and evolutionary characteristics of the complex system.

In the first situation, theories are required to address how learning processes should be designed to support the adaption of the several system network nodes involved and thus keep the overall network interoperable. Moreover, theories must also address how interoperable networks, as complex integrated systems, will face transients whenever internal or external "interference" occur, e.g. update in one of its nodes.

Within the second set of issues, i.e. conformance testing and checking for complex systems interoperability, theories are needed to address how new system nodes may be integrated in networks, or when networks are updated, how updates can be dealt with by the networks, and how the networks should react to become interoperable or keep their interoperability, with the news nodes or updates, through the understanding of the intrinsic knowledge and behaviour of the nodes. Theories for checking for the conformance of data, models, knowledge and behaviours of the systems and applications in dynamic environments must also be addressed.

The third set of issues and challenges deal with the need to develop theories for harmonisation of ontological structures to support the application dynamics and enable adaptability of users' semantic specifications. This will require theories to address mutation of ontologies using stochastic methods to support updates in the representation of concepts and their instances, and that support semantic harmonisation and adaptative mapping in dynamic environments. Finally, theories on knowledge management are needed to address the information and behaviour of the complex system at each node and in the integrated network and to support the dynamics and evolutionary characteristics of the complex system.

Whilst there is a lack of specific theories for EI, our research has identified the principal theories recognised to be of greatest importance for the development of EISB. Description of the complete elaboration that resulted on the synthesis presented in Table 2 is available in Agostinho *et al.* (2011). The intention of the information presented in the table is to address broadly the set of theories suitable for EI, including those that are associated with the identified related research areas and methods.

As a conclusion, the current scientific Foundation of Interoperability has been lacking specific theories. Despite the abundance of theories in fields that are related in one way or another with Interoperability, such as artificial intelligence theories or more mathematical theories like patterns theory, set theory, category theory, first-order logic, graph theory, information theory, etc., there has been little progress in terms of developing Interoperability's own theories, although there is a clear identification of where such theories are required in order to improve EI. Moreover, in recent years, there has also been the acknowledgment of developing economic theories in the context of EI (Li and Yang 2008). The main rationale is twofold: first, current economic theories have difficulty in explaining digital ecosystems; and second, there is a trend to shift the focus of enterprise from a pure profit-based results' orientation to more sustainable and community based activities (see e.g. FInES Research Roadmap by Missikoff *et al.* 2010).

Overall, there is large scope for theory as far EI is concerned, and research effort in this area should be increased in order to have more sustainable development of EI.

6. Interoperability models

According to the Stanford Encyclopedia of Philosophy, models are of central importance in any scientific context. The EISB can be supported by combining different types of models, which can be classified as Reference Models, Architectures, Enterprise

Table 2. Formal methods for the establishment of the EISB.

Neighbouring domain	Formal methods/Systemic approaches	Benefits and contributions for EISB
Mathematics	• Logic • Set Theory • Graph Theory • Category Theory • Calculus and Analysis • Number Theory • Fractal Theory • Petri Nets • Queuing Theory • Stochastic Processes • Bayesian Networks • Markov Chains	Mathematical methods provide a body of definitions, axioms, theorems and examples that are essential for the development of the EISB. They provide mathematical techniques and embrace mathematical methods that have been typically used, or should be used, in the EI domain. These methods are essential to the applied research and engineering of EI systems and applications, which are used to assist in the research and development of solutions for EI problems.
Computer Science	• Event systems • Multi-Agent Systems • Services Science • Web Science • Simulation • Concept-Knowledge C-K Design Theory • Information Systems • Software Science • Programming • Information Theory • Database Theory • Data Encryption • Data structures • Meta-Modelling • Algorithms and Data structures • Artificial Intelligence • Pattern Recognition • Simulation • Computational complexity theory • Distributed and parallel computation • Machine learning • Computational biology • Computational geometry • Cryptography • Quantum computation • Knowledge Representation • Computational number theory and algebra • Program semantics • Program verification • Systems Security • Automata theory • Randomness	Enterprise systems are implemented by computer systems and applications. Thus, computer science provides the fundamental source of theories and methods valuable for the development of the EISB. From the large list of established computer science methods, these identified have higher relevance for EI, considering the specifications and functionalities applied in the EI framework levels. From Computer Science, EISB can obtain the theoretical foundations on information and computation. Also, it obtains the methods for the implementations of EI computational systems and applications. This includes, for example, algorithmic processes that create, describe and transform information and formulate suitable abstractions to model interoperable enterprise complex systems.

(*continued*)

Table 2. (*Continued*).

Neighbouring domain	Formal methods/Systemic approaches	Benefits and contributions for EISB
Interdisciplinary	• Cybernetics • Complexity Theory • Systems of Systems Theory • Complex Adaptive Systems • Catastrophe Theory • Systems Thinking • Chaos Theory • Edge of Chaos • Cognitive Science • Network Theory • Axiomatic Design Theory	By its nature, EI has been developed through applied research and engineering addressing two or more disciplines, taking approaches from multiple traditional theories and methods, combining and modifying them so that they are better suited to address the EI problem at hand. By addressing to interdisciplinary methods, EISB is seeking to synthesise broad perspectives, knowledge, skills, interconnections, and epistemology in an integrated complementary setting. As such, it may be founded in order to facilitate the study of subjects which have some coherence, but which cannot be adequately understood from a single disciplinary perspective (for example, the complexity of the networked enterprise systems).
Economics and Management	• Coordination Theory • Decision Theory • Game Theory • Economics of Innovation • Behavioural Economics • Coordination Theory • Game Theory • Innovation Economics • New institutional economics • Risk analysis • Process modelling • Balance Sheets • Value Stream Mapping	EI should not be addressed exclusively from a technical point of view. The economic and business aspects related with EI are of relevance for the organisations and also for the environment in which they are integrated. Typical examples are theories and methods concerning the impact of interoperability in the business of the enterprises, and the creation of value proposition.
Communication Sciences	• Universal Theory • Constructivist Theory • Action Assembly Theory • Elaboration Likelihood Model • Inoculation theory • Coordinated Management of Meaning • Uncertainty Reduction Theory • Social Penetration Theory • Predicted Outcome Value Theory • Relational Systems Theory • Relational Dialectics • Structuration Theory • Unobtrusive and Concertive Control Theory	These theories provide insights into the aspects of Enterprise Interoperability concerning universal communication, message production and processing, and the interaction between systems and individuals. They address at the individual and organisational level, aspects such as culture, small and large groups, social worlds and networks.

(*continued*)

Table 2. (*Continued*).

Neighbouring domain	Formal methods/Systemic approaches	Benefits and contributions for EISB
	• Functional Theory • Symbolic Convergence Theory • Social Cognitive Theory • Communication Codes Theory • Face-saving Theory • Coordinated Management of Meaning • Symbolic Interactionism	
Sociology	• Intercultural communication theory • Critical Theory • Phronetic social science • Rational choice theory • Social Network Analytics	EI is an enabler for networked enterprise systems, and its integration in the society in general. Thus, EI should account for the origin, growth, structure and activities of society by the operation of physical, vital and physical causes when making interoperable enterprise systems and applications. These methods address the impact of EI in the society, groups, its relationship and interactions.
Psychology and Philosophical Sciences	• Activity Theory • Applied Performance Psychology and physiology • Actor-Network Theory • Phenomenology • Epistemology	These methods provide the basis for the reasoning and philosophical development of EISB.
Healthcare Sciences	• Medicine • Pharmacology	Healthcare sciences address strong problems of interoperability. Their theories and methods can be used as examples for the studies of application in EI. Typical examples are found within the theories related with compatibility of medications, blood and organs, e.g. blood transfusion, transplantation of organs, efficacy of medications.

Models and Meta-models. To achieve seamless EI, the practice has been to adapt well-established computer science and engineering models, along with the technical standards, that have been adopted, sometimes supported by the creation of ontologies for semantic mapping and mediation. Most of these models have been developed within research and development projects together with standardisation bodies.

6.1. Reference models

A reference model is an abstraction of objects that is crucial for EI for the development of norms and for the deployment of models that instantiate the considered abstractions as a reference. For example, in EISB, several reference models can be found in the ISO 10303 standards, with the application protocols in use as reference models in different manufacturing and engineering areas. This includes product data and engineering product and process models. Several technical committees have been developing reference models under the umbrella of standardisation organisations, as in the cases of ISO TC 184 SC4 and SC5, the latter specifically addressing general reference models for interoperability, integration and architectures for enterprise systems and automation applications (TC 184/SC4 (2011), TC 184/SC5 (2011), AP 236 (2011)). Common languages for reference model development include XML, EXPRESS, ebXML, XML Schema Definition, UBL and RDF.

6.2. Architectures

Architectures are formal descriptions and representations of systems, organised in a way that supports reasoning about the structure of the system components, the externally visible properties of those components and the relationships (e.g. the behaviour) amongst them that will work together to implement the overall system. Model Driven Architecture (MDA) and Service Oriented Architecture (SOA) are two examples of those architectures that have been identified as a reference to the development of EI (see MDA 2003, Mellor and Balcer 2002 and SOA 2008). Model Driven Interoperability (MDI) is considered today as a major methodology for EI, adopting the MDA layers of CIM, PIM and PSM for the development of model-morphims that implement the transformations between different enterprise models in the deployment of interoperable enterprise systems (Panetto 2007). Moreover, SOA has been identified as the reference architecture for the use of web services in seamless exchange of information between enterprise systems and applications (WS-I 2008).

6.3. Meta-models

Meta-models are abstractions representing the properties of a model itself that are used to represent concepts (processes, data, etc.), within a certain domain. Meta-models are used as a schema for semantic data, as a language that supports a particular method or process, or as a language to express additional semantics to existing information. The Unified Modelling Language (UML) is an example of a commonly used language of modelling (Mellor and Balcer 2002). For enterprise modelling at the business level, the UEML (Unified Enterprise Modelling Language) has been developed to provide a suitable language for exchanging enterprise models between systems and applications (Panetto 2007). In the EISB domain, meta-models enable metadata modelling, model transformation and ontology development for the analysis and construction of specific models to be used in the domains of application. For example, the OMG has proposed the QVT standard for Queries/Views/Transformations (OMG 2008). QVT is based on the Meta-Object Facility (MOF). Examples of implementations of Model Transformation Languages (MTLs) using this standard are VIATRA (Eclipse 2011, Tefkat 2011) and Eclipse (McAffer *et al.* 2010).

Ontologies complement the role of meta-models to semantically support the description and analyse the relationships between concepts. OWL and RDF are two main modelling languages in use for EI ontology development (Sirin *et al.* 2007). Nevertheless, interoperability issues are identified when using instances of meta-models from different sources. Semantic annotation, ontology harmonisation and merging are examples of important methods for the EISB (Sarraipa *et al*. 2010).

6.4. Enterprise models

An enterprise model is a representation of the structure, activities, processes, information, resources, people, behaviour, goals and constraints of enterprises. Enterprise models provide an abstraction of the whole or part of an organisation modelling process, data, resources and ontologies, based on the knowledge about the enterprise (Vernadat 1997). The main modelling approaches identified for EISB are Active Knowledge Modelling (AKM) (Lillehagen and Krogstie 2008), Design & Engineering Methodology for Organizations (DEMO) (Dietz 1999), Dynamic Enterprise Modelling (DEM) (Koning 2008), Extended Enterprise Modeling Language and Multi-Perspective Enterprise Modelling (MEMO) (Ulrich 2002). Regarding process modelling, the most important identified are, amongst others, CIMOSA (CIMOSA 2011), PERA (Williams 1994) or IDEF3 (Kim 2001).

Enterprise models also consider the conceptual enterprise architecture for implementation in the organisations. Main examples to support the EISB are ARchitecture of Integrated Information Systems (ARIS), US Department of Defense Architecture Framework (DoDAF), OBASHI Business & IT methodology and framework (OBASHI), Reference Model of Open Distributed Processing (RM-ODP), Open Group Architecture Framework (TOGAF) and IBM's Zachman Framework (for further review see Jardim-Goncalves *et al*. 2006b, Grilo and Jardim-Goncalves 2010 and Jardim-Goncalves and Grilo 2010).

In the current stage of development of EISB, there is still a great deal of latitude for further development of interoperability models. The FInES Research Roadmap (Missikoff *et al*. 2010) highlights that there are forthcoming model platform challenges within the context of federated open applications for services devoted to business operations and enterprise resources management; awareness and intelligence capacity of an enterprise to look at its own operations, understanding how it is doing, identifying innovation needs and opportunities; business specification methods and tools, simulation, what-if methods to support business experts' work through engineering methods, business process modelling tools, enterprise ontologies; methods and tools aimed at transforming higher level abstract specifications into technical specifications; meta-knowledge infrastructures; interoperability and cooperation infrastructures deploying seamless cooperation between people, things and computers and digital elements, which will largely reflect what exists in the real (analogical) world, such as creatures and entities, both simple and complex, animated and inanimate, tangible and intangible.

These challenges will require that new technological and business models, algorithms and tools be developed, identified in the FInES Research Roadmap as Emergent Technologies (mesh-sensor networks, CaaS, convergent networks, identify-aware networks, ubiquitous communication, tracking and traceability and real-world web); Roadmapping Enterprise Applications Systems (visualisation and interaction, intelligent proactive behaviour, automated service discovery, tera-architectures, IaaS/PaaS, software as a service, IoS, FOT, ISU, intelligent digital elements and knowledge representation); and Organisational Concepts and Supporting Technologies (social mining, GRC, participative business engineering, business modelling and simulation, globalised micro-business, business ecosystem modelling, socialisation and web 2.0 impact in organisations, and business rules).

7. Discussion

The challenge of developing an EISF that has recently emerged has led some of the academic agents to seek to systematise the IBoK. Still in the embryonic stages, these efforts have been looking to organise and aggregate information from very fragmented and disparate sources, and with different granularities of detail, distinct epistemology origins, and disparate academic fields.

The efforts of creating an EISF within the context of the IBoK require a more structured approach from academics towards organising existing research work. This paper has outlined the current state-of-the-art and future challenges in terms of Interoperability Frameworks, Interoperability Theories and Interoperability Models. It is possible to conclude that Interoperability Frameworks have now stabilised to some extent. The weakest part of the IBoK is clearly Interoperability Theories, since researchers have been "borrowing" theories from other scientific fields but have rarely, if at all, developed Interoperability-specific theories. There is a clear challenge in this area. The IBoK is also very populated with Interoperability Models. Most research and engineering work has surfaced no shortage of Interoperability Models. However, it is argued that in light of the recent FInES Research Roadmap, more sophisticated models are needed, covering technology, business and people, along with a need to deal with new methods for models' meta-morphims.

Taking into consideration the fundamentals in establishing a science, ESBF evolution can be described in comparison with the human development as: Infancy, Childhood, Adolescence, Young Adulthood and Maturity on the way toward structuring the EISB, there will be an evolution through three different, but logically connected, "waves" of activities (Lampathaki *et al.* 2011a,b):

- EISB Wave 1 – Basic Elements, corresponding to the "Infancy" and "Childhood" stages. It aims at providing the ability to identify and describe problems and solutions in the field of EI and establishing the research community, towards a sound convergence on the concepts in use.
- EISB Wave 2 – Hypothesis and Experimentation, which corresponds to the "Adolescence" and "Young Adulthood" stages. It builds upon the initial EISB foundations defined in Wave 1, i.e. the identification and description of EI scientific problems and EI foundation principles, with a view to stabilising research products, methods and tools in a reusable, extendable and sustainable manner as well to constructing application scenarios that will prepare for the popularisation of EI in the third wave. Impact assessment and simulation, together with the development of a training curriculum, is a requirement for the accomplishment of this stage. Furthermore, targeting a broader community, this wave focuses on identifying hypothesis and nurtures discussions and experiments in order to reach consensus on the challenges or to improve the basic elements defined in the first Wave.
- EISB Wave 3 – Empowerment, matching the "Maturity" stage. It aims at empowering the scientific foundations for EI through proper liaisons with the scientific, research and stakeholders communities, highlighting the quality of the industrial solutions and the substantiation of value.

The condition for systematising existing research is necessary for deriving the state-of-the-art of the EI research domain, but it is not sufficient for laying the scientific foundations, and a proper methodology should be put in practice, as the one proposed based on the three waves towards the EISB. Thus, the EISB has been initiated during the ENSEMBLE project (2011) – Phase 1 – that sorts out the fundamental aspects of the Interoperability scientific foundations towards the formation of inclusive and solid definitions of the main issues of the domain, while dealing with the identification and description of open scientific problems. Returning to the research question and guiding statements proposed in this paper, it can be argued that triggering the EISF structuring around the frameworks, theories and models levels is a useful and valid starting point to make a gap analysis of where current academic scientific state-of-the-art is and where it needs to go. Also, as mentioned above, there are different degrees of maturity, and the needs of research vary accordingly. Hence, the EISB first wave should include the following actions:

- **Foundational principles**: investigation of basic ideas and concepts, initial formal methods to describe problems and solutions, patterns identification and critical research questions. Formal approaches in this area include mainly EI-specific theories development along with a higher degree of convergence on current EI models, grounded on current mature EI frameworks.
- **Concept formulation**: circulation of solution ideas, development of a research community, convergence on a compatible set of ideas, solutions on specific sub-problems and refinement of fundamental problems structure. This step will have to work extensively on the definition of solution ideas for various interoperability issues, as they are defined in the previous step, while also developing and stimulating the research community.

To contribute for a long-term stable interoperable enterprise operating environment, a possible EI strategy might include the integration of traceability functionalities in information systems as a way to support such sustainability (Agostinho *et al.* 2010). Thus, either data or semantic and structural mappings between enterprises in the complex network should be modelled as tuples and stored in a knowledge base for communication support with reasoning capabilities, thereby allowing researchers to trace, monitor, and support the maintenance of stability of a system's interoperable state. Further research is expected to be developed along this path.

The formalisation of EI problems and abstraction of their description according to the frameworks, theories and models will empower the ability of researchers to similarly identify, describe and resolve EI-related applied engineering problems, with the identification, analysis and abstraction of the solution space and its included methods.

At the same time, such a formalisation will assemble the research community that will undertake each of the issues identified above and will disseminate results to a wider audience, thus attracting the interest of the major stakeholders in the domain and other experts and stakeholders belonging to neighbouring domains.

8. Conclusions

The analysis about Interoperability Frameworks, Interoperability Theories and Interoperability Models offers interesting insights regarding the current state of play on the systematisation of IBoK and also provides relevant perspectives about directions for future research and development in the field. Concerning Interoperability Frameworks, it is undisputable that there is maturity around in the current body of knowledge. Several authors have developed Enterprise and Government Interoperability specific frameworks, with more or less layers and variables, but overall most frameworks are structured similarly, considering the technological, business and organisational perspectives. Regarding future work on this area, it is recommended that researchers abstain from creating more diversity in terms of approaches since the problem space is overall confined and rather focus on the opportunity to further refine the details along with providing more clear detailed analysis about the interrelationships between the various variables on the different layers and perspectives and aim at delivering a systematised cause-effect framework.

Interoperability Theories are the weakest elements of the IBoK. Indeed, Interoperability researchers have fall short from offering solid field specific theories, as most theory related work borrow theories from other scientific domains. Our analyses have presented many formal methods, systemic approaches from disparate adjacent scientific domains that may provide useful contribution to the EISB and indeed may be useful starting points to the Interoperability research community develop their own theories. Clearly, this is an area where the Interoperability research community must deploy more effort as theories are fundamental to explain Interoperability reality and design interoperability model solutions.

Finally, IBoK is well populated with Interoperability related models. Our research has stressed that EISB has been supported by Reference Models, Architectures, Enterprise Models and Meta-models, mainly adapting from models from adjacent scientific domains. The emergence of these models derives mainly from the engineering need to provide technological solutions to the interoperability problem

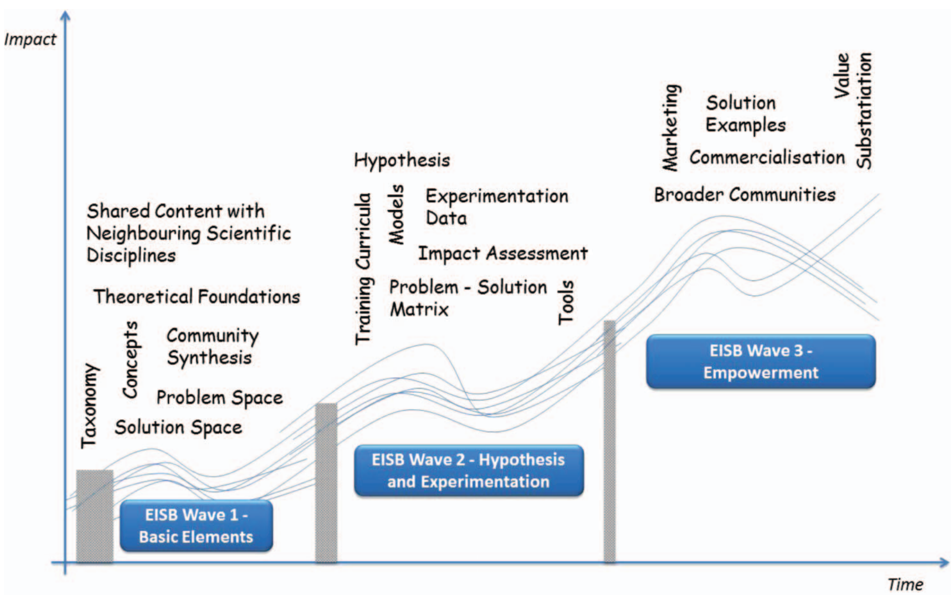

Figure 2. The three "waves" towards Enterprise Interoperability Science.

space. It can be seen as a bottom-up response to the interoperability challenges and the requirement of connectivity in real contexts. However, the analysis has also suggested that there is still open room for large developments regarding qinteroperability models, and current efforts on the FInES research community cluster has been mainly focusing their efforts addressing the various identified needs in terms of improved models.

Relating the paths to the waves for Enterprise Interoperability Science (Figure 2), it can be concluded that in the first Wave, the Foundational principles and Concept formulation shall direct relevant effort towards Interoperability theory principles and conceptualisation, mainly providing solid formalisation mechanisms to explain interoperability, which will provide the backbone for the second most relevant effort that shall be in further developing and converging Interoperability models.

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