Towards a Sustainable Interoperability in Networked Enterprise Information Systems: Trends of Knowledge and Model-Driven Technology

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Abstract

In a turbulent world, global competition and the uncertainty of markets have led organizations and technology to evolve exponentially, surpassing the most imaginary scenarios predicted at the beginning of the digital manufacturing era, in the 1980's. Business paradigms have changed from a standalone vision into complex and collaborative ecosystems where enterprises break down organizational barriers to improve synergies with others and become more competitive. In this context, paired with networking and enterprise integration, enterprise information systems (EIS) interoperability gained utmost importance, ensuring an increasing productivity and efficiency thanks to a promise of more automated information exchange in networked enterprises scenarios. However, EIS are also becoming more dynamic. Interfaces that are valid today are outdated tomorrow, thus static interoperability enablers and communication software services are no longer the solution for the future. This paper is focused on the challenge of sustaining networked EIS interoperability, and takes up input from solid research initiatives in the areas of knowledge management and model driven development, to propose and discuss several research strategies and technological trends towards next EIS generation.

Keywords: Sustainable Interoperability, Model-Driven Interoperability, Knowledge Management Semantic Matching, Ontologies, Model-Driven Service Engineering, Enterprise Information Systems.

1. Introduction

Traditional ways of doing business do not provide the expected leverage any more. Companies do not survive and prosper solely through their own individual efforts and isolated knowledge; and speeding up the rate of industrial transformation to high added value products, processes and services has been the key message of policy makers and industrial roadmapping initiatives for the last decade [1]. Enterprises have to become agile, sensitive to changes in market forces, and capable of responding with incremental modifications in business and services provided (adaptation) as well as anticipating radical changes by responding with new and breakthrough business models (innovation) [2]. This involves a mix of both cooperative and competitive elements, and the use of networking concepts such as the virtual enterprise or the enterprise ecosystem, is becoming more common [3,4].

Envisaging to marshal more resources than they currently possess, enterprises can use extended and virtual enterprise concepts to enable collaborations both inside and outside their boundaries [5], [6]. These collaborative organizational forms allow them to pursue goals such as co-designing, co-manufacturing, co-marketing, etc.[7]. In fact, companies should focus on their core competencies while improving relationships with customers, streamlining supply chains, and creating valued networks between buyers, vendors and suppliers to gather all the skills in the network instead of in the single enterprise. Also, with the *Future Internet* initiative and the novel technology associated to it, it is highly likely that new opportunities for creativity and innovation rise, and new forms of participation that span the world are enabled [8]. However, even though this demonstrates an enormous potential for economic improvement, enterprise information systems (EIS) designed for collaboration are still far from an industry-wide adoption, and issues as trust and interoperability are impairing a wider impact.

Hence, ensuing the original work on interoperability [9–13], followed by the advent of XML technology and motivated by the reasons presented before, enterprise and EIS interoperability is nowadays a strong focus of research [14–16]. Defined as the capacity that two or more enterprises, and their systems, have of cooperating over a period of time towards a common objective, Enterprise Interoperability (EI) is being addressed across several areas, such as, data, processes, objects, software, culture, knowledge, services, social networks, cloud, and even ecosystems interoperability [16,17]. EI complements the disciplines of enterprise architecture, and systems engineering, providing the tools necessary to incorporate new and legacy systems to both inter and intra-enterprise needs, while facilitating cooperation in large value added networks [18]. System methodologies for EI allow organizations to keep its technical and operational environment, while improving its methods of work and the effectiveness of the installed technology.

Nevertheless, traditional EI solutions are often inflexible and difficult to adapt to meet the requirements of dynamic and evolutive networks that characterise the novel networked environments. By and large interoperability is a broad and complex subject, and the development of generic solutions capable of mediating different types of EIS is difficult. Thus most development is either relying on international accepted standards for data exchange, e.g. STEP, EDI/EDIFACT, ebXML, UBL [19–22], or is implemented on a peer-to-peer basis. However, as EIS evolve and become more complex, the need for interoperable operation, automated data interchange and coordinated behaviour of large-scale infrastructures becomes highly critical [14]. Architectures, modelling frameworks and tools, as well as methodological approaches have been continuously evolving to cope with emerging collaborative organizations in industry and society, but in spite of research efforts up-to date, the proper scientific foundations for EI remain scarce [16], and fast and efficient re-adaptation of solutions is still a need.

1.1. The Grand Challenge: *Sustainable Interoperability*

The previously explained gap has been preventing the generalization and full reuse of the methods and tools that have been developed so far, and is threatening EI as a long-term domain for research. Indeed, reaching an interoperable state has been target of research teams for some time with many results already available. In the future, the real grand challenge resides in enabling this reuse to streamline EIS evolution and adaptation while **sustaining the interoperability of networked systems**, or in short, **sustainable interoperability (SI)**, the interoperability that convenes the needs of the present without compromising the ability of future changes, meeting new system requirements, and performing adequate adaptation and suitable management of the transitory elements.

In the scope of this research, "sustainability" concerns the quality and efficiency of EIS interoperability, which delineates the capacity to endure and improve cooperation within a networked environment. In a business-to-business perspective, SI categorises enterprise information systems and networks that are considering interoperability along the adaptive organisation's lifecycle, enabling enterprises to evolve at their own pace without harnessing the overall performance of the networks they are inserted in, causing downtime and service outages. This grand challenge crosses multiple industrial domains. Indeed, in a 2010 study by Gartner, information systems configuration management is identified as a key process for any IT endeavour [23]. The study foresees that in a near future, a large percentage of mission critical service outages would be caused by change/configuration/release, integration and hand-off issues.

As new technologies are adopted, new dynamics will be introduced opening doors to external service providers, increasing the relevance of interoperability. This complexity requires more rigour in the configuration management process. Not understanding the impact of a single change to a system or software on the broader service or application may have a negative effect (e.g., outage transient) in the network. As illustrated in the scenario of Figure 1, even with the EI research available, a network disturbance can cause relatively large transient intervals where the measured interoperability can fall bellow a certain threshold, the network sustainability line, below which the network ceases to be viable (see the study in [24] for interoperability costs). Financial services, telecommunications, manufacturing and energy lead the list of industries with a high rate of revenue loss during IT downtime [25]. In the scenario, actions marked as A, B, 1, or 2, represent the EIS adaptation/evolution that causes network disturbance. The grand challenge proposed in this paper targets the development of research that helps to (semi) automatically detect, reduce and avoid transient periods, keeping the network sustainable.

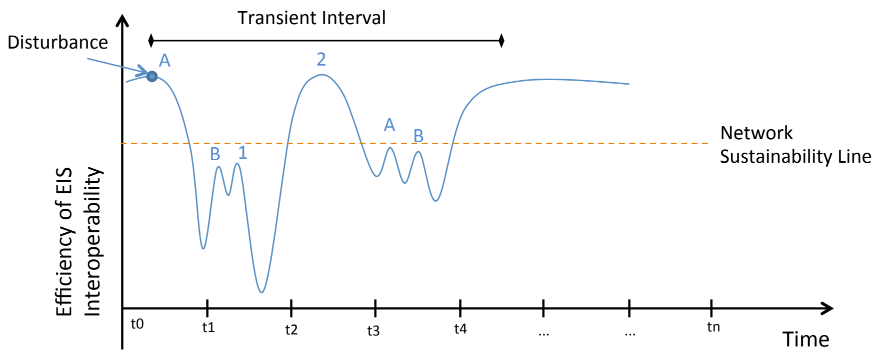

Figure 1: Grand Challenge: A Scenario for Sustainable Interoperability of Networked EIS

2. Concerns on EIS Engineering and Interoperability: A Technology Outlook

Several international research initiatives have shown a considerable progress in EI over the last years [16]. Developments on enterprise architectures for modelling and engineering, model-driven development, or the endorsement of several standards for EI are just some examples that will be further detailed along this section. Such advancements provide the baseline technology for roadmapping future research targeting the SI grand challenge, and have also unveiled new challenges and trends concerning a sustainable interoperability among networked EIS. With the introduction of the Human and social activity in the interoperability investigations, dynamicity, uncertainty and complexity increase exponentially [26,27]. Indeed, following Holland's perspective, adaptation also builds complexity [28]. It needs to be managed at the risk of loosing efficiency.

A common way for changes to occur is by including or excluding particular EIS function, adding or eliminating service connections among enterprises, or even changes in data representation or structuring. However, such change at the EIS level embodies an immediate evolution and presents a disturbance to the enterprise network, more specifically to its direct business partners. They will most likely need to adapt in face of that evolution, thereby changing the environment for the original agent. Considering the systems engineering adaptive loop has two different entry points, triggered by a disturbance at the EIS level, or at the network level when the change occurs in the frame of its business partners, reflexivity might arise (see Figure 2), risking positive self-fed loops into the networked system, and possibly, non-linearity [29,30]. As a consequence, if not properly monitored and controlled, systems models and semantics can change chaotically, resulting in long "low-interoperable" periods and service outage. The transient interval depicted in the scenario of the previously presented Figure 1 represents that phenomenon. In the example, starting with an evolution at the enterprise level, only after 1,5 adaptation cycles (stages A and B are instantiated twice) does the network become sustainable again. This exercise demonstrates that EIS engineering has been a target of complex behaviour [31,32].

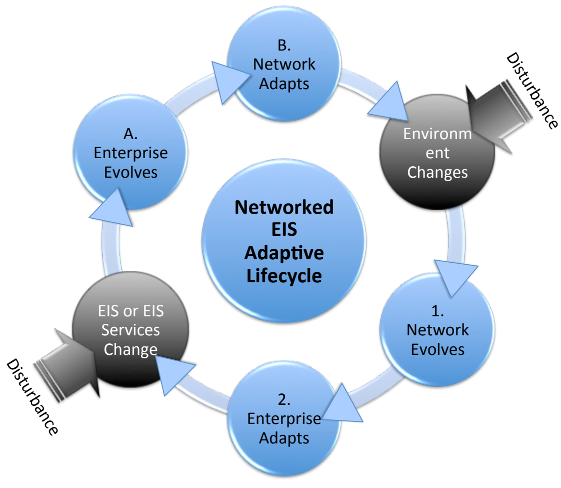

Figure 2: Networked EIS Adaptive Lifecycle

2.1. Enterprise Architectures (EA) for Modelling and Engineering

During the 80's, significant research was carried out in Europe and USA to develop EA frameworks. Among them the most known are: CIMOSA [33] that coined the term enterprise architecture; the Purdue Enterprise-Reference Architecture (PERA) [34]; the GIM architecture [35]; and ARIS [36]. These type 2 architectures ([14]) are mainly elaborated along the system life cycle, defining the components that make up the overall system and providing a blueprint from which the integrated enterprise system, including the EIS, can be developed. Zachman [37], another well-known example, defines a robust modelling framework that differentiates modelling according to different stakeholders, using different levels of abstraction and deliverables for each. All these architectures are heterogeneous and complementary rather than contradictory. CIMOSA and ARIS present strong similarity and are both process oriented approaches aiming at integrating functions by modelling and monitoring the action flow. GIM is oriented towards decision processes. Hence, the IFAC/IFIP Task Force on architecture for enterprise integration has studied them to propose harmonization under a Generalized Enterprise-Reference Architecture and Methodology (GERAM) [38]. A relevant state of the art of these EA is proposed in [14] and [39].

EA has actually influenced not only enterprises, but also governments, with several e-Government Interoperability Frameworks having been introduced at national and international levels, and recommendations having been made for the adaptation of enterprise architectures in the public sector [15,40].

Enterprise integration is an essential component of enterprise engineering, concerning the usage of specific methods, models and tools, to design and to continually maintain an enterprise in an integrated state so that it can fulfil domain objectives [18]. However, from a technical point of view, traditional legacy information systems are rigid with predefined functionality created at design time as an interpretation of the then valid rules and regulations. The rigidity of such legacy systems makes them less sustainable to face the changes in the enterprise organisation in order to be adapted to the rapid changes of its environment [32]. This lack of flexibility might be filled by the use of enterprise models from several points of view: information, but also process and decisions. This is why dynamicity in enterprise modelling and enterprise architecture is an appropriate tool to support the continuous evolutions of system's specifications, i.e. the first steps in the process of change and configuration management of EIS. Answering the need to improve the quality and access to information, techniques like model-based systems engineering (MBSE - mbse.gfse.de) have been introduced with the intention to model complex dynamic relationships/dependencies, and facilitate and reduce the complexity of EIS engineering activities such as design and redesign [41].

Modelling, architecture, and engineering techniques are therefore the pillars supporting the achievement of EI and also a sustainable interoperability. Generally speaking, an EA should be organised in a way that supports reasoning about the structure, properties and dynamic behaviour of the system. Complementing the many EA developed around the world to support enterprise engineering; some degree of flexibility is required, evolving these architectures to meet ever- changing business demands. In many scenarios not covered by the above frameworks, enterprises encounter the challenging task of enabling coexistence between new and existing systems. They need to split functionalities, and besides integration and interoperability, they also need SI.

2.2. Model-Driven Development in EIS

In the past, there was an unbridgeable abyss between the business requirements and EIS implementers themselves, but today Model Driven Architectures (MDA) and Model Driven Interoperability (MDI) have introduced the concept of integrated design from the business level down-to the implementation targeting to mitigate that gap [42,43].

More recently, and supporting the servitization concept in manufacturing [44], the Model Driven Service Engineering Architecture (MDSEA) took up the same principles to model and guide the transformation from the business requirements into detailed specifications of systems' components at Human, Physical and IT dimensions of an enterprise service [45]. Previous research works have been done in the domain of service modelling, such as SoaML, developed by OMG [46]. It provides a metamodel and a UML profile for the specification and design of services within a service-oriented architecture, and covers extensions to UML2.1 to support the: identification of services; specification of services; definition of service consumers and providers; description of policies for using and providing services; definition of service and service usage requirements; and linkage to related OMG metamodels, such as the BMM course-of-action, BPDM Process, UPDM Operational Capability, and/or UML Use Case model elements they realise, support or fulfill. However, SoaML is focused on modelling and design of services for a computer service-oriented architecture while MDSEA is focused on manufacturing services. Hence, SoaML is a modelling language applied to IT service while MDSEA has a more generic objective including different modelling languages and putting them in coherence from a global to a detailed view (Human, Physical, IT). This is why SoaML could have a relevant position at the technology independent level (TIM) of the MDSEA for the IT perspective.

Nonetheless, even if presenting an important contribution to complement the work in EA, today, MDA/MDI is still an open issue, as incomplete applications have been developed capable of realising the proposed vertical integration and interoperability by design, particularly from the business specification to the platform independent architectural models. Apart from MDSEA (as in the work of Bazoun et al. [47]) and some isolated initiatives [48], solutions are scarce for this purpose, and new concepts, methods and tools are still necessary and desired. In addition, model transformations are traditionally static processes, and it can be argued if semantics are being given a proper attention and formalization along the model-driven strategies [49]. Semantics are recognised by the research community as an important area for models alignment and one of the levels of interoperability to consider within an enterprise [50].

2.3. Relevant Standards for EI

Standards are of key importance to enable enterprise interoperability. They are great enablers to the agreement of terminology, allowing communication and cooperation between EIS, processes, organization units and humans [51]. Nonetheless, being supported by a large number of standardization groups, even they display a clear replication of efforts [52].

Data standards are fundamental to exchange data effectively among stakeholders regardless of the applications and software used by each one of them. They provide a means for enabling and facilitating compatibility between systems and sub-systems, supporting interoperability, as well as enterprise collaboration. Specific data standards are available for industrial use, namely the ISO's standard for the exchange of product data (STEP) [19]. STEP has the objective to provide means of describing computer-interpretable data throughout the life cycle of a product, independently of any particular system. The standard is many times embedded within computer software associated with particular engineering applications, thus transparent to an end user. However, with technology unfamiliar to most application developers, its acceptance has been facing difficulties when applied to sectors primarily composed by SMEs. STEP requires a wider tool support, and SMEs don't have the resources that larger companies do to hire or educate specialised personnel [53,54]. Frequently they prefer the usage of open technologies from the web community standards (e.g. W3C - www.w3c.org) or from open consortia as the OASIS (www.oasis-open.org), Open Applications Group (OAGi - www.oagi.org/), which are more intuitive and tool supported. EDI/EDIFACT, ebXML, UBL are amongst the most prominent. Additional advantages may also result from the use of completely open standards, e.g. an easier integration of multiple data formats, applicability to a wider range of domains and a more efficient contribution to design by specialist departments. However none can claim a truly universal adoption in the domain for which it has been developed.

Among the huge panoply of standards, not only the product data standards can be of relevance for EI. Also plain data encoding standards as the XML language, communication protocols as TCP/IP, but most importantly modelling standards and frameworks such as EA or OMG's MDA can provide a valuable contribution by regulating the way developers should use available technologies to model systems, software, and interoperability solutions addressing all levels of the enterprise. Concerning EI, one of the most important standards available is ISO 11354 [55] that proposes a framework for enterprise interoperability. Nevertheless others closely related to EI exist, e.g. GERAM, already discussed, ISO/IEC 11179 [56] ruling the specification and standardization of data elements, among others, etc. A relevant state of the art of these EI related standards is proposed in the work of Zelm and Kosanke [57] as well as in the work of Lampathaki et al., on [58].

2.4. Envisaged Research on Next Generation EIS

This paper identifies and characterises the emerging challenges of EIS rising from the evolution of enterprises and virtual enterprises, and analyses how model-driven and knowledge-based approaches can be applied together to improve the design and alignment of next generation EIS in the scope of sustainable interoperability. Studying and discussing the technology advances and concerns on EI engineering and interoperability (chapter 2), the authors analyse past and future research policies on next generation EIS (chapter 3), introducing **sustainable interoperability** as a new grand challenge in EI research that must deal with issues such as design and redesign of EIS, but also of dynamic interoperability enablers, while providing ubiquitous, plug-and-play integration. Stakeholders should be able to implement the several updates required in their businesses, independently of the technology they use, and without prejudice to the network "harmony" and the subsequent reflexive effect. Self-explanatory models together with enterprise context awareness or physical and networked sensing capabilities, now present new opportunities for a SI implementation, accommodating dynamicity, while addressing novel research trends such as the ones presented in chapter 4.

Today, system's design and network interoperation is seen as an abstract "black box", but concerning evaluation, and following the vision of Yahia et al. [59], interoperability needs a more detailed and accurate "white box" analysis to see what is happening inside collaboration networks and enterprise systems in terms of relationships. Figure 3 captures the essence of the sustainability of networked systems interoperability addressed in this paper. On the left, it is possible to see a generic systems engineering approach [60], where the authors envisage that modelling needs to contribute and support all stages, from the requirements identification to implementation, delivering robust enterprise services and information systems. On the right part, following ISO 11354 EI framework [55], one can verify that the enterprise (and the EIS) is composed by many complementary levels and interoperability is threatened by different barriers. Semantics across interoperability levels support unification and a common understanding between stakeholders and system engineers.

Enriched with domain knowledge and semantics, the authors believe that pervasive information models and enterprise architectures can automatise the alignment activities (e.g. among data structures at the services and applications level) and development of dynamic interoperability enablers. Hence, especially targeting the issues behind the conceptual barrier, this approach provides a robust framework to support the iterative adaptive loop of EIS (re)engineering, embracing new requirements whenever needed until the system decommission, without harnessing the overall network interoperability.

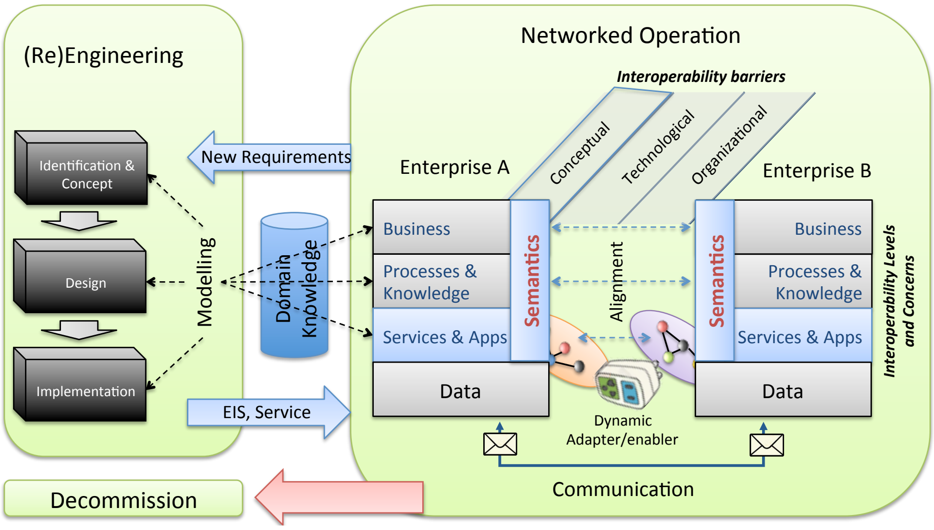

Figure 3: Sustainable Interoperability Levels, Barriers, and Engineering Dynamics

3. Past and Future Research Strategy for Next Generation EIS

Changes occur at a speed that cannot be compared to earlier changes in systems, markets and society. Short-term planning and adaptation is essential, but understanding the myriad of new possibilities and shifts able to impact EIS will also be an important asset for the future enterprise. In fact, as analysed by Santucci et al. [61], our digital society is redefining the *"enterprise"* in a context where *"the network is the business"*, and research needs to provide the tools to aid systems' networking potential. The next subsections provide a global perspective on the past and future strategy for next generation EIS. The support at European level is well acknowledged with many researchers working in the domain, but also in Asia and the USA, researchers and institutions demonstrate significant advancements. In many cases, model driven and knowledge-based technology is being promoted to develop EIS, however they are rarely applied together and there is little concern on the enterprise network sustainability, currently addressing interoperability only at the network design time. Hence, the SI grand challenge represents a gap to be addressed in the years to come, not only at technology level but also at strategic level.

Major activity lines promoted by the European Commission (EC) are analysed below framing past and future research perspectives within networked EIS interoperability. Together with complementary research in America and Asia, they are the *"breeding environments"* towards novel knowledge-based approaches that could improve a future model-driven sustainable interoperability.

3.1. Enterprise Interoperability Body of Knowledge – *the means to an end*

The definition of a solid Enterprise Interoperability Body of Knowledge (EIBoK) is the means to an end, i.e. without proper scientific foundations, EIS will continue to be designed without early addressing major interoperability concerns and taking little advantage of the methods and tools that have been developed so far [62,63].

Generalization, systematization, repeatability of processes, and reuse of tools and methods developed so far has been one of the great challenges on EI research. Acknowledging that, the EC DG Information Society and Media initiated a Task Force on Enterprise Interoperability Science Base (EISB) and included it in the 2008 EI Research Roadmap [64], as one of four main grand research challenges. Upon studying the fundamentals in creating a science in the history of science and epistemology, a handful of experts from the ENSEMBLE project consortium were supported by a larger team of researchers and practitioners, creating more than 100 contributions to an initial version of the EIBoK [65]. A theoretical science base structure has been defined and state of the art collected in the multitude of EI sub domains (http://finespedia.epu.ntua.gr/) However, due to the increasingly fuzzy boundaries of each domain, the loosely coupled architectures, and virtual resources of enterprises, it can be agreed that in terms of content, EI exists in an ecosystem of neighbouring domains (including for example complexity, systems and design sciences), and should recognise relationships, boundaries between application fields, shared methodologies, techniques and tools, as well as conflicts in approach [27,66].

The first steps towards EIBoK have been taken [62,65], but today the birth of a new scientific domain still remains a challenge to revolutionise the way enterprises organise themselves, develop and use enterprise information systems. It is fundamental to have *harmonised interoperability standards*, agree on clear definition and principles so that paradigms such as *interoperability by design* [67], the *unified digital enterprise (UDE)* [68], or *Sustainable Interoperability* become closer to the reality.

3.2. The Digital and Sensing Enterprise (DSE) – *hand in hand research*

In the advent of the *internet-of-everything*, enterprises need to reconcile traditional business paradigms, many times not Internet-friendly, with the unaccounted possibilities offered by the cyber worlds, where reconfiguration and reprioritization of industrial processes, information models, and even terminology is seen as a requirement for survivability. Embracing new models for innovative business relations and business models, supporting extended, virtual and agile enterprises in the Future Internet, the combination of FInES and the IoT is extending the "Digital" to the "Sensing" capability [61].

Being highly acknowledged at the EC level, and part of the FInES 2025 Research Roadmap [68], DSE has the goal to harmonise developments rather than delivering something very tangible or a single solution. Envisioned as a smart complex entity capable of sensing and reacting to stimuli, the DSE needs the sustainable interoperability concept, including context awareness capabilities and sensorial technology to build improved dynamic decision support enablers, capable of extracting internal and external information, and transforming it to knowledge that can be used in the benefit of interoperability as well as business operations [69]. The inverse path is also valid. The initial concepts introduced by Agostinho and Jardim-Goncalves [26] for a SI framework are aligned but can be extended to better integrate the "Things" world. The sustainability recovery cycle that supports the adaptive organization lifecycle and reacts to internal and network stimuli can also contemplate sensor-based networks and *Cyber Physical Systems* [70], enlarging the network to the surrounding objects. Harmonization can be seen not only at the level of business but also at physical interaction.

NIST's[1] researcher Ram Sriram is aligned with the EC's DSE concept, defending next generation enterprise networks that utilise a wide variety of resources with significant sensing capabilities [71]. Such networks extend beyond physically linked computers to include *multimodal-information* from biological, cognitive, semantic, and social networks. However, there are trade-offs in resources required, costs and benefits, priorities, risk levels, and the ability of the enterprises to absorb change. The cost of development and implementation based on common standards remain high, creating a significant barrier to the entry of SMEs in these next generation networks. The NIST's Smart Manufacturing Systems Design and Analysis program (www.nist.gov/el/msid/syseng/smsda.cfm) is addressing these issues, pushing R&D in *cyber-physical infrastructures*, *compositional modelling*, *and real-time improvement of dynamic production system*.

3.3. Digital Business Innovation (DBI) – *a contribution to advancing societies*

The surging "App" Economy, manifested within a platform-oriented, mobile-driven and collaboration-rooted era, has already paved new paths for business innovation in the USA. Stimulating break-through innovation for added value products and services is in fact well acknowledged at policy level and embedded in the mind-sets of leading enterprises, successful entrepreneurs, and forward-looking researchers, yet recognised philosophies of doing business 'better' in a sustainable manner are still not integrated in the strategies of many companies, especially in Europe.

In this context, Digital Business Innovation reflects the delivery of viable new (to the world, or just to a market or industry) solutions capitalising on existing EIS and sustainability methods that create value and address specific problems and market needs. It shall provide the scientific, research, innovation and technical foundations so that a transition can be facilitated from "reactive enterprises" to "highly dynamic and proactive enterprises", which effectively capture the value of Digital Economy in the Future Internet, detecting opportunities real-time and generating value at any stage of development.

The trends related to Digital Business Innovation range from [72]: *Internet of Things*, *Cloud Computing*, *Big Data* value chains [73], Enterprise *3D Printing*, *Mobile Money*, and *5G to Gamification* in Enterprises, *Crowdsourcing*, *Contextual Computing* and *Wearable/ultra-portable computing*. Such trends can be firmly associated with EIS and Digital Business Innovation aspects.

3.4. Model-based Enterprise (MBE) – *ubiquitous view on manufacturing systems*

NIST has been supporting the development of the *model-based enterprise*, which has been gaining momentum in the manufacturing domain. MBE merges different descriptive models with

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[1] National Institute of Standards and Technology

computational models to facilitate the manufacturing process implementation [74]. Relating with the INCOSE MBSE initiative [41], it also supports engineering activities in the sense that, having a digital file that incorporates CAD, CAM, quality and lifecycle data allows enterprises, customers and personnel to more fully understand the product, its parts, and their respective responsibilities.

Being a paradigm more directed to the manufacturing product, MBE can effectively contribute to a sustainable interoperability, not so much at the level of the networked software applications, but addressing interoperability between machinery, planning and design systems.

3.5. Emerging EIS – *a paradigm shift in enterprises*

In the USA and the UK, research promoting the use of complexity and network theory as enablers for *emergence* and *co-evolution of business and information system strategies*, have been promoted along the late 2000's by authors such as Yasmine Merali and Bill McElvey [75,76]. They advocate complexity science can contribute to the development of novel computational modelling, ontological and epistemological frameworks for management information systems in the networked world. Complex adaptive systems agents' interactions suggest a chain of causal dynamics, where enterprise effectiveness is a function of information systems alignment and arrangements that enable processes to coevolve via scale-free dynamics. Following that paradigm, Mitleton-Kelly suggests that encouraging co-evolution between the domains and enterprise networks requires an enabling infrastructure, which provides the conditions for *self-organisation* [77], and Alaa & Fitzgerald defend *information systems emergence through agile development practices* [78].

In Asia, Hu et al. [79] investigated the design and development of complex System of Systems (SoS). They presented a model driven approach for *service oriented SoS* architecting, modelling and simulation, providing multi-level models, model transformations and the generation of service artefacts that facilitate the alignment between high-level business requirement and systems.

3.6. Agility and Context Dependency – *cultural support*

Complementary work has been previously proposed towards the *rapid development of SaaS* and Mashup applications [80]. Kim et al. [81] simplified the virtual enterprise collaborative process development, associating an ontology-based collaborative business process model to a technical-level architecture by a model driven approach, and Guo et al. [82] projected a semantics-based model-driven approach to semi-automatically derive domain functional requirements from product functional requirements in software product lines. In the same direction, the IBM China Research Laboratory has been utilising model-driven technology to address challenges in *business process integration* and *reusable software* [83].

In fact *agile software reconfiguration* could be an important challenge, as, in Japan, the effect of investment in EIS is not high enough compared with the levels of other countries. There is a high level of management dissatisfaction with regard to the EIS used in their enterprises, mostly due to the need to use more custom-made software to tackle cultural issues. For example, *Business Process Re-engineering* needs to be taken in consideration when implementing ERP systems. Japanese companies value "suriawase", a strategy for mutual understanding and compromise among people within organizations without applying a strict scheme of decision-making [84,85]. Hence, cultural matters such as a common sense and society rules have a high impact on enterprise information systems design, which cannot be modelled only as a functional system of information processing. Various policy packages, including e-Japan and u-Japan, have been supporting the development of *feature driven development* to organise software modules features with semantic primitives, for requirement specification and work breakdown management. Indeed, the National Institute of Advanced Industrial Science and Technology (AIST) is promoting *semantics-driven development* and customization of EIS based on ontologies [86]. This supports the need for knowledge applied to model-driven technology in support of SI, as explored in the next section.

4. Novel Research Trends Towards a Sustainable Interoperability in Networked EIS

Being the definition of some slice of reality, which is being observed and interpreted, models are a requirement in a self-sustainable interoperable network. They formalise the bridge between the real and digital world and enable the necessary reasoning to enable a dynamic adaptation of the network's EIS to the constant market changes. In some contexts such as MDI/MDSEA, they represent different aspects of one reality, derive from different natures and can be created using varied modelling languages, paradigms, concepts and formalism levels. Derived from the mathematical morphism concept, model management has been mostly used in Model Driven Engineering (MDE) methods where modelling should change from contemplative (e.g., used for documentation) to productive, envisaging transformations from high-level business models focusing on goals, roles and responsibilities down to detailed use-cases and scenario models for software execution.

Knowledge management, especially at the level of ontologies and semantic alignment, is currently leading edge research to a more advanced EIS approach, intending to emulate human reasoning behaviour. As traditional organizational boundaries become more blurred and distributed, and crowd sourcing and open source are integrated into business models, the Boisot's I-Space (information, social and economic intersection) continues to afford a powerful framework for research about the way in which invention and innovation are coupled in this dynamic context, and it is yielding new insights [87]. Research in the area is trying to be more participative, gathering more knowledge to consume in further situations, e.g. solving interoperability issues. Cross-boundary works handling *sentiment analysis* is one of its examples, which uses data from social media in pursue to gather tacit knowledge. Such approaches have required specific *machine learning* algorithms to access to big data sources and use such knowledge to handle complex *semantic interoperability* issues.

Under the background domains discussed, the authors consider there is a great margin for research progression, and knowledge-intensive techniques, such as ontologies or linked data, could be explored and improved as reference conceptual models to support the model-driven design and redesign of interoperability enablers. Contributing towards the grand challenged identified earlier (section 1), some novel research trends are hereafter described, where more specific technology challenges both concerning the system design and the interoperability enablers, are emphasised in *italic*. As represented by Figure 4, these trends crosscut several policies and strategies (section 3). The specific challenges are several and are addressed non-exhaustively along sections 3, 4 and 5 of this paper.

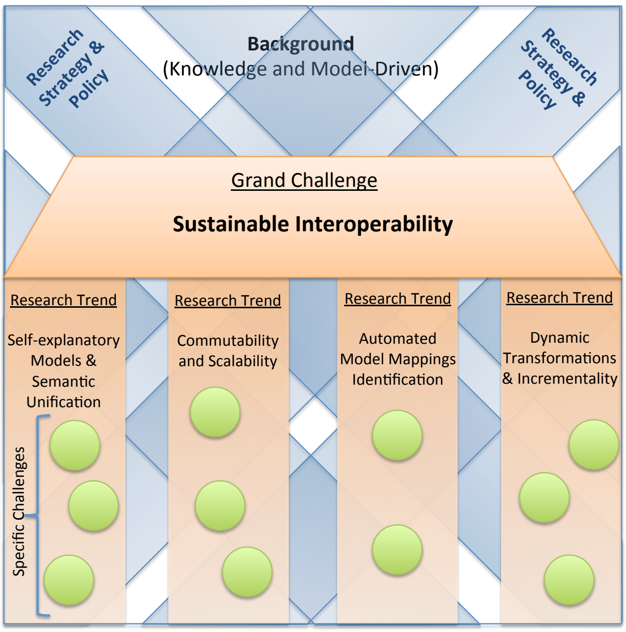

Figure 4: Sustainable Interoperability Research Framework

4.1. Self-explanatory Models and Semantic Unification

Typically models are analysed under the form of diagrams to empower the human understanding, but due to graphical and space constraints, the information annexed to each modelling concept is implicit (each symbol means a different thing), and the model itself depends on the context to which is related or used to, as well as on the personal understanding to the one who defined it. Hence its analysis might not be straightforward, and today requires a time-consuming semantic annotation to describe and clarify the used concepts' meanings. The research area includes specific challenges at system design-time, e.g. *interoperability-by-design*.

Each model represents a segment of the reality at the eyes of the modeller. It represents a thing's conceptualization or view that intends to be commonly understood and shared by the community to which the model is related. To accomplish such complete understanding each concept or taxonomic structure used has to be sharply and commonly comprehensible by all. Even knowing the same domain and the used meta-model language, it is very difficult to understand a model, created by another person, in the right way. Thus, it is needed to enrich the model with conceptual and structural descriptions to supply it with the necessary semantic annotations to become self-explanatory. The same concept in different contexts can represent completely different meanings.

Today's most common formal approach for knowledge representation uses ontologies. However, an ontology is a special kind of an information model. A reference ontology in the domain (*upper ontology for modelling*) should be used to support further modellers to understand a model, e.g. to define and develop a link in the model specification pointing to the ontology element or part; or even include the required semantics represented by an ontology part, inside the model (*self-contained semantics*). Another solution would be to develop a thesaurus or glossary to have a stable (reference) representation of the lexicon, which will have the reference concepts in the domain. Through this approach, *semantic unification* between stakeholders would be accomplished. In addition to this, specific context descriptions are expected from the modeller. Such descriptions would be addressed as the "javadoc" de facto industry standard to present JAVA function's explanations (*modeldoc*). The *standardization of the knowledge enrichment procedure* for models would be expected in the future. All these approaches would support the appearance of the so-called self-explanatory models.

4.2. Commutability and Scalability

In a collaborative modelling process the possibility of reengineering some parts of the model should be ensured even if the person responsible for a specific part or version of the model becomes unavailable. The knowledge bases used to enrich the model are useful to spread the idea or view of the original modeller. To enable an efficient commutability of modellers, reference ontology in the domain is required (*upper ontology for modelling*). Having an ontology with knowledge aligned with the model but that doesn't share the same vision of the substitute modeller will not work. Thus, to ensure the effective commutability it is required to accomplish a solution as MENTOR [88], to impose the building of a reference ontology, which lexicon is used in the model and to which a wider number of modellers are semantically aligned.

It is foreseen in the future that the view of the models will be depending in the profile of the modeller. Advanced adaptations would be expected in the modelling software to potentiate the smooth transition from one modeller to another. It is possible to include advanced IoT components in modelling software systems able to gather the modeller mood and dynamically propose an adequate support or guideline (*adaptive modelling*). A personalised way of visualizations and other functional related solutions based in the profile or in the mood of the modeller would be expected. With the proposed solutions, or similar ones, it will be possible to reach the scalability of the modelling process. The formal, explicit and *standardised procedure for models knowledge enrichment* will potentiate a smooth on-board access of other modellers into previous modelling works facilitating their understanding and promoting its collaborative development or increment.

4.3. Automated Model Mappings Identification

In an EIS engineering project, many models at different levels of abstractions are created, analysed and evolved. Manually tracking the variety of relationships among the models (e.g., versioning, refinement, dependency) adds significant complexity to the model-driven process, and current modelling tools do not provide the support needed to effectively manage these relationships [89]. In fact, within a model-driven approach for interoperability (e.g. MDI), the major difficulty resides on the mapping process, a manual procedure that typically needs to involve specialists on the source and target models as well as some transformation specialists. The definition of mappings between different EIS is knowledge intensive and requires an extensive understanding of the information models as well as of the domain of application (*adaptive modelling*). Due to this, normally it requires a complex manual process, but the challenge is that in some cases such mappings could be semi-automatic generated based on explicit knowledge base repositories. These would enable to reason associations between concepts.

Further R&D in the area of *Megamodelling* ([90]) in which models are the units of manipulation, managing and relating other models would help. Since mechanisms that manipulate models work at the metamodel level, if models become self-explanatory (as in section 4.1) and also computer interpretable, information about the modelling concepts would be available in a rich knowledge-intensive repository capable of describing syntax, behaviour, domain, and could be possible to infer manipulations and identify mappings.

Automated model mappings identification can be also useful in the case of collaborative modelling, improving the efficiency of co-modelling, models reuse and versioning. Despite the advances of diff-merge algorithms especially in EMF Diff/Merge, a generic, domain-independent solution has not been developed yet [91]. In this line, a model management repository (e.g. *modelstore*) based on the *megamodelling* must have the capability to handle models produced by a variety of development tools, and must be open and extensible. It can be local to a single EIS or centralised to a certain domain network, accessible through public services to enable reasoning and inference. However, scalability could become a problem for large model repositories. XMI (www.omg.org/spec/XMI/), the reference in MDA implies large files. OWL (www.w3.org/standards/techs/owl), the standard language for ontologies or RDFS (www.w3.org/standards/techs/rdf) for knowledge representation suffer from the same drawback, with most reasoners needing to load all the data into memory. Further research in this line is also required.

4.4. Dynamic Transformations and Incrementality

Model transformation can be described as a model management operation where a model is transformed using a function that applies a mapping to the source model and outputs a target model. Traditionally a simple non-formal table, relating multiple modelling concepts, can express this function, but once created it should be coded using a transformation language (e.g., ATL - www.eclipse.org/atl/). Several techniques and languages are available for achieving model transformations at various levels [49,92]. The top-level *"model-to-model"* technique promotes interoperability among different EIS, while the *"model-to-text"* is more focused for software development. However, once implemented, transformations cannot not be tested and updated dynamically to enable incrementality or a sustainable interoperability between both models.

Most approaches focus only on classical one-way batch-oriented transformations, which can be executed any number of times but always following the same mapping rules, thus do not allow *incremental synchronization* and regular updates of either the source or target models [93]. The complex structure of the models may stretch the limits of current formal static analysis and testing techniques [89]. Moreover, especially in *"model-to-model"* cases, when there is not an explicit and formal representation of the mappings defined, neither a dynamic association between the mapping and the transformation execution language (in an MDE style), it is not possible to change something or verify the transformation correctness without having to navigate through code. This is a very time consuming activity, requiring the participation of programmers, domain technicians, and software architects, which discourages business people from being innovative, and preventing them from upgrading their EIS. In *incremental transformations* the context should be preserved to efficiently perform incremental updates. Paradigms such as *reactive programming* could be applied to handle the propagation of changes through data flows. Hence, a reactive transformation engine could take care of activating only the strictly needed computation in response to updates or requests of model elements. The reactive engine would offer a combination of incremental and lazy computation that transparently keeps the system consistent and sustainable according to the provided transformation rules [91]. Nevertheless, to enable the above, further research is required on the areas of *formalization*, *knowledge enrichment*, and *runtime models* (e.g. Morin et al. [94], and Bencome et al. [95], for the last case).

As suggested in section 4.3 with the *knowledge-intensive repositories for enrichment of models*, the same could be applied to mappings for managing the transformations context. Agostinho et al. [96] conducted some work on that direction, proposing a Communication Mediator (CM) ontology, distributed along a collaboration network, where each pair of morphims (mappings and transformations) is stored in a way that each organisation keeps track of the inner-elements relationships with its business partners. With the CM, they maintain a traceable record of relationships to support monitoring and intelligence activities such as *"on-the-fly" composition of transformations*. In [69], the work is extended with a proposal to use model-driven paradigms to generate automatically ATL transformations from the CM metadata.

A particular challenge faced by developers of *"model-to-text"* transformations is integrating generated code with handcrafted or legacy code [89]. Current code generation tools assume that generated code (can be seen as a very low level model) is standalone and provide very little support for integration. Architectural choices that are made by the generators are not made explicit and formal which makes it difficult to guarantee that a code generator will produce code that is architecturally compatible with foreign code. As in the cases described above, the result is that some time-consuming manual refactoring of the generated models is required. Hence, *modular model generation* is required to change this, contributing to scalable and incremental systems.

5. Possible Future Scenarios on SI

The absence of a universal solution for interoperability is an evidence of the complexity currently existing in collaborative business networks. As illustrated by Figure 5, even when collaborating, networks are filled with complexity at macro and micro levels. They are formed by enterprises from the same or complementary domains (represented as Entr A to Entr D), which are managed by people with different ideas and backgrounds based on several factors such as culture, professional experience, family, etc. In fact, humans and social behaviour plays a fundamental role on networks (Human in the decision loop). They manage, work, and are themselves customers of the different enterprises, which can belong to several networks at the same time. On the other hand, enterprises have different EIS (e.g., Entr D has EIS D' and D'') structured according to several information models and standards, implemented on multiple software platforms and technology while using a multitude of physical devices. Besides being influenced by people, enterprises influence each other, which lead to a high dynamicity of requirements, models or even systems. Therefore, all this heterogeneity leads, in most cases, the network to experience interoperability problems, needing dynamic enablers/adaptors to react and ensure the sustainability of their communications. The problem of sustainability along the network lifecycle is emerging and needs focused research as addressed in this paper.

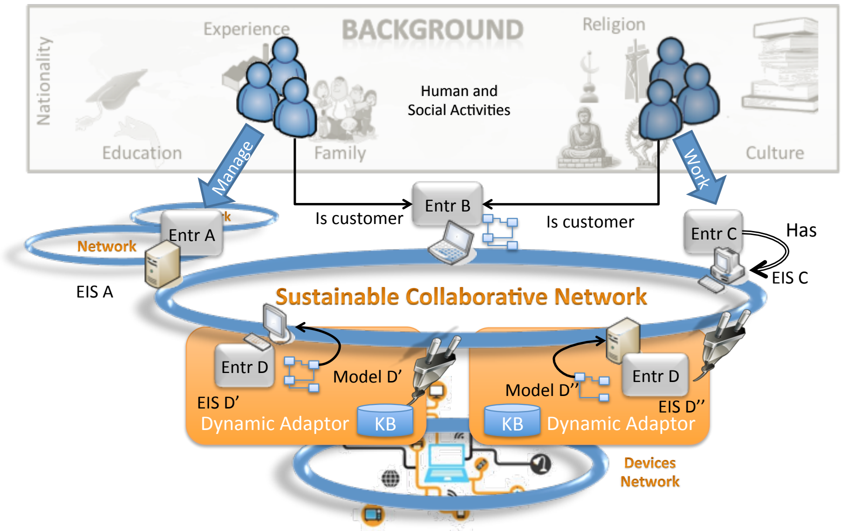

Figure 5: Complex Dynamic Networks

Understanding the network and enterprise information systems' relationships is considered a major factor in contributing for the success of interoperable solutions and the performance of the entire enterprise. Implicit in both is the view that enterprises are Complex and Adaptive Systems. While adapting to new market and customer requirements (e.g., replying the need to respond with faster and better quality products and services), they may decide to change or upgrade their EIS or the services provided by them, enabling constant fluctuation and evolution of networks and system models. Different scenarios are possible where solutions arising from one or more of the research trends could contribute to a better level of interoperability sustainability:

- Bringing new partners to the network would mean new EIS, information and communication models, thus implying the development of specific adaptors. In this case there is a clear need for <u>automated model mappings identification</u> as well as dynamic transformations to accelerate the adaptor's implementation. In the case there are no formal information models for the new EIS, modelling with a <u>self-explanatory</u> vision and <u>commutability</u> would be key for a future dynamicity.

- Acquiring a new EIS means that the corresponding information models need to be (re)analysed to develop a novel adaptor capable of maintaining the existing network relationships. It is a scenario similar to the previous one.

- Develop new services updating existing EIS functionalities or extending the enterprise portfolio. In this case, since a large time frame may have passed since the system initial modelling, <u>self-explanatory models</u>, <u>commutability</u> and also <u>incrementality</u> to update existing transformations become quite important. This is a pertinent scenario for the software industry.

- Replace components such as IoT devices. In this particular case, different device manufacturers use different communication protocols, which reinforces the need to have well defined models and <u>scalable</u> adapters with <u>automated mappings identification</u> features, capable to accommodate similar devices independently of the provenance.

The following sub-sections synthetise some specific challenges that can be derived from the analysis of these scenarios. They are categorised in terms of temporal placement considering the maturity of exiting knowledge and background research. Since this is an exploratory work, the focus of the analysis was directed more towards the identification of future directions to complement the research trends of section 4, rather than detailing possible solutions already implemented or being implemented.

5.1. Short-term challenges: Focus on Self Explanatory Models (1 to 3 years)

Seamless information exchange is a primary focus of EIS interoperability, challenged by the complicated exchange of information semantics. Information science studies the intrinsic properties and characteristics of information, such as how to use mathematics and other formalisms to represent them, how to deal with uncertainty in information, what are the fundamental units of measure, what are useful metrics, how to measure those uncertainties and metrics. The authors highlight short-term challenges focused on the *formalization* aspects and *knowledge enrichment methods* towards the first self-explanatory models and model mappings representation.

5.2. Medium-term challenges: From Commutability to Dynamic Transformations (3 to 5 years)

Medium term research challenges include the *semantic aspects of interoperability*, in particular the definition of the basic properties and characteristics of information needed for *inference* and *reasoning* at industrial level; the *meaning and "common understanding" of modelling objects*; the *comparison between information objects*; *measurement of information objects*; applying methods such as crawling, scraping or data mining to gather information about the EIS surrounding environment, as well as knowledge of technological developments. Most of the challenges identified in this paper, from models commutability, mappings identification or dynamic transformations are expected to become visible in a medium term perspective.

5.3. Long-term challenges: Incrementality and Intelligence Towards Industry-wide Acceptance (5 to 10 years)

Intelligent reconfiguration of components for a run-time sustainable interoperability, supporting evolutive-networked EIS, including learning and adaptability methods. The long-term perspective envisages incrementality and *interoperability by design* also to become a reality. In this time frame most of the concepts addressed in all research trend are expected to be matured enough to enable industry acceptance of the technology. The scenarios list is not extensive, but all of the previous cases of dynamicity may impact external enterprises as well, risking a self-fed loop of adaptations. Hence, a fast re-adaptation or *pre-emptive adaptation* is also envisaged as a specific challenge in SI, to maintain the network harmony.

6. Conclusions

This paper has presented sustainable interoperability as a new grand challenge for next generation enterprise information systems. With the adoption of different technologies and external service providers, new dynamics are introduced in systems and networks management. Business paradigms are evolving, and the impact of a single change to a system or software on the enterprise network may have an unforeseen negative effect in the desired collaboration, endangering interoperability and ultimately causing service downtimes. Hence, to remain reliable in a very dynamic collaborative network, future EIS need to be properly monitored and controlled to enable a sustainable innovation.

Solid research in the domain of EIS engineering and interoperability provides the baseline technology for roadmapping future research targeting the SI. Analysing them, alongside with past and future research strategies promoted worldwide, led to the identification of a set of novel research trends and specific challenges, addressed in the paper to contribute to the grand challenge. The authors believe that the combined use of model-driven and knowledge-based approaches can improve next generation EIS, dealing with issues such as design and redesign, generation of dynamic interoperability enablers to tackle conceptual interoperability barriers, and plug-and-play integration of services and applications.

The knowledge enrichment of models introduced by semantic annotations clarifies the understanding of the model itself and its mapping with the environment. When the modeller tacit knowledge about the modelling objects, and the EIS functional parameters are introduced into a formal internal or external solution to enrich the model-driven processes, then the EIS re-engineering is facilitated, minimising the problems caused to enterprise network interoperability. Indeed, the mixed study of MDA/MDI technology and knowledge management techniques as enablers for a self-sustainable interoperability is motivated by modularity and repeatability through the existing landscape of tools available to support transformations and the implementation of interoperability enablers. Together, both technologies have the potential to free business and domain experts to take the necessary decisions to evolve their businesses, without being concerned with the technical implications. However, model-driven approaches are linear, not taking into account disturbance. Hence, to complete a full sustainable lifecycle, the paper points that usual approaches have to be extended to become more dynamic and include the decommission steps of a full reengineering process.

Under that premise, the paper delineates a research framework for sustainable interoperability, focusing in the exploration of four major research trends: Self-explanatory models and semantic unification, Commutability and scalability; Automated model mappings identification; Dynamic transformations and incrementally. They are grouped into pillars addressing scenarios and identifying a non-exhaustive list of specific challenges along a 10 years timeframe. Current EIS research converges on the fact that Enterprise Interoperability should be considered from the initial conceptual description of the future EIS as an unavoidable requirement. Then modelling approaches have been identified has one necessity for non-ambiguous EIS specification. Enriched with enough knowledge, the paradigm of models used at runtime can be used by different system stakeholders to observe the runtime behaviour of EIS, and to monitor specific aspects of the environment. Adaptation and scalability can use models together with knowledge-based technology to detect the need for adaptation and to act accordingly, submitting the changes to interpretation mechanisms. The change can be guided thanks to cultural support. A model-based runtime change interface can also provide constraints on how changes are done, checking the impact of change before applying it. Thus, dynamic and automatised remote configuration facilities need to be provided for enabling self-management applications to automatically configure the parameters required for the applications and the users.

Sustainable Interoperability tackles many of the limitations of the traditional document-based engineering approach. It provides a more rigorous and intelligent method for capturing and integrating requirements, design, analysis, verification and validation throughout the system's life cycle phases in a robust knowledge basis. The self-explanatory models will support a faster and safer access to context of the models realization. Also the scalability will give opportunity to change dynamically the perimeter of the system to adapt to the environment in small amount of time. In summary, EIS models should be able to evolve to increment the EIS without rebuilding it from scratch, and techniques such as *megamodelling* are expected to facilitate the mappings identification. All this provides a comprehensive understanding between development teams and the other stakeholders, as well as traceability features that facilitate properties, such as backward compatibility, where the enterprises of the Future should be able to interoperate with non-evolved enterprises. Through appropriate ontologies or knowledge bases developed for the operational context of an enterprise, model-based systems and services will empower the enterprise with semantic enriched capabilities.

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