Enterprise Integration and Networking: Challenges and Trends

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IFAC TC 5.3 Enterprise Integration and Networking *

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Abstract: Research and developments in Enterprise Integration and Networking requires to identify challenges and trends in order to establish a set of coherent vision for future research. This paper summarizes the need for Enterprise Integration and Networking solutions and defines challenges for enterprise modelling and integration.

Keywords: Enterprise Integration, Enterprise Modelling, Enterprise Interoperability, Enterprise Integration Engineering, Collaborative Networked Organizations

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1. Introduction

Future scenarios place Information and Communication Technologies to be core in new developments. Digital megatrends such as: e-Tailing, e-Government, Entertaiment on demand, virtual education and a wide set of online services (finance, publishing, marketing) will be part of everyone life's. However all these applications and systems will require satisfying the following fundamental requirements (Molina et al 2005):

- Enterprise integration and interoperability
- Distributed organization
- Model-based monitor and control
- Heterogeneous environments
- Open and dynamic structure
- Cooperation
- Integration of humans with software and hardware
- Agility, scalability and fault tolerance.

This paper summarizes the need for Enterprise Integration and Networking Solutions and describes the challenges and trends that IFAC TC 5.3 has identified as important and relevant for future research work. The challenges have been classified according to the following areas (Figure 1):

- Collaborative Networked Organizations
- Enterprise Modeling and Reference Models
- Enterprise and Processes Models Interoperability
- Validation, Verification, Qualification and Accreditation of Enterprise Models
- Model Reuse and Repositories

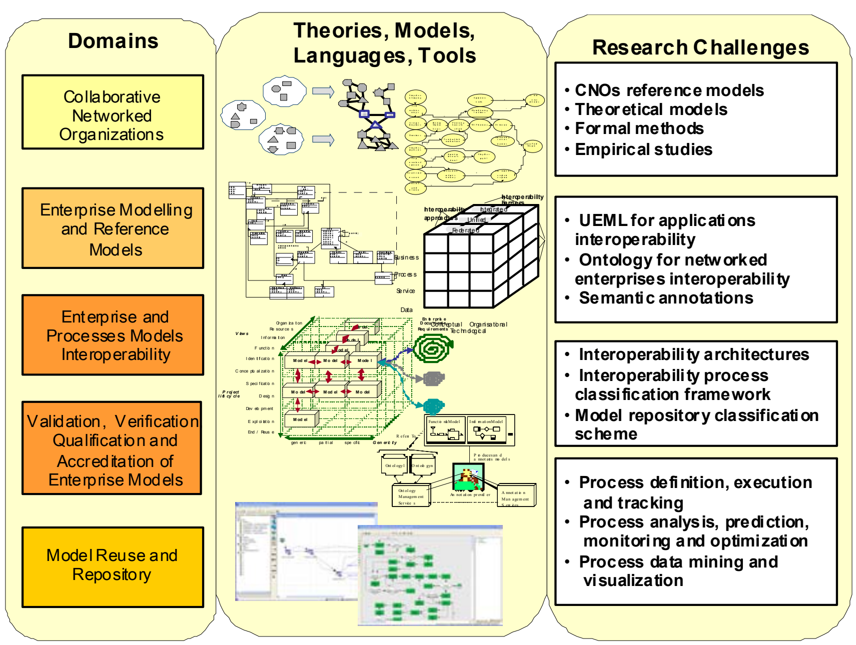

Figure 1. Research Challenges for Enterprise Integration and Networking

2. The Need for Enterprise Integration and Networking Solutions

2.1 Key Concepts of Enterprise Integration

Enterprise integration is a domain of research developed since 1990's as the extension of Computer Integrated Manufacturing (CIM). Enterprise integration research is mainly carried out within two distinct research communities: enterprise modelling and Information Technology (IT). The notion of Enterprise Integration as it is understood in the frame of enterprise modelling refers to a set of concepts and approaches such as for example the definition of a global architecture of the system, the consistency of system-wide decision making (coherences between local and global objectives), the notion of the process which models activity flow beyond the borders of functions, the dynamic allocation of resources as well as the consistency of data (Vernadat 2002).

It is to notice that enterprise integration is an essential component of enterprise engineering which concerns the set of methods, models and tools that one can use to analyse, design and continually maintain an enterprise in an integrated state.

Enterprise integration can be approached in various manners according to the interest of the study (Chen and Vernadat, 2004). CEN TC310/WG1 has recognised three levels of integration: (1) Physical Integration (interconnection of devices, NC machines, PLCs, via computer networks), (2) Application Integration (dealing with interoperability of software applications and database systems in heterogeneous computing environments) and (3) Business Integration (co-ordination of functions that manage, control and monitor business processes). Michel (1997) considers that integration can be obtained in terms of: (1) data (data modelling), (2) organisation (modelling of systems and processes) and (3) communication (modelling of computer networks, for example the 7-layer OSI model). Integration can be total, i.e. the standard is the software or system itself. Integration can be achieved by unification (the possible standards are methods, architectures, constructs and reusable partial models) or by federation (the possible standards are interfaces, reference models or ontologies). Some other approaches allow complementing the above considerations: (1) integration through an integrated enterprise modelling (Shorter, 1997) such as for example CIMOSA, or (2) integration as a methodological approach to achieve consistent enterprise-wide decision-making (Doumeingts et al 1998) as proposed in the GRAI methodology.

Since the end of 1990's enterprise integration is being challenged by emerging concept 'Enterprise interoperability'. Enterprise interoperability is believed to be more adapted (less cost and quicker implementation) in decentralised, flexible and networked manufacturing system environment. Generally, interoperability has the meaning of coexistence, autonomy and federated environment, whereas integration refers to the concepts of coordination, coherence and uniformatisation. From the point of view of degree of coupling, the 'tightly coupled system' indicates that the components are interdependent and cannot be separated. Therefore it is the case of an integrated system. The 'loosely coupled system' means that the components are connected by a communication network; they can exchange services while continuing their own logic of operation. It is the case of interoperability.

Integration is generally considered to go beyond mere interoperability to involve some degree of functional dependence. While interoperable systems can function independently, an integrated system loses significant functionality if the flow of services is interrupted. An integrated family of systems must, of necessity, be interoperable, but interoperable systems need not be integrated. Integration also deals with organisational issues, in possibly a less formalised manner due to dealing with people, but integration is much more difficult to solve, while interoperability is more of a technical issue. Compatibility is something less than interoperability. It means that systems/units do not interfere with each other's functioning. But it does not imply the ability to exchange services. Interoperable systems are by necessity compatible, but the converse is not necessarily true. To realize the power of networking through robust information exchange, one must go beyond compatibility. In sum, interoperability lies in the middle of an "Integration Continuum" between compatibility and full integration. It is important to distinguish between these fundamentally different concepts of compatibility, interoperability, and integration, since failure to do so, sometimes confuses the debate over how to achieve them. While compatibility is clearly a minimum requirement, the degree of interoperability/integration desired in a joint family of systems or units is driven by the underlying operational level of those systems.

One interesting question to answer is how Enterprise Integration and Modelling can deal with the technological challenges that allow an enterprise to face global competition and fluctuating market conditions. Technologies can help doing things faster but the system-wide consistency can only be analysed and designed at conceptual level. The advances in technologies requires closer tie between enterprise models and architecture elaborated at conceptual level and IT architecture and platform for implementation. The MDA (Model Driven Arquitecture) approach provides best hope to the meet this requirement. Using a reference model for Enterprise Integration, the contributions of the research area of Enterprise Integration and Networking can be classified into: Business, Knowledge, Application and Communications. In Molina et al. 2005 how the different challenges faced by next generation manufacturing systems are discussed in detail.

2.2 Enterprise Integration Evolution: from Physical Integration to Business Integration

The ultimate goal of enterprise integration is to achieve business integration to support intra and/or inter enterprise operations. However business integration needs the support of physical integration and application integration for easy communication and exchange of information. Currently physical integration has been achieved in many enterprises and application integration is also in progress in many companies. However business integration, although addressed since 1980's, is still not developed to a satisfactory level.

Physical system integration (Information and Communication Technologies) essentially concerns systems communication, i.e. interconnection and data exchange by means of computer networks and communications protocols. Physical system integration dates back to the early 1970's and is still evolving. Work done has first concerned the 7-layer OSI/ISO standard definition, and then the development of specialized manufacturing and office automation protocols such as MAP, TOP, and field-buses. It now continues with developments on ATM, fast Ethernet, Internet and web services, SOAP (Simple Object Access Protocol), or RosettaNet. Message queueing systems (such as IBM's MQ Series) and message-oriented middleware (MOM) are important corporate components of the basic infrastructure at this level (Vernadat 1996).

Application integration concerns interoperability of applications on heterogeneous platforms. This type of integration allows access to shared data by the various remote applications. Distributed processing environments, common services for the execution environment, application program interfaces (API's), and standard data exchange formats are necessary at this level to build cooperative systems. Application integration started in the mid 1980's and is still on-going with very active work concerning STEP, EDI, HTML, XML, or eb-XML for the exchange of common shared data, development of common services for open systems around the web (web-services), integration platforms for interoperable applications in distributed environments (e.g. OSF/DCE, OMG/CORBA, WSDL, and more recently J2EE or Java to Enterprise Edition environments and .NET). Other tools used at this level are workflow management systems (WfMS) and computer support to collaborative work – CSCW (Gorason et al 2002).

Business/Knowledge integration relates to the integration at the corporate level, i.e. business process coordination, collaboration, knowledge sharing, and consistent enterprise-wide decision-making. This mostly concerns enterprise interoperability and requires externalizing enterprise knowledge to precisely model business operating rules and behaviour. Early work has only been pursued by major programs financed by governments such as the ICAM and IPAD programs. More recently, the CALS Initiative and the Enterprise Integration Program (EIP) in the United States, as well as CIMOSA by the ESPRIT Consortium AMICE, GRAI decisional approach by LAPS/GRAI of University of Bordeaux, AIT Initiative or the IST program of EU in Europe plus the Globeman Project of the IMS program investigated the issue (Chen and Doumeingts 2003). Business integration also relates to the challenge of achieving collaboration among companies to build up worldwide networks. This mostly concerns with the concept of virtual organizations and how they can be designed, implemented and operated. The ECOLEAD project, FP6 IP-506958, is investigating this important aspect of integration (Camarinha-Matos et al. 2005).

Business integration is considered as a key step towards the networked enterprise. Starting the physical integration at lower level to move towards business integration is typically a bottom up engineering approach. Integration at lower levels has often impacts on the business run at the higher level, thus to business integration. The process of bottom-up integration needs to be combined with a top-down global design to define consistent global enterprise architecture so that incremental bottom up integration implementation can be based on long term strategy of the company. Even when business integration has been achieved at one point in time, business opportunities, new technologies, modified legislation will make integration a vision rather than an achievable goal. In this sense, enterprise integration is also seen as a methodological process to periodically measuring the gap between desired integration goal and actual status of the system, and to adjust both the goal and integration actions if necessary (Molina et al 1999).

2.3 The Interoperability Challenges

Since the end of nineties and beginning of 2000´s, more research efforts have been directed to developing enterprise interoperability. At European level, Interoperability of enterprise applications and software is considered as a strategic issue by European Commission. A thematic network IDEAS (Interoperability Development of Enterprise Applications and Software) was launched (July 2002 - June 2003). The objective was to elaborate a roadmap to develop interoperability Two main European initiatives relating to interoperability development within FP6 (Framework Programme 6) are running: ATHENA Integrated Project (IP) focused on industrial applications and INTEROP Network of Excellence (NoE) more oriented to research works. Three main research domains that address interoperability issues were identified, namely: (1) Enterprise modelling (EM) dealing with the representation of the inter-networked organisation to establish interoperability requirements; (2) Architecture & Platform (A&P) defining the implementation solution to achieve interoperability; (3) Ontologies (ON) addressing the semantics necessary to assure interoperability (IST, 2002).

Vernadat (1996) defines interoperability as the ability to communicate with pier systems and access the functionality of the pier systems. In IDEAS project, the interoperability is considered as significant only if the interaction between two systems can, at least, take place at the three levels: data, application and business process with the semantics defined in a business context.

Interoperability extends beyond the boundaries of any single system, and involves at least two entities. Consequently establishing interoperability means to relate two systems together and remove any incompatibilities in between. Incompatibility is a fundamental concept used in interoperability domain. It is the obstacle to establish seamless interoperation. The concept 'incompatibility' has a broad sense and is not only limited to 'technical' aspect as usually considered in software engineering, but also 'information' and 'organisation', and concerns all levels of the enterprise. Another fundamental consideration is the generic characteristic of the interoperability research. Indeed there are generic problems and solutions regardless of the content of information exchanged between two systems.

From another point of view and according to ISO 14258, there are three ways to develop interoperability:

- Integrated where there is a standard format for all constituent systems. Diverse models are interpreted in the standard format. This format must be as rich as the constituent system models.

- Unified where there is a common meta-level structure across constituent models, providing a means for establishing semantic equivalence.

- Federated where models must be dynamically accommodated rather than having a predetermined meta-model. This assumes that concept mapping is done at an ontology level, i.e. semantic level.

The federated approach is seen as the most interesting one to develop full interoperability. However, the choice depends on the context and requirements. If the need of interoperability comes from a merger of enterprises, the integrated approach would be the most adapted one. If the need of interoperability concerns a long term based collaboration, the unified approach seems a good solution. For that, a common meta-model across partners' models provides a means for establishing semantic equivalence allowing mapping between diverse models. On the other hand, for a need of interoperability originated from the short-term collaboration project (e.g. virtual enterprise); the federated approach can be used. To interoperate partners must dynamically adapt to achieve an agreement.

To day, most of research and development are concerned with unified approach, for example PSL, UEML, Semantic Annotation technique using ontology for solving semantic mismatch etc. One of the challenges in developing interoperability in the future is the use of federated approach (Panetto et al 2004).

In a recently published roadmap by European Commission to develop enterprise interoperability under FP7 (Framework Programme 7) for the next years to come, four Grand Challenges have been identified that collectively constitute a long-term strategic direction for research in Enterprise Interoperability:

- An Interoperability Service Utility (ISU) to provide interoperability as a commoditised technical functionality, delivered as services to enterprises, independent of particular IT deployment.

- Leveraging Web Technologies for Enterprise Interoperability, with the focus on value creation through the delivery of novel and improved services in next-generation Enterprise Interoperability solutions.

- Knowledge-Oriented Collaboration to enable enterprises, through the sharing and use of knowledge, to successfully form and exploit Virtual Organisations, to the mutual benefit of the VO partners.

- A Science Base for Enterprise Interoperability that comprises a new set of concepts, theories and principles derived from established and emerging sciences, with a view to long-term problem solving as opposed to short-term solution provisioning.

Many interoperability projects and approaches have been developed to date; however a precise and unambiguous problem statement is still missing. Interoperability has many definitions and connotations to different people in different sectors and roles. As a consequence research on interoperability is not as efficient as expected or needed. Interoperability is taking on a wider meaning than it had 10 years ago, to cover the many knowledge spaces, dimensions and layers of single and collaborating enterprises. A clear categorisation/characterization of various kinds of interoperability is urgently needed in order to improve our understanding. On the other hand to clearly define the meaning of the interoperability concept, measures to evaluate the degree of interoperability are required. The challenge is to define the concepts and metrics for measuring different degrees of interoperability. It has been considered that there are three types of interoperability measurement (Daclin and Chen, 2006): (i) interoperability potential measurement, (ii) interoperability compatibility measurement, and (iii) interoperability performance measurement. This allows going far beyond existing approaches which only consider maturity evaluation. Developing metrics for interoperability measurement also allows basing interoperability research and practice on a more rigorous and scientific principles.

2.4 The emergence of Enterprise Integration Engineering

Since the middle of 1990's, enterprise integration has been emerged as a new engineering discipline to deal with the heterogeneity of enterprise sub-systems and so called 'inlands of automation' with a company.

Enterprise integration as engineering discipline involves the use of (Molina et al 2005):

- Reference architecture and models for helping analysis of existing systems and supporting the design of high level integration solution;
- Engineering methodology providing a structured approach to follow in order to avoid hazardous approach;
- Enterprise modelling language and tools allowing representing the enterprise integration requirements and specifications of integrated solutions.
- Design principles and patterns helping enterprise integration engineer reusing proven solutions (usually a pattern incorporates the experience that has been gained by repeatedly building solutions and learning from the mistakes).

Enterprise Integration Engineering uses reference models to guide the development of information systems by applying life cycle principles, enterprise models and instantiation concepts in different domains such as: business process management, integrated product development, design or redesign of process, and knowledge/project management (Figure 2).

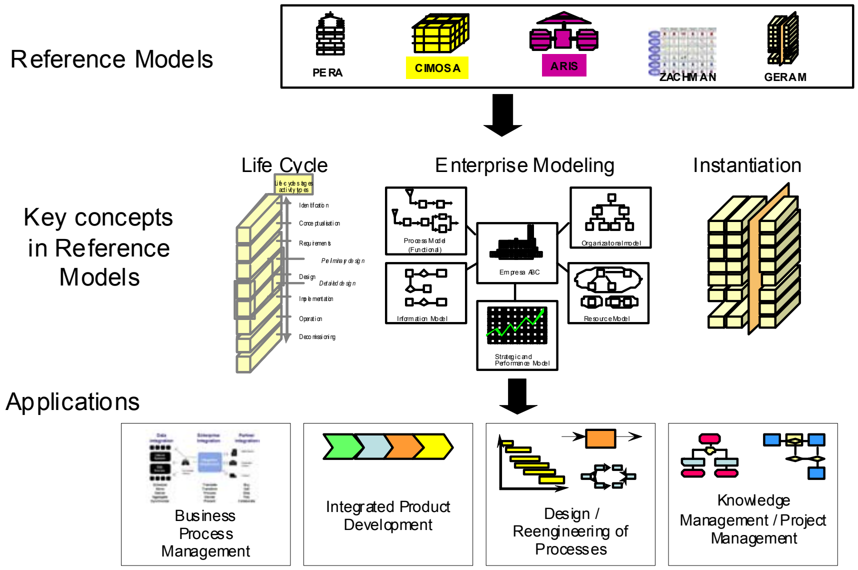

Figure 2. Use of Reference Models in Enterprise Integration Engineering

Enterprise Integration engineering can concern different levels and be approached from different perspectives. At the sub-enterprise level, the functionality of the integrated application or system is limited to a relatively homogeneous area, typically a single local site under a single ownership. For example, flexible manufacturing systems are at the integrated sub-enterprise level. Complete functional integration at the single-site enterprise level assures that business processes, manufacturing processes and product realization are united using a common architecture to fulfil a common goal. This is most likely for a single plant under single ownership, such as an automated factory.

The next three levels of EI – multi-site, extended, and virtual – occur over multiple geographic settings. Multi-Site enterprise integration is generally an issue faced by large enterprises (e.g., Boeing, IBM, General Motors, and EADS) in integrating heterogeneous systems throughout their facilities. An extended enterprise, which generally involves complex supply chains, concerns the integration of all members of the supplier and distribution chain to the common goal of market share capture through product realization. Virtual enterprises are very similar to extended enterprises, but they have the feature of being created and dissolved dynamically on a as-needed basis, and integration of member entities is largely electronic (Browne and Zhang 1999). All levels, to varying degrees, influence and are influenced by integrated product realization, integrated business systems, and tools enabling integration. While the objective is to support creation and operation of extremely efficient, flexible, and responsive extended manufacturing enterprises, the path to reach this will require capturing the wisdom achieved at each of the enterprise integration levels (Panetto et al., 2004).

The final achievement of Enterprise Integration Engineering is to integrate at all levels different types of e-technologies (Telecommunications, Internet/Intranet/Extranet, Database, Web Applications), e-applications (ERP- Enterprise Resource Planning, MES – Manufacturing Execution System, SCI Supply Chain Integration, EPS-Electronic Procurement Systems, CRM – Customer Relationship Management, SRM – Supplier Relationship Management) and e-services (e-Supply, e-Engineering, e-Marketing, e-Brokerage, e-Productivity, e-Factory) in order to create the concept of e-Enterprise (Molina et al 2006)

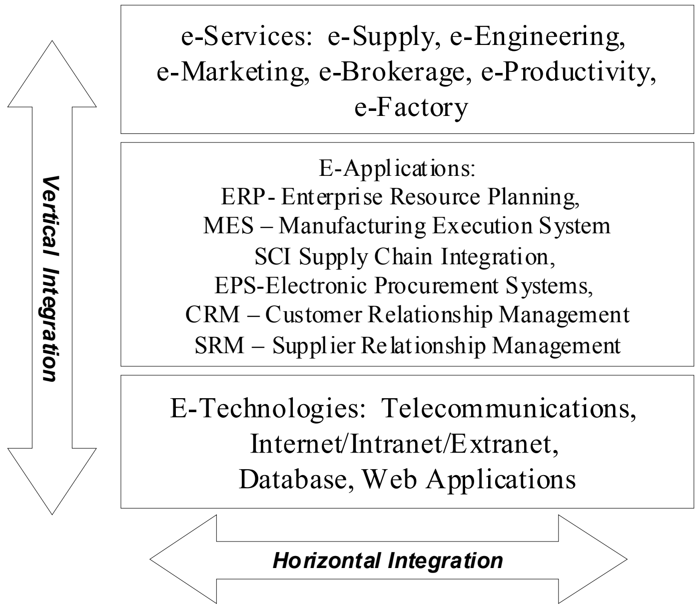

Figure 3. The concept of e-Enterprise by integrating e-Technologies, e-Applications and e-Services.

3. Challenges of Enterprise Integration and Networking

3.1 Collaborative Networked Organizations

Collaboration networks continues to grow in a number of manifestations including not only virtual organizations and virtual enterprises, but also dynamic supply chains, professional virtual communities, collaborative virtual laboratories, global research and global collaborative education with a wide spectrum of application domains. The realization that all these collaboration forms represent variations of general paradigm has lead to their consolidation into Collaborative Networks Organizations (CNO) as a new scientific paradigm (Camarinha-Matos, et al. 2005).

Key challenges for research in the area of CNOS are:

- The definition of reference models for CNOs, to address their different aspects including their behavior, structure, topology, cultural/legal framework, infrastructure, and social interactions.
- Empirical studies related to coordination, administration and management of highly distributed activities, and development of value added-services, dynamic evolution of revenues, rights and liabilities, in combination with the understanding of new value system.
- Theoretical models to create risk management and assessment tools, soft-modeling and reasoning applications, e-contract management, and advanced simulation tools for collaborative networks.
- New methodological approaches for the creation and support of CNOs, information and communication technologies (ICTs) to foster innovative products and business processes based on collaborative paradigms.
- Development of new applications, architectures, and infrastructures to support CNOs.

An European project named ECOLEAD – European Collaborative Networked Organization Leadership Initiative (www.ecolead.org) has been undertaken to create the necessary foundations and mechanisms for establishing an advanced collaborative and network-based industry society in Europe. ECOLEAD addresses three most fundamental and inter-related focus areas as the basis for dynamic and sustainable networked organizations: Virtual Breeding Environments, Virtual Organizations, and Professional Virtual Communities (Camarinha-Matos 2005).

A new reference model for CNOs has been reported by Camarinha-Matos and Afsarmanesh (2006). Empirical studies have been presented by Giraldo et al (2007), Kaihara (2004), Nemes and Mo (2004), and Rabelo and Pereira-Klen (2004) to demonstrate how value added companies can be created and operated under the principles of CNOs. New approaches for the development of collaborative environments have been presented based on the concept of Action Research. (Mejia et al 2007). HUBs that integrate the necessary e-services have been created to support the creation and operation of CNOs (Molina et al 2006).

3.2 Enterprise Modeling and Reference Models

In Enterprise Integration there are two types of architectures. Type 1 describes an architecture or physical structure of some component or part of the integrated system such as the computer system or the communications system. Type 2 presents an architecture or structure of the project which develops the physical integration, i.e., those that illustrate the life cycle of the project developing the integrated enterprise. Today, the architecture concept is not sufficiently exploited. One of the reasons is the lack of proper architecture representation formalism supporting significant characterization of features and properties of enterprise systems. Therefore the review of the past and recent enterprise architecture approaches clearly shows the insufficient development of type 1 architectures, in particular the reference architectures at higher abstraction level are needed. This would help reuse of mature architecture solution (types) to save time and cost while performing enterprise engineering and integration projects. There is also a need to harmonise and map existing type 2 architectures (frameworks for enterprise integration and/or interoperability).

The following research issues are considered challenging for the next years to come:

- Enterprise architecture needs addressing more on how to align of business strategy to technology for implementation, and not just focused on business or IT with separated research and development

- It is necessary to develop an Enterprise architecture language at a high level of abstraction for representing enterprise architectural structure, characteristics and properties at early stage of design.

- Existing architecture design principles and patterns were not developed to a satisfactory level to allow bringing significant improvement to enterprise architecting. More research is also needed in this area to promote the reuse of good practices and theories.

- The development of an ontology precisely defining concepts and properties of enterprise architecture domain is challenging. This ontology is needed to allow a clear understanding of the universe of discourse in this domain and avoid multiple and sometimes redundant developments of architectural proposals. Enterprise architecture ontology also contributes to semantic interoperability between different enterprise architecture proposals.

Since several years, frameworks for enterprise interoperability have been developed to identify and structure issues, problems and knowledge on interoperability (Panetto 2007). They are all type 2 architectures. To mention just a few such as:

- The NATO C3 Technical Architecture (NC3TA) Reference Model for Interoperability focuses on technical interoperability and establishes interoperability degrees and sub-degrees The degrees are intended to categorize how operational effectiveness could be enhanced by structuring and automating the exchange and interpretation of data.

- At a conceptual level, Tolk (2003) has developed the Levels of Conceptual Interoperability (LCIM) Model that addresses levels of conceptual interoperability that go beyond technical models like LISI.

- Systems interoperability is not only a technical problem (as stated by LISI or LCIM) but also deals with organisational issues (OIM). These aspects of interoperability are coherent with the definitions proposed by the EIF (European Interoperability Framework)[1] which aims at supporting the European

[1]European Interoperability Framework for PAN-European EGovernment services, IDA working document-Version 4.2–January 2004

Union's strategy of providing user-centred eGovernment services. Although this approach is not developed for manufacturing area per se, its concepts are also suitable for the domain.

- IDEAS Interoperability Framework based on ECMA/NIST Toaster Model, ISO 19101, and ISO 19119 and augmented through the Quality Attributes.

- ATHENA Interoperability Framework (AIF) defines the three levels (conceptual, technology and applicative) to categorise and structure interoperability solutions.

- Enterprise Interoperability Framework defined under INTEROP NoE proposes a barrier-driven approach to identify barriers to interoperability and knowledge to remove the barriers.

There is also trend to develop Model Driven Interoperability (MDI) architecture which is based on MDA (Model Driven Architecture) approach. Some initial work has been done within INTEROP NoE. Regarding reference models and in the area of standardization, some partial approaches can be mentioned. For examples, ISO 15531 MANDATE is a reference model focusing on information and resource views of manufacturing domain; the IEC 62264 series standard is a reference model on production management and control focusing on the information flow between the control domain and the rest of the enterprise. All these approaches are still on-going works and not mature. More recently, a European Technical Specification (CEN TS 14818: Decisional Reference Model) has been approved. It is based on the GRAI approach and shows a basic decision-making structure defined at high level abstraction.

3.3 Enterprise and Processes Models Interoperability

To meet new industrial challenges, there is a shift from the paradigm of total integration to that of interoperation. Relevant standardization activity focusing on interoperability is just starting and most of work remains to be done in the future. The key challenges are:

- Reach a broad consensus for model information and processes exchange between enterprise modelling tools.

- Domain modeling information should be associated with the software development from the beginning and should be continuously maintained.

- Standards for interfaces between an enterprise’s business systems and its manufacturing control systems should be developed.

- Meta-ontology and ontology to describe various languages used in systems engineering is required to facilitate models interoperability between heterogeneous applications.

A significant initiative to develop interoperability between process models is ISO CD 18629 - Process Specification Language (PSL). In PSL a formal semantic approach (called PSL ontology) is used. However, important efforts are still needed to get effective implementation in industry. Another relevant initiative is the standard dealing with manufacturing software capability profiling carried out by ISO TC184/SC5/WG4.

The standard IEC 62264 (2002) defines models and establishes terminology (semantics) for defining the interfaces between an enterprise’s business systems and its manufacturing control systems. It describes in a rather detailed way the relevant functions in the enterprise and the control domain and the objects normally exchanged between these domains. It is becoming the accepted model for B2M integration and interoperability.

The UEML project (Panetto *et al.*, 2004; Vernadat, 2002) has defined an initial set of generic constructs with the aim of achieving interoperability between them. In recent years, one of the most notable research efforts has been directed to improvement of interoperability (mainly software interoperability), a critical success factor for enterprises striving to become more flexible and to reduce the effort required to establish and sustain cooperation. Software interoperability has been especially addressed by specific software markets such as EAI and XML based solutions. However, these solutions mostly focus on compatibility of distinct formats without looking at the so-called modelling domain, i.e., the domain stating the rationale behind the software and providing reasons for building software. Information about the modelling domain, without taking into account any software issues, is essential to achieving greater interoperability. It is likely to be really difficult or even impossible to understand and recover this kind of information from software.

UEML could solve the issue of horizontal interoperability at the enterprise level. Thus, as information is controlled at the automation level, it should need to be defined through a vertical interoperability approach from the product that produces it through the Manufacturing Execution System that consolidates it to the Enterprise Business Processes that use it. Standards such as the IEC 62264 together with the IEC 61499 function block draft standard for distributed industrial-process measurement and control systems could partially solve the vertical interoperability problem from the Business to the Manufacturing levels.

Consequently, as a prerequisite to building such a vertical information system dealing with physical process constraints, the TC5.3 UEML working group is aiming at defining and formalizing a practical and pragmatic language that should serve as a pivotal language ensuring a common understanding of the product information along its whole life cycle (Tursi *et al.*, 2007). At the European level, the INTEROP network of excellence will further develop UEML v1.0 and deliver an extended UEML specification v2.1. ATHENA Integrated Project and in particular project A1 is using UEML 1.0 as a baseline to develop a set of modelling constructs for collaborative enterprise called POP* (Process, Organisation, Product etc.) while UEML 2.1 is now a meta-ontology based on the generic BWW- Bunge, Wand, Weber-ontology (Wand and Weber, 1995), of the various languages used in systems engineering that will facilitate models interoperability between heterogeneous applications (Berio, et al, 2006).

Applying AUTO-ID (Morel *et al.*, 2003), that information can be embedded in physical objects according to the HMS (Holonic Manufacturing System) paradigm, in order to ensure the traceability of customized products, goods for manufacturing issues and services for logistics issues. Such a holonic approach requires aggregating separate object views and constructs of the IEC 62264 standard in order to define the relevant holons field, lack of established standards, which sometimes happen after the fact, and the rapid and unstable growth of the basic technology with a lack of commonly supported global strategy.

3.4 Validation, Verification, Qualification and Accreditation of Enterprise Models

Verification, validation, qualification and sometimes certification or accreditation (VVQA) activities are considered in complex system engineering approaches as strategic and fundamental activities. They can be informally defined as follows:

- Verification: consists to prevent any misunderstanding about the meta model interpretation during the modeling phase, to avoid modeling errors or incoherence, to detect mistakes concerning the behavior or the structure of the model and last to assume that functional and non functional requirements for which the model has been built are covered.

- Validation: intents to demonstrate that the model is an accurate and relevant representation of the real enterprise part. It allows detecting semantic errors and omissions which can interfere with the human expert interpretation of the reality taking into account restrictive hypothesis.

- Qualification: intents to determine a confidence level which characterizes the knowledge gathered into the model as a relevant and reusable knowledge for the enterprise.

- Accreditation: The model is then recognized by an authority Organization as sufficiently close to a norm or a standard and relevant for the enterprise.

The goal is then clearly to assume and to improve the correctness, the completeness, the relevance and more globally the level of quality and the level of confidence of a given model. Indeed, following the well known Model Driven Engineering principles, engineering projects, whatever may be their goal (software development, integration, risk analysis, business and organisational interoperability analysis and amelioration in a network of enterprises) manipulate models from different natures and covering different objectives. Then, system engineering provides integration, verification, validation and qualification processes all along the life cycle of a system. In the same way, lot of works in information software engineering and integration domain provides formal techniques and tools in order to fulfil these activities (Bérard *et al*. 2001, Balci 1998, Love and Back 2002).

However, VVQC activities remain difficult in enterprise modelling and enterprise integration domains. They are not realty taken into consideration due to the required time and competences which are not present in the enterprise, the costs which thus notably reduce their interest in certain projects, the tools and concepts too limited for providing a significant help for the user in this domain and so on. At this time, used techniques for verifying and validating enterprise models offer advantages and limitations. They are essentially based on:

- Anticipative approach by respecting modeling best practices, rules and constructs such as (EN 2004) for example. This is a classical way in order to obtain 'good' models but cannot be considered as a demonstration taking into account the interpretation of the standards and reference models which remains possible.

- Human expertise (document checking, project review or prototype testing for example).

- Model execution such as provided by simulation or emulation. This is the most popular, recognized and equipped approach in the domain. However it does not provide a formal and exhaustive demonstration of the model quality.

- Formal approaches can provide actors with rigorous proof based on model checking or theorem proving mechanisms. This allows highlighting exhaustive counter examples demonstrating then the non correctness behavior modeled or to detect mistakes in the model.

- Qualification and accreditation require a human expertise and decision.

Assuming more efficiently VVQC activities in enterprise integration domain will provide relevant solutions facing to different challenges. This has already been done concerning for example organisational interoperability analysis (Vallespir and Chapurlat 2007), risk analysis (Chapurlat and Aloui 2006) or also integration and platform development (Archware 2004).

Model driven engineering principles require proving and demonstrating all along a project the quality and relevance of model. Enterprise integration is based on these principles and must raise benefits to develop a VVQC tool box integrating and mixing formal and non formal approaches. Therefore key challenges are:

- To adapt and to formalize a set of concepts coming from other scientific domains. This implies defining the formal foundations of a set of relevant and important modeling languages such as UEML 2.0. This also requires defining and promoting a set of mechanisms and tools for supporting VVQC tasks when using this new modeling language. This must be done by mixing semi-formal and formal approaches.

- There is a need to produce an overview of existing usable techniques, tools and best practices which can be employed all along a project in the enterprise taking into account the project objectives, constraints and actor's profile (competencies and skills, role and profile).

- A guide is required to VVQC practitioners in industry working on information and software systems development projects following on a Model Driven Engineering approach. This guide will have to be generalized in the future for other kinds of projects.

3.5 Model Reuse and Repositories

The key artefact of the previous sections is the increasingly pervasive enterprise model. As these models become more ubiquitous, a mechanism to promote awareness of existing models as well as to facilitate model reuse is required. The primary motivation for model repositories is to enable different modellers with different backgrounds to arrive at the same model and, therefore, to reuse other models. However, according to Vernadat (1996), “If a part of an enterprise is modelled separately by 20 different modellers, we will come up with 20 similar but different models.” Interoperability is needed due to precisely this situation. True interoperability will enable model reuse. Model reuse is also enabled with a repository that promotes awareness of models.

By promoting awareness of models within an enterprise, the methods for creating and using the models will progressively mature. A repository may be used for cataloguing the models within an enterprise, enabling model reuse and aiding the understanding of the breadth and depth of models available. Determining the most appropriate method for creating this awareness considering the external constraints of time, costs, and the usage of additional resources is the objective of the working group ‘Enterprise Models repository’. A definition of repository in many fields is, “A repository is a shared database of information about engineered artifacts, such as software, documents, maps, information systems, and discrete manufactured components and systems (e.g., electronic circuits, airplanes, automobiles, industrial plants)”.

The significant challenges concerning an enterprise model repository enabling model reuse are:

- To collect and classify a disparate number of enterprise models and repositories. This encompasses the identification of existing repository and model reuse concepts in use in other domains. Enterprise model use is ubiquitous and there are countless models and countless enterprises with these models.

- To propose a comprehensive method for developing, maintaining and using an enterprise model repository. This will include the adaptation of existing repository and model reuse concepts in use in other domains.

- To develop and implement sample repositories providing the ability to store and retrieve enterprise models. These repositories will be both for demonstration purposes and for testing and evaluation of the proposed methods.

Key future trends for an enterprise model repository enabling model reuse are (Whitman and Santanu 2005):

- Interfacing and interoperating enterprise repositories with enterprise systems (ERP, MES, etc.). As Enterprise Resource Planning and Manufacturing Execution Systems become more pervasive, these systems must interface and interoperate with Enterprise Model Repositories. The interoperating must be bi-directional as each system may be informed and inform the other. This bi-directionality is vital to maximize investment and opportunities.

- Developing a search engine to access existing models that are applicable in different manners. For example, a search engine should not only retrieve models applicable to product type, but also to process types and should provide insight into any interfacing functions.

- Generation of macro-repositories for accessing models between members of a standard supply chain as well as access within virtual networks. As the repositories become more useful within an enterprise, the repository scope should be expanded across the supply chain including virtual networks. The ubiquitous availability of information will only improve the success of the supply chain in meeting and exceeding the needs and wants of the end consumer.

4. Conclusion

Much attention is focused on Enterprise interoperability development. However, these approaches and technologies would better penetrate and serve any kind of enterprises if:

- There is a reference model for enterprise networking towards the realization of Collaborative Networked Organizations.

- There are design patterns and model-based components available as (commercial) building blocks to design, build, and reengineer large scale systems no only to support single Enterprise Integration but also Collaborative Networked Organizations

- There is a standard, user-oriented, interface in the form of a unified enterprise modeling language (UEML) based on the previous consensus to be available on all commercial modeling tools

- There are enterprise models that can accurately verified, validated, qualified and accredited to be readily be used in enterprise process execution.

- There are real enterprise modeling and simulation tools commercially available taking into account function, information, resource, organization, and financial aspects of an enterprise including human aspects, exception handling, and process coordination. Simulation tools need to be configurable, distributed, agent-based simulation tools.

- There are commercially available integration platforms and integrating infrastructures (in the form of packages of computer services) for plug-and-play solutions

- and finally, there is a clearly established framework for enterprise interoperability to identify barriers, problems, issues and solutions to let enterprise interoperate in a structured and unambiguous way.

Current R&D in enterprise integration and interoperability is dominated by model-based or model driven approaches. Future trends in enterprise integration and enterprise modelling would be toward loosely-coupled interoperable systems rather than high-cost monolithic solutions and low-success holistic integration projects. Main challenge would be to develop models and methodologies leading to interoperability solutions inside and between enterprises in federated environment, taking into account, not only the technology needs but also the semantics of concepts to be exchanged and unanimously understood by all enterprise actors.

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REFERENCES

1. ARCHWARE, **European Architecting Evolvable Software project**, IST 2001-3236 (see hhtp://www.archware.org/), 2004.
2. ATHENA, **Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Applications**, FP6-2002-IST-1, Integrated Project, April 2003.
3. BALCI, O., **Verification, Validation and Accreditation**, Proceedings of the 1998 Winter Simulation Conference, D. J. Medeiros, E. F. Watson, J. S. Carson and M.S. Manivannan, eds., 1998.
4. BERARD, B., BIDOIT M., FINKEL A., LAROUSSINIE F., PETIT A., PETRUCCI L., SCHNOEBELEN PH. MCKENZIE P., **Systems and Software Verification: Model Checking Techniques and Tools**, Springer, 2001.
5. BERIO, G., OPDHAL A., ANAYA V., DASSISTI M., PANETTO H., WOHED P., BAÏNA S., et al., **DEM1: UEML 2.1, Interoperability Research for Networked Enterprises Applications and Software Network of Excellence**, no. IST 508-011, 2005, November.
6. BROWNE, J., ZHANG J., **Extended and Virtual Enterprises - Similarities and Differences**, International Journal of Agile Management Systems, 1/1, 1999, pp. 30-36.

7. CAMARINHA-MATOS, LUIS M.; AFSARMANESH, HAMIDEH and OLLUS, MARTIN, **ECOLEAD: A Holistic Approach to Creation and Management of Dynamic Virtual Organizations**, Collaborative Networks and Their Breeding Environments, IFIP TC5/ WG5.5 Working Conference on Virtual Enterprises, September 26-28, 2005, Valencia, Spain. Boston: Springer.

8. CAMARINHA-MATOS, L.M., H. AFSARMANESH, **Towards a Reference Model for Collaborative Networked Organizations**, in Proceedings of 7th BASYS'06, Information Technology for Balanced Manufacturing Systems (W. Shen, Ed.) (Springer), Niagara Falls, Ontario, Canada. IFIP Series, Vol. 220, ISBN: 0-387-36590-7, 4-6 Sep 2006.

9. CHAPURLAT, V., ALOUI S., **How to Detect Risks with a Formal Approach? From Property Specification to Risk Emergence**, MSVVEIS 2006, Proceedings of Modeling, Simulation, Verification and Validation of Enterprise Information Systems, 2006, Paphos, Cyprus, pp. 134-147.

10. CHEN, D., DOUMEINGTS, D., **European Initiatives to Develop Interoperability of Enterprise Applications - Basic Concepts, Framework and Roadmap**, Journal of Annual reviews in Control, 27(3), 2003, pp. 151-160.

11. CHEN, D., VERNADAT, F., **Standards on Enterprise Integration and Engineering – A State of the Art,** International Journal of Computer Integrated Manufacturing, 17(3), 2004, pp. 235-253.

12. DACLIN, N., CHEN, D., VALLESPIR, B., **Enterprise Interoperability Measurement – Basic Concepts**, Enterprise Modeling and Ontologies for Interoperability, Luxemburg, 2006.

13. EN ISO/DIS 19440, **Enterprise integration: Constructs of Enterprise Modelling**, Draft version, Genève, 2004.

14. GIRALDO, J., GALEANO N., MOLINA A., **Virtual Organization Breeding Environment: Experiences from its Implementation in Mexico**, in preprints of COA'07 - 8th IFAC Symposium on Cost-Oriented Automation, Habana, Cuba, 12-14 Feb 2007.

15. GORANSON, T., JOCHEM, R., NELL, J., PANETTO, H., PARTRIDGE, C., SEMPERE RIPOLL, F., SHORTER, D., WEBB, P., ZELM, M., **New Support Technologies for Enterprise Integration**, IFIP International Conference on Enterprise Integration and Modeling Technology (ICEIMT'02), Kluwer Academics Publisher, Valencia, Spain, 24-26 April 2002, pp. 347-358.

16. DOUMEINGTS, G., VALLESPIR B., CHEN D., **GRAI GridDecisional Modelling**, in Handbook on Architectures of Information Systems, Second Edition, Peter Bernus, Kai Mertins and Günter Schmidt (Editors), Springer Berlin Heidelberg, 1998, pp. 321-346.

17. IST (2002), IST–2001–37368, **Thematic Network, IDEAS: Interoperability Development for Enterprise Application and Software – Roadmaps**, Description of Work, 13-05-2002.

18. KAIHARA, T., **A Challenge Towards VO in Japanese Industry: Industrial Cluster**, in Collaborative Networked Organizations: A Research Agenda for Emerging Business Models, Camarinha-Matos, L.M. and Afsarmanesh, H. (Eds.), Springer Science Publisher, 2004, ISBN: 1-4020-7823-4, pp. 91-96.

19. LOVE G., BACK G., **Model Verification and Validation for Rapidly Developed Simulation Models: Balancing Cost and Theory**, white paper of the Project Performance Corporation, 2002 (see http://www.ppc.com/).

20. MEJÍA, R., LÓPEZ A., MOLINA A., **Experiences in Developing Collaborative Engineering Environments: An Action Research Approach**, Computers In Industry, 58, 2007, pp. 329-346.

21. MICHEL, J.J., **Manufacturing, Modelling and Integration**, Presentation at a meeting of the computer department at CETIM (slides), 1997.

22. MOLINA, A., SANCHEZ, J.M., KUSIAK, A., **Handbook of Life Cycle Engineering: Concepts, Models and Technologies**, Kluwer Academic Press, 1999.

23. MOLINA, A, CHEN, PANETTO H., VERNADAT F., WHITMAN L., **Enterprise Integration and Networking: Issues, Trends and Vision**, in Knowledge Sharing in the Integrated Enterprise, P. Bernus, M. Fox and J.B.M. Goossenaerts (Editors), Springer / Kluwer, 2005, ISBN 0-387-26608-9, pp. 303 – 313.

24. MOLINA, A, MEJÍA R., GALEANO N., NAJERA T, VELANDIA M**., The HUB as an Enabling IT Strategy to Achieve Smart Organizations**, Chapter III in Integration of ICT in Smart Organizations, Istvan Mezgar (Editor), Idea Group Publishing, 2006, ISBN: 1-59140-390-1, pp. 64-95.

25. MOREL, G., PANETTO H., ZAREMBA M-.B., MAYER F., **Manufacturing Enterprise Control and Management System Engineering: Paradigms and Open Issues**, IFAC Annual Reviews in Control, 27 (2), 2003, pp. 199-209.

26. NEMES, L., MO J., **Collaborative Networks in Australia - Challenges and Recommendations**, in Collaborative Networked Organizations: A Research Agenda for Emerging Business Models, Camarinha-Matos, L.M. and Afsarmanesh, H. (Eds.), Springer Science Publisher, 2004, ISBN: 1-4020-7823-4, pp. 97-102.

27. PANETTO, H., BERIO, G., BENALI, K., BOUDJLIDA, N., PETIT, M., **A Unified Enterprise Modeling Language for Enhanced Interoperability of Enterprise Models**, Preprints of the 11th IFAC INCOM2004 Symposium, April 5-7, 2004, Salvador, Brazil.

28. PANETTO, H., **Towards a Classification Framework for Interoperability of Enterprise Applications**, International Journal of CIM, Taylor & Francis, ISSN: 0951-192X, 2007.

29. RABELO, R. J., PEREIRA-KLEN A. A., **A Brazilian Observatory on Global and Collaborative Networked Organizations**, in Collaborative Networked Organizations: A Research Agenda for Emerging Business Models, Camarinha-Matos, L.M. and Afsarmanesh, H. (Eds.), Springer Science Publisher, ISBN: 1-4020-7823-4, 2004, pp. 103-112.

30. TOLK, ANDREAS, **Beyond Technical Interoperability – Introducing a Reference Model for Measures of Merit for Coalition Interoperability**. In Proceedings of the 8th International Command and Control Research and Technology Symposium (ICCRTS), Washington, DC, June 17-19, 2003. Washington DC: Command and Control Research Program (CCRP), 2003.

31. TURSI, A., PANETTO H., MOREL G., DASSISTI M., **Ontology-Based Products Information Interoperability in Networked Manufacturing Enterprises**, Proceedings of the IFAC CEA'2007 conference on Cost Effective Automation in Networked Product Development and Manufacturing, October 5-7, 2007, Monterrey, Mexico.

32. VALLESPIR, B., CHAPURLAT V., **Enterprise Modeling and Verification Approach for Characterizing and Checking Organizational Interoperability**, ETFA2007, 12th IEEE Conference on Emerging Technologies and Factory Automation, September 25-28, 2007 - Patras – Greece.

33. VERNADAT, F.B., **Enterprise Modeling and Integration: Principles and Applications**, Chapman & Hall, London, 1996.

34. VERNADAT, F.B., **Enterprise Modeling and Integration (EMI): Current Status and Research Perspectives**, Annual Reviews in Control, 26, 2002, pp. 15-25.

35. SHORTER, D.N., **Requirements for Enterprise Model Execution and Integration Services**, in: Kosanke K. and Nell J.G. (Eds.) Enterprise Engineering and Integration: Building International Consensus, Springer-Verlag, Berlin, 1997, pp. 235-243.

36. WAND, Y., WEBER R., **On the Deep Structure of Information Systems**. Information Systems Journal, 3, 1995, pp. 203-223.

37. WHITMAN, L., SANTANU, D., **Enterprise Model Repository**, IFAC World Congress Praha 2005, Prague, Czech Republic, July 3-8, 2005.