Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

# Advances in e-Manufacturing, e-Logistics, and e-Service Systems

Milestone report prepared by IFAC Coordinating Committee on Manufacturing & Logistics Systems

**S.Y. Nof[a], F.G. Filip[b], A. Molina[c], L. Monostori[d], C.E. Pereira[e]**

[a]*School of Industrial Eng. Purdue Univ. 315 N. Grant St., West Lafayette, IN 47907-2023 USA*
[b]*Romanian Academy, Calea Victoriei 125, 71102 Bucharest, Romania*
[c]*Tecnologico de Monterrey, Av. E. Garza Sada 2501, N. León 64849 Mexico*
[d]*Comp. & Aut. Res. Inst. Hungarian Academy of Sciences, Kende u. 13-17 H-1518 Budapest, Hungary*
[e]*Electrical Engineering Dept., Federal University of Rio Grande do Sul, Brazil*

**Abstract:** Key problems in manufacturing plant control, modeling and information management, enterprise integration and interoperability, and large-scale complex systems are described. Recent major accomplishments in developing solution methods and tools are reviewed in e-Manufacturing, e-Service, and bio-inspired manufacturing and control; Real-time, cooperative/collaborative enterprises; autonomous, collaborative networked organizations; enterprise integration and processes models; and complex systems-of-systems. The article concludes with emerging trends, applications forecast, and future roles of engineers and managers in manufacturing, logistics and service systems. *Copyright © 2008 IFAC*

**Keywords:** Bio-Inspired Control, Collaborative Control, Complex Systems, Digital Enterprise, Distributed Manufacturing, Enterprise Networks, Large-Scale Systems, Multi-Agent Control, System-of-Systems.

## 1. INTRODUCTION

Recent developments in manufacturing and logistics systems have been transformed by the influence of information and communication, e-Work and e-Service collaboration and wireless mobility, enabling better services and quality to consumers and to communities, while bringing new challenges and priorities. The transformative influence of e-Work on manufacturing and logistics can be described by this quote: “As power fields, such as magnetic fields and gravitation, influence bodies to organize and stabilize, so does the sphere of computing and information technologies. It envelops us and influences us to organize our work systems in a different way, and purposefully, to stabilize work while effectively producing the desired outcomes” (Nof, 06a).

Surveys of emerging e-Work applications since the previous Milestone Report of this Committee (Nof et al., 06) range from human-agent-robotic machine cells, maintenance and logistics networks, multi-nanosensor arrays and networks, multi-robot teams, supply and distribution networked enterprises, to collaborative virtual networked organizations. Observations indicate several common characteristics of emerging manufacturing and logistics with strong emphasis on service engineering, and several new principles and foci for their design. (Fig. 1, 2).

In this Milestone article, we review the main emerging control and automation problems, challenges, recent developments and future opportunities and directions in this area.

## 2. KEY PROBLEMS

### *2.1 Manufacturing Plant Control*

Applications of automation, information and communication to control manufacturing plants within e-enterprises address scientific challenges. The purpose is intelligent control and integration of MEMS (micro-electromechanical systems), mechatronics, MES (manufacturing execution systems), MAS (multi-agent systems, HMS (human-machine systems) and e-technologies to digitally control with more agility the entire manufacturing chain, from design through manufacturing, to maintenance and service, over the whole product and processes life cycle (e.g., Raffler, 07). This emerging new area is sometimes termed “digital manufacturing.”

The main active topics include: Modeling and experiments of production and logistics over enterprise networks; manufacturing automation over networks; dependable systems and collaborative control; discrete event systems control; e-facilities. Several themes that have received attention are:

• *Intelligent Manufacturing Systems*: This direction seeks new solutions for manufacturing control that merges know-how from control engineering, software engineering and complex systems/artificial life research. New designs promise scalability, reusability, integrability and robustness. Recent efforts focus on broad efforts of concepts’ validation on industrial test cases. A suitable benchmarking platform is being developed. More fundamentally, concepts of emergent and self-organizing systems, often in designs inspired by biological systems, are addressed.

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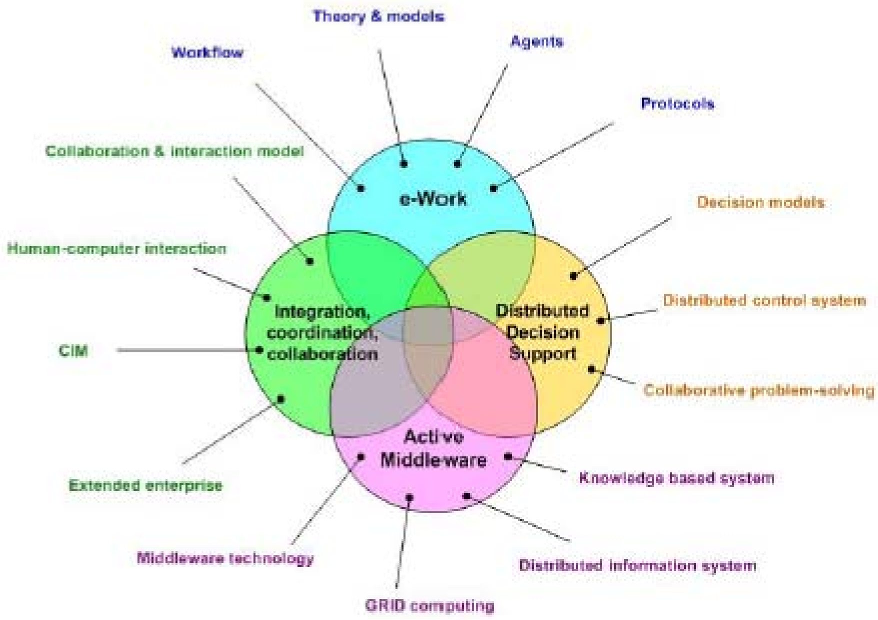



Fig. 1. e-Work, e-Production, e-Service: The four wheels of e-Work (Nof, 06b)

• *Dependable Manufacturing Systems*: Problems of dependability are driven and supervised by hardware and software controllers that usually communicate through networks. The main interest are: Formal description techniques for design, implementation and validation of system components and communication systems; Safe and secure algorithms and middleware (software/hardware bridging separate subsystems, creating systems-of-systems); Dependability and mode management in networked automation.

• *Networked, Collaborative Manufacturing Systems*: In an effort to significantly improve effectiveness and quality of service in a global economy, there is increased interest in solving problems of 'automation over and with networks'. This scope includes distributed automation systems. Problems include: Design, programming, operation and diagnosis of automation behavior in distributed environments; Industrial informatics methods for embedded devices and sensors; System integration models, configuration and parameterization for communication connected devices; Heterogeneous (industrial and private) networks, called VAN (Virtual Automation Networks) to provide automation-based Quality of Services; Life cycle aspects for distributed automation systems and remote maintenance.

• *Agent-based decentralization of automation*: Increasing autonomous behavior and self-X ability (self-recovery, self-configuration, self-healing, self-protect, etc.); Increased abstraction level (from signals, to data, to information, to knowledge, to decision or wisdom); Integrated solutions for MES, LES (logistics execution systems), warehousing, etc.

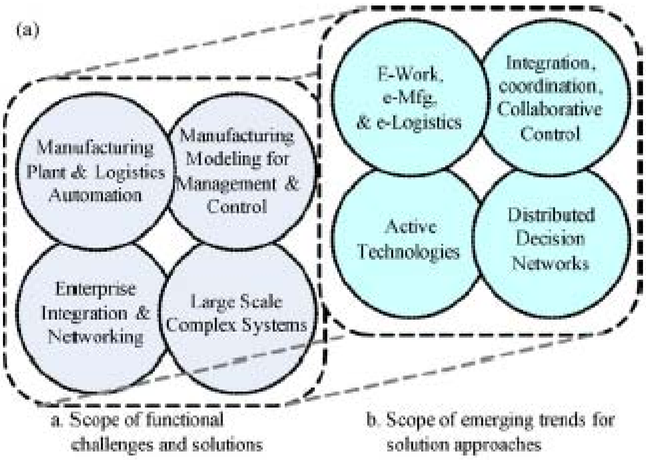
Typical application areas include high-performance and zero-breakdown manufacturing and logistics systems and services, smart building/home automation systems, energy aware control/ automation systems, closed-loop product life-cycle management (PLM), and intelligent healthcare systems.

### *2.2 Manufacturing Modeling for Management & Control*

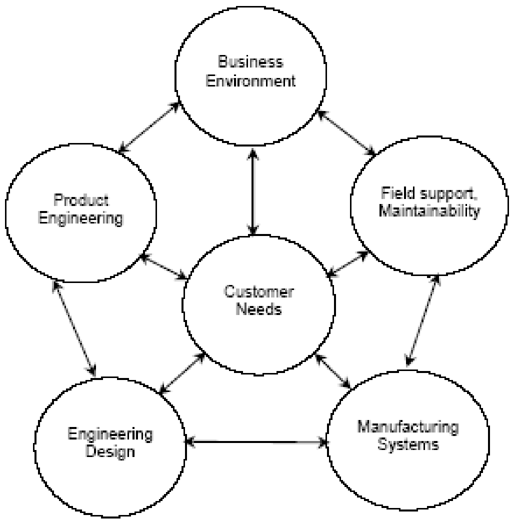
Three main overlapping issues continue to be of high interest: Real-time, collaborative enterprises; Production evolutionary structures, e.g., Complex Adaptive Systems, and Autonomous manufacturing and logistics systems.

The 2005 Milestone report of the IFAC CC5 (Nof, et al., 06) underlined the key problems, such as management of complexity, scalability, increasing costs, coordination, market-based resource allocation, and more. Recent accomplishments and trends were also discussed, and have been further investigated since then. Manufacturing systems now work in a *fast changing environment* full of *uncertainties*. Increasing *complexity* is another feature showing up in production processes and systems, and in enterprise structures. A recent area of interest relates to *globalization* of production. *Production networks* (*PNs*) are formed from independent companies collaborating by shared information, skills, and resources, driven by a common goal of exploiting market opportunities.

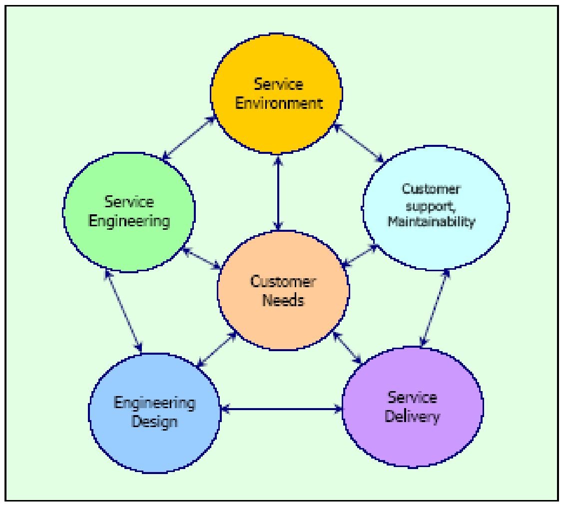
The *digital enterprise*, i.e., mapping the key enterprise processes to digital structures by means of information and communication technologies (ICT) gives a unique way of managing the above problems. With recent ICT advances, theoretically, all the important production-related information is manageable in a controlled, user-dependent repository. The optimal or near-optimal exploitation of this vast information, however, cannot be imagined without effective application of methods and tools of *artificial intelligence* (*AI*), sometimes, more specifically, *machine learning* (*ML*) techniques. Agent-




2a. Scope of e-Production challenges and solutions (Nof et al., 06)




2b. Concurrent engineering – manufacturing oriented (after Sanchez et al., 94)




2c. Collaborative engineering– service oriented

Fig. 2. Scope of e-Production and e-Service: Design and engineering concerns (Nof, 07)

based (holonic) systems are also highlighted as promising tools for managing complexity, changes, and disturbances in production systems (Monostori et al., 06).

*2.3 Enterprise Integration and Networking*

New industrial paradigms have emerged in recent years as an answer to fast changing socio-economic challenges, such as the lean enterprise, agile manufacturing, fractal factory, and holonic manufacturing. Emergence of virtual enterprise/virtual organizations falls in the natural sequence of these evolution processes searching for alliance when additional skills/resources are need to fulfill business opportunities creating collaborative networks of the best available competencies.

• **Collaborative networked organizations**: A new area has been defined as Collaborative Networked Organizations (CNOs), representing a new dynamic world based on cooperation, competitiveness, world-excellence, and agility. A CNO identifies and exploits new business potential, boosts innovation, and increases collaborative competencies. Research and education of CNOs represents a new trend to pursue global collaboration; learning and technology transfer to build the knowledge-based society. Collaborative entertainment networks (an emerging social networking culture especially with teenagers), collaborative remote diagnosis, collaborative problem solving and data mining, and virtual institutes for education and research are some prominent examples. Understanding the structure and associated behavior of these collaborative forms, and the required infrastructure, support tools, regulations and operating principles, economic models, and support institutions, are major new research issues.

• **Enterprise Modeling, Reference, and Interoperability**: Various modeling techniques have emerged to cover enterprise-modeling needs. Interoperability among them is challenging and limited. Most of these modeling tools are


Fig. 3. Automation and control for mining, manufacturing, logistics and services in CODELCO, Chile (clockwise): Driverless mining via GPS; help center; logistics and wireless communication center; robotic quality assurance; application co-design; control lab and training hall (Cerda, 07).

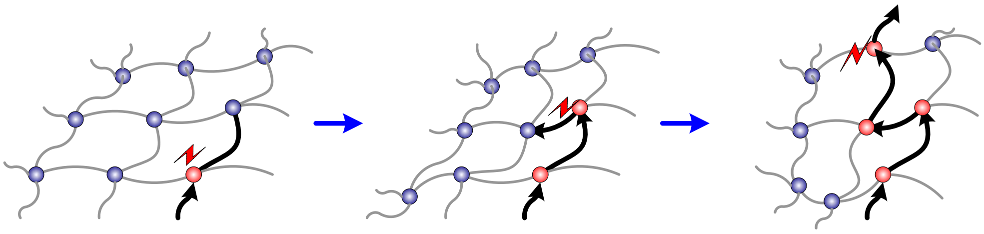


Fig. 4. Bio-inspired network models for collaborative control: Cascading causality (propagation) leading to changes in both arteries and network structure (Nof, 07)

merely graphical model editors, lacking analysis functions and built-in rules. Unified languages have therefore been developed as consensus such as PSL (Process Specification Language) for manufacturing processes, supported by NIST (National Institute of Standards & Technology) in the US, and UEML (Unified Enterprise Modeling Language) for business processes, supported by EU. Further developments are necessary to better consider human and organizational aspects. Several frameworks for enterprise interoperability have been developed recently to identify and structure dependencies, problems, and interoperability knowledge. Future work will be to compare these different frameworks, to harmonize their concepts and possibly to federate them into one consistent and unique framework.

### *2.4 Large-Scale Complex Systems*

Large-scale, complex systems include continuous/ discrete manufacturing and services, water and power systems, and communication and transportation networks. Key problems are that increasingly, systems of interest are characterized by higher complexity, uncertainties, non-linearities, high dimensionality, time-delays, and networked structure of interconnected systems and system-of-systems with multiple technologies. Traditionally, system decomposition and model reduction methods have been applied with hierarchical optimization and decentralized control. But the complexity features now lead to severe difficulties in analyzing these systems, designing and implementing appropriate control and decision strategies. Several methodologies have been advanced to cope with these challenges. Promising approaches rely mainly on integrating decoupling, decomposition, approximation and robustness, decentralization, coordination, cooperation, and collaboration. A recent extension of these methodologies is directed towards including communication issues in the feedback.

## 3. RECENT MAJOR ACCOMPLISHMENTS

### *3.1e-Manufacturing, e-Service, and Bio-inspired Manufacturing and Control*

One of the most prominent achievements recently in emerging automation and automatic control has been the ability to integrate manufacturing and logistics with services. It relies on the maturity and experience gained in integration and in collaborative control, as well as better understanding of fundamental processes, including bioprocesses. An interesting example is CODELCO, Chile (Fig. 3) where bioprocessing enriches copper ores in-site before they are mined, packaged and delivered by integration of e-Production and e-Logistics.

Bio-inspired control and optimization have continued to evolve, including swarm-based, bio-tracking and evolutionary algorithms and protocols applied for control, optimization, decision-making, and network modeling for collaborative control (Fig. 4).

### *3.2 Real-time, Cooperative/Collaborative Enterprises*

Four main directions have continued to attract attention (e.g., Manufuture initiative in Europe, among many others): adaptive manufacturing, digital manufacturing, knowledge-based manufacturing, and networked manufacturing. Two key requirements of the whole system are real-timeliness (ability of recognizing and acting on internal and external changes and disturbances within the required timeframe) and cooperativeness: complex production structures – from machine tools, robots, etc. to production networks, including humans involved – are increasingly designed as autonomous but cooperative/ collaborative entities. (They are collaborative when in addition to cooperation they also share in value-added activities, e.g., airline alliances, supply partners, etc.) A major trend in manufacturing now is customized mass production: producing customized products at a price near to the level in mass production. The main challenges: research and development of solutions from production networks level through single enterprises to production lines, ensuring optimal/near-optimal delivery, and moreover, in real-timeliness as required by given customers.

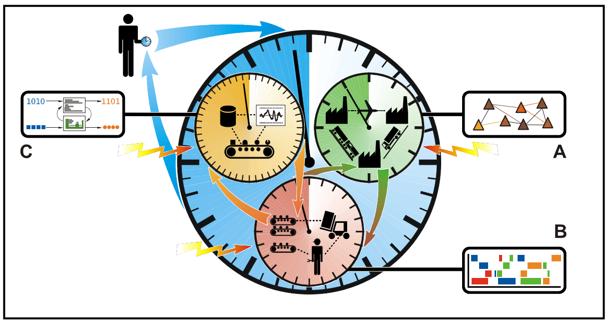



Fig. 5. Real-time cooperative enterprises for customized mass production (Monostori et al., 06)

The problems to be solved include: Integrated production planning and scheduling (B), real-time production control (C), and management of distributed, cooperative/collaboration systems (A). The following R&D issues are being addressed:

• *Integrated production planning and scheduling*: Mathematical models and combination of operations research (scheduling theory, linear and integer programming) and artificial intelligence (constraint programming); estimation of solutions' goodness; parametric, scalable modules for production optimisation; systems to be installed for use as e-service.

• *Real-time production control*: Modeling of disturbance and change sensitivities; automatic situation recognition and related problem solving, decision support; machine learning; reactive and proactive rescheduling algorithms, and production control support systems; integration of active identifiers (e.g., RFID) into production control.

• *Management of distributed, cooperative systems*: Multi-agent systems; ontologies for exchanging production-related information; negotiation mechanisms and communication protocols; models for describing production networks, behaviour networks analysis, and efficient behaviour patterns.

**Production structures as Complex Adaptive Systems**

The theory of *Complex Adaptive Systems* (CAS) by Holland attempts to study the structures and dynamics of systems focusing on how their adaptability creates complexity. A CAS can be considered as a multi-agent system with seven basic elements in which any given adaptive agent can consist of and interact with other adaptive agents. Four of the seven basic elements characterizing agents, aggregation, non-linearity, flow, and diversity, are important in adaptation and evolution, while the other three, tagging, internal models, and building blocks, are agent mechanisms for communicating with the environment. Environmental conditions are changing, due to agents' interactions as they compete/ cooperate for the same resources or for achieving a given goal. The most remarkable phenomenon exhibited by CAS is the emergence of highly structured collective behaviour over time by the interaction of simple subsystems, usually, without any centralized control, for instance, dynamics involving interrelated spatial and temporal effects, correlations over long length- and time-scales, strongly coupled degrees of freedom and non-interchangeable system elements, etc. Both the CAS and its environment simultaneously co-evolve in order to maintain themselves in a state of quasi-equilibrium, i.e., on the edge of chaos. Production structures can be considered as complex adaptive systems, as manufacturing systems presently work in a *fast changing environment* full of *uncertainties*. Increasing *complexity* is another feature showing up in production processes and systems, furthermore, in enterprise structures, including supply chains and production networks. According to a recent, comprehensive survey on agent-based systems for manufacturing (Monostori and Ueda, 06), their further evolution will proceed hand in hand.

In designing CAS, non-linear phenomena, incomplete data and knowledge, a combinatorial explosion of states, dynamic changes in environment and the frame problem are some notable examples of difficulties to be solved. One can benefit from the knowledge of how to manage such systems with an appropriate *balance between control and emergence*.

**Autonomous manufacturing and logistics systems**

Autonomous manufacturing, logistics and service systems correspond closely with agent-based systems and depend heavily on embedded systems (Pereira and Carro, 06). An underlying topic of interest has been AutoID-based tracking and tracing (Kemény et al., 07). Recent trends are marked by a growing demand for improved *observability* in processes, due to product customization, customers beginning to demand better up-to-date information about the products they order, and for efficient handling of quality feedback and tracking. Aside from changing demands, the typical structure of industrial production is undergoing changes: Often, companies are not involved in a fixed *supply-chain*; instead, they take part in *supply networks*, where participants team up only for the procurement of a single product and may even act as competitors in other cases. All this calls for measures which can securely deliver timely and error-free information about material flow in production; even at the level of individual work-pieces. Two related activities are:

1. *Tracking* – observing the spatial motion of an entity, e.g., by *checkpoint and time-stamp* pairs, or *spatial coordinates* (GPS data, length of path travelled, etc.) Tracking is mainly used for providing information about the advance of a given shipment.

2. *Tracing*, focusing on changing relations with the production environment, including other components the given entity may enter a relation with, e.g., assembly of a product from sub-components or mixing of materials. Mainly for quality control and warranties.

### *3.3 Collaborative Networked Organizations*

Collaboration network organizations (CNOs) continue to grow, including virtual organizations and virtual enterprises, dynamic supply networks, professional virtual communities, collaborative virtual laboratories, global research and collaborative education with a wide spectrum of application domains. Key challenges in the area 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 approaches and decision models for the creation and support of sustainable CNOs, to foster innovative products and business processes based on collaborative paradigms.

• Development of new applications, architectures, and infrastructures to support CNOs.

Empirical studies have been conducted to demonstrate how companies can be created and operated as CNOs. New approaches for the development of collaborative environments have been presented based on the concept of Action Research (Molina et al., 06; Mejia et al., 07). Hubs that integrate the necessary e-services have been created to support the creation and operation of CNOs.

**Enterprise Integration 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 for the future. Frameworks for enterprise interoperability have been developed to identify and structure problems and knowledge on interoperability (Chen and Daclin, 06). Emerging work compares different frameworks (Panetto, 07) to harmonize them and possibly federate them into a consistent, unique framework.

There is a new trend to develop Model Driven Interoperability (MDI) based on MDA (Model Driven Architecture). Standardization efforts include ISO 15531 MANDATE, a reference model for information and resource views of manufacturing; IEC 62264 series standard for production management and control. Recently, a European Technical Specification (CEN TS 14818: Decisional Reference Model) has been approved (Chen, 05). A significant initiative to develop interoperability between process models is ISO CD 18629 - Process Specification Language (PSL ontology), but efforts are still needed for effective implementation in industry (Whitman and Panetto, 06).

Enterprise Integration (EI) is also becoming a reality for many companies, especially networked companies or enterprises in large supply-chains (extended or virtual enterprises). Major projects for enterprise integration have been conducted in Europe (AIT Initiative) and in the US (EIF, Enterprise Information Framework; NIIIP, National Industrial Information Infrastructure Protocols; NGM, Next Generation Manufacturing). The problem is that EI is both an organizational problem as well as a technological problem.

The technological problem has been the focus of major advances over the last decade, mostly concerning computer communications technology, data exchange formats, distributed databases, object technology, Internet, object request brokers (ORB such as OMG/CORBA), distributed computing environments (such as OSF/DCE and MS DCOM), and now J2EE (Java to Enterprise Edition and Execution Environments), .NET, and Web services. Projects for integrating infrastructure (IIS) technology for manufacturing environments continue. EI must be seen as a goal, not a solution, to continuously progress towards more integrated enterprises.

In a recently published roadmap by European Commission to develop enterprise interoperability under Framework 7 four Grand Challenges have been identified that offer a long-term strategic direction for Enterprise Interoperability: Interoperability Service Utility (ISU) as a commodity function, independent of particular IT deployment; Leveraging web technologies and improved services for EI; Knowledge-oriented collaboration to enable mutual benefit of

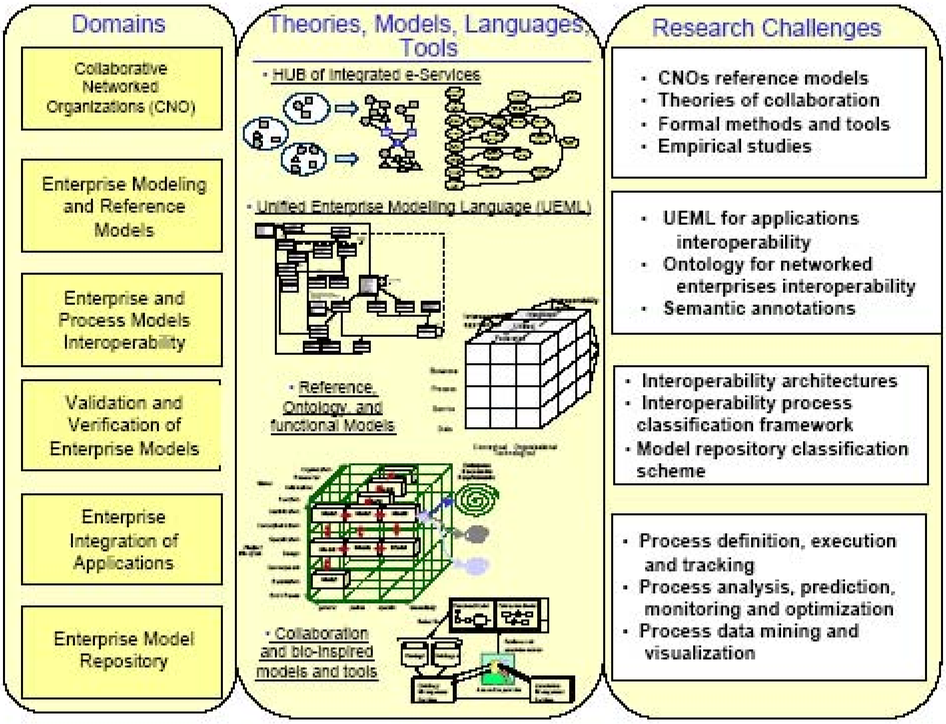



Fig. 6. The scope of emerging challenges in enterprise integration and interoperability.

virtual organizations partners; Science base for EI with a view to long-term problem solving.

Facing new challenges, Enterprise Modeling has to address and provide concepts, tools and techniques for achieving verification, validation, qualification and accreditation (Chapurlat and Braesch, 06). Future trends in enterprise integration and modeling would be toward loosely-coupled interoperable systems rather than high-cost monolithic solutions and low-success holistic integration projects (Fig. 6).

### *3.4 Large-scale, complex systems and systems-of-systems*

New developments in our increasingly information rich and interconnected world will require a significant expansion of basic tools in control, decision, and risk analysis. The development of these tools is motivated by their insufficiency with respect to the increasing complexity of recent emerging technologies and social expectations in global markets.

**Tools – emerging trends**: Serious efforts address the lack of relevant theoretical and methodological tools to support the scalable solution of new networked complex large scale problems including asynchronous issues. Recent accomplishments are aimed at broadening the scope of dynamic interaction coordinator design to ensure the desired level of interconnections (Šiljak et al., 06); advances decentralized control strategies for complex switching systems; hybrid large scale systems and Petri nets; large scale supply decentralized coordination (Inalhan et al., 06); distributed control systems with network communication (Langbort et al., 06). Advanced control strategies are also being extended into new areas such as flexible structures (Bakule et al., 06), hydrographic systems, and many others.

These achievements can be progressively extended into integrated/embedded control, distributed control over communication networks, hybrid/discrete-event systems and networks, and autonomous systems to solve various manufacturing and service challenges.

**From Coordination to Cooperation in Large-Scale Complex Systems Control**

Nowadays there is a growing trend to understand the design, management and control aspects of complex "super systems" or systems of systems (SoS). Systems of systems can be found in space exploration, military and civil applications such as: computer networks, web-based services, integrated education systems, air transportation systems, and more. There are several definitions of SoS, most of them articulate the context of particular applications. For example, some define SoS as a non-monolithic entity that possesses the majority of the following characteristics: geographic distribution, operational and management independence of its subsystems, emergent behavior and evolutionary development.

Unlike management and control schemes developed in the past with pure hierarchies, the more recent solutions exhibit increased communication and cooperation capabilities of the management and control units. For example, in 1977 Binder introduced the concept of "decentralized-coordinated control with cooperation", which allowed limited communication among control unit placed at the same level. Hatvany in 1985 proposed the heterarchical scheme, allowing information exchange among units placed at various levels of the hierarchy. The term *Holon*, articulated first by Koestler in1967, implies an organization scheme able to explain the evolution and life of biological and social systems. A holon cooperates with other holons to build up a larger structure (or solve a complex problem) and, at the same time, it works toward attaining its own objectives and handles the various situations it faces without waiting for instructions from higher-level entities. A holarchy, a hierarchy made up of holons, can combine respective benefits of hierarchical, heterarchical, and collaborative control. New methods based on multi-agent systems can increase the autonomy, cooperation and collaboration among various decision and control units and are increasingly viewed as the approach that can help automatic control of large scale, complex systems (e.g., Duviella et al., 06). An intelligent software agent encapsulates its code and data and is able to act in a proactive way and interact with other agents to form a community (society). Control structures utilizing agent technology have the advantage to incorporate existing legacy systems that can be encapsulated in and served by specific agents. Promising new forms of coordinating and anticipating the actions of the intelligent agents at different levels of complex systems, and systems-of-systems, have been demonstrated and validated, and continue to evolve for industrial solutions.

## 4. SUMMARY AND CONCLUSIONS

This article summarizes major recent development in automation and control aimed at solving the challenges encountered by manufacturing, logistics, and services in this new century. Global trends in information and communication, in enterprises, enterprise integration, and networking social systems introduce daily more complex challenges. Observing these recent developments, emerging trends in manufacturing, logistics and service systems have been compiled by IFAC-CC5 (Jamsa-Jounela et al., 06) and in the discussion above:

a) Multi-level collaboration and "ambient Intelligence" in human-centered organizations and life-cycle management – motivated by benefits from respective strengths of participants;

b) More autonomy, adaptivity and self-X-ability, e.g., self-recover, self-repair, self-protect – for faster response, safety, and unmanned maintenance;

c) Agent-based decentralization of decision and control with anticipation in networked systems – aimed at better management of globalization while mastering complexity;

d) Integrated knowledge-based modeling and simulation of an entire system and its supply and demand network – for effective planning and execution

e) Real-time, collaborative control mechanisms embedded at every level of the control hierarchy – for interoperability through open-source integration platforms

f) Innovative, improved flexibility, e.g., in human - automata interaction, energy trading, telematics in transportation – since optimized global interaction is key to sustainability.

Applications forecast for manufacturing, logistics and service systems include:

- Enhancing prediction and decision-making in managing networked business, manufacturing and logistics, and other socio-economic organizations;
- Improving the safety and security of critical infrastructure including transport systems, power grids, and water distribution;
- Global environment monitoring and early warning systems for natural disasters (earthquakes + tsunami, floods, etc.);
- Development of sustainable "green" technologies;
- Intelligent healthcare systems, including prevention, diagnosis, and therapeutics;
- Autonomous assembly, smart factory, building, and home automation with high-performance, zero-breakdown, and energy-aware control.

Based on the above observations, the view of future roles for engineers and managers in manufacturing, logistics and service systems ("Engineer 2020") is as follows:

1) Manage changes, uncertainties, complexity and adaptiveness – to avoid introducing 'artificial' limitations, and relax constraints to manufacturing, logistics and services;

2) Address both problem formulation and problem solving; learn to predict things as well as analyze them

3) Apply intelligent data mining for information and knowledge-rich decision objectives vs. conventional data-rich computing approach;

4) Use active learning and education technology to enhance collaboration, knowledge sharing and reuse of models/ techniques/ best practices;

5) Develop and apply formal engineering methods to support validation and verification of enterprise and multi-enterprise models.

6) Establish and embrace diversity considerations and standards for factory, enterprise, supply-network and socio-economic organization models -- metrics for benchmarking are needed.

## ACKNOWLEDGMENT

The authors wish to thank our colleagues and members of the IFAC Technical Committees and Technical Board, who have contributed significant ideas for the development of this article. Thanks also to the reviewers who helped us improve the quality of this article. In addition, each of us wishes to thank our colleagues and graduate students in our respective institutes, whose great ideas have also enriched this work.

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