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Manufacturing plant control challenges and issues

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Abstract

Enterprise control system integration between business systems, manufacturing execution systems and shop-floor process-control systems remains a key issue for facilitating the deployment of plant-wide information control systems for practical e-business-to-manufacturing industry-led issues. Achievement of the integration-in-manufacturing paradigm based on centralized/distributed hardware/software automation architectures is evolving using the intelligence-in-manufacturing paradigm addressed by IMS industry-led R&D initiatives. The remaining goal is to define and experiment with the next generation of manufacturing systems, which should be able to cope with the high degree of complexity required to implement agility, flexibility and reactivity in customized manufacturing. This introductory paper summarizes some key problems, trends and accomplishments in manufacturing plant control before emphasizing for practical purposes some rationales and forecasts in deploying automation over networks, holonic manufacturing execution systems and their related agent-based technology, and applying formal methods to ensure dependable control of these manufacturing systems.

Keywords: Manufacturing plant control, networked automation, intelligent manufacturing systems, dependable manufacturing systems, education.

1 Manufacturing Plant Automation Context

Manufacturing enterprises are intensively deploying a host of hardware and software automation and information technologies to meet the changing societal environment required by the increasing customization of both goods and services desired by customers.

Legacy models and standards^{1,2} enable manufacturing enterprise control system integration and interoperability (Table 1) from the business level to the process level, to meet industry-led Business-to-Manufacturing (B2M) issues (Panetto *et al.*, 2006).

Table 1: Enterprise Control System Integration in Manufacturing

B2M Systems Integration	
CRM	Customer relationship management
SSM	Sales services management
APS	Advanced planning system
SCM	Supply chain management
ERP	Enterprise resources planning
MES	Manufacturing execution system
SFC	Shop floor controls
MECHS	Mechatronic systems
MEMS	Micro mechanical systems
AUTO ID	Automatic identification

The resulting automation model (Fig. 1) is a wide network of automata that is challenging researchers and developers to achieve synchronic (in time) integration of shop-floor process controls in the large (robotics, assembly, machining, ...) into plant-wide information control systems and diachronic (through time) integration of product life cycles over the manufacturing chain, as addressed by the overall Integration in Manufacturing (IiM) paradigm.

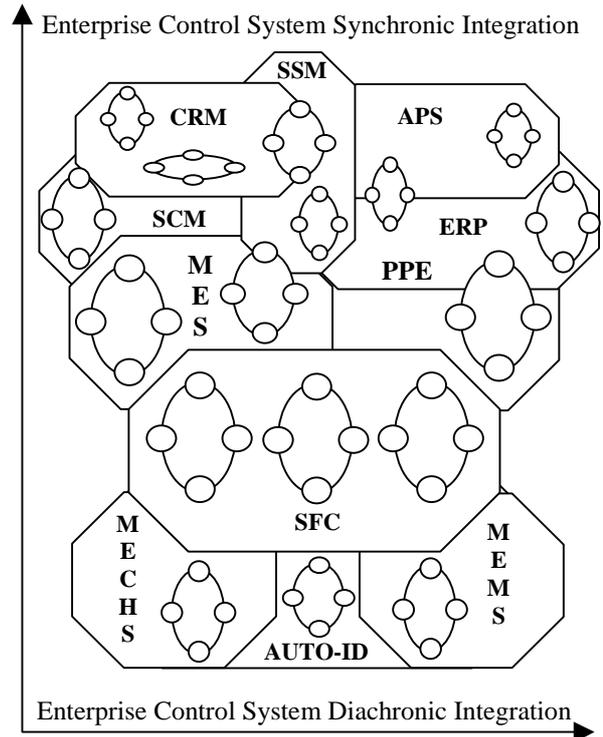


Fig. 1: IiM plant-wide automation context

Although web-enabled technologies are strengthening distributed automation in manufacturing (Banaszak and Zaremba, 2003), the pivotal technology will require a form of technical intelligence that goes beyond simple data, through information to knowledge. This will be embedded in manufacturing system components and within the products themselves, and will make it possible to meet agility in manufacturing over flexibility and reactivity, as addressed by the shifting Intelligence in Manufacturing (IiM) paradigm. This complexity of efficiently deploying interoperability and autonomy for manufacturing plant control and production management issues is challenging the industry-led international Intelligent Manufacturing Systems³ (IMS) initiative that will define, develop and deploy the next generation of open, modular, reconfigurable, maintainable, and dependable manufacturing systems.

The IFAC Coordinating Committee on Manufacturing and Logistics Systems (Ollero *et al.*, 2002, Nof *et al.*, 2006) and the IFAC Technical Committee on Manufacturing Plant Control contribute to promoting the related scientific challenges of intelligent manufacturing systems (Monostori *et al.*, 2003, Morel and Grabot, 2003), intelligent assembly and

¹ www.mesa.org; www.omg.org/mda

² IEC62264, 61499, 61131
www.opcfoundation.org www.mimosa.org
www.isa.org

³ www.ims.org

disassembly (Borangiu, 2003) and of information control problems in manufacturing (Kopacek *et al.*, 2005).

This special issue deals with some current key problems and applications, recent major accomplishments and trends, and the main research–development forecasts related to information control in the field of networked manufacturing automation (Section 2), IMS modeling and experiments (Section 3), dependable control of discrete systems (Section 4), and education and training (Section 5). The conclusion (Section 6) of this introductory paper addresses some rationale issues among the many that are complementary to those of this special issue and that should be debated.

2 Networked Manufacturing Automation

There is an increasing deployment of web technology to monitor the ubiquitous coherence between the physical flows of goods and the related information flows of services throughout product life cycles in production and logistics networks.

These networking issues involve the two-dimensional integration of automation (Galara and Hennebicq, 1999) for both vertical (synchronic) integration through the IEC/ISO 62264 standard for B2M applications and the IEC 61499 standard for SFC applications as well as horizontal (diachronic) integration through e-manufacturing de facto standards for SCM and CRM applications.

Among these interoperability issues between e-manufacturing applications, Neumann addresses in this special issue *what is going on in communication in industrial automation* to control the communication problems that arise from this increasing impact of the worldwide distribution of the Internet on the manufacturing automation domain.

2.1 Current key problems

Embedding distributed technical intelligence (data and information processing, storage and communication) into field automation has been studied extensively to enable actuation and measurement system interoperability as well as to ensure control, maintenance and technical management system integration (Iung *et al.*, 2001). Among many rationales to assess and predict the performance degradation (Leger and Morel, 2001) of a process, a machine or a service, on-site and remote infotonics components can be merged in a closed device-to-business loop to move from traditional *fail and fix to predict and prevent* practices (Erbe *et al.*, 2005). Embedded accurate algorithms improve the precision of

customized information and enable the prognosis of when the performance is becoming unacceptable, the diagnostic of why the performance is degrading and the decision as to what maintenance action to perform as well as the performance benchmarking coming from similar operating *Watchdog Agents*TM (Lee, in Kopacek *et al.*, 2005).

Another major technological challenge in the development of distributed embedded systems is to guarantee both the reliability and the temporal predictability of the underlying software and hardware infrastructures, which must be flexible enough to accommodate the requirements imposed by new applications and services. Vertical communication at the control level and horizontal communication between elements in the factory hierarchy must also be managed.

Finally, the efficient use of these promising mechatronics, infotonics and communication technologies is highly dependent on dealing with the complexity of intelligently combining a host of existing techniques for global rather than local performance. These engineering issues require field device metamodels to integrate the devices in the entire engineering life cycle of the automation system (Diedrich *et al.*, 2001). The de facto industrial Unified Modeling Language (UML) is the candidate for designing distributed automation architectures in a collaborative and multidisciplinary way, and there are several so-called UML profiles being promoted. Special profiles for real time, safety and dependability must be evaluated carefully, such as the following.

- Profile for schedulability, performance, and time specification.⁴
- Profile for modeling quality of service and fault-tolerance characteristics and mechanisms.⁵

2.2 Recent major accomplishments and trends

Networked controlled systems should integrate all new technologies such as wireless networks, embedded systems, nomad components and electronic tags, to meet new requirements such as mobility, modularity, control and diagnosis decentralization or distribution, autonomy and redundancy, allowing quick and easy maintenance.

A major industrial communication challenge of the related multilevel communication architectures is to unify plant networking with

⁴ <http://www.omg.org/docs/formal/03-09-01.pdf>

⁵ <http://neptune.irit.fr/Biblio/02-01-02.pdf>

Ethernet. The resulting automation challenge is to guarantee the same deterministic features as those of more specific fieldbuses currently applied in shop floor manufacturing.

That opens a new field of applications for intelligent control techniques to model, evaluate and optimize the communication system behavior within distributed automation architectures.

For example, applying fault detection and isolation/fault tolerant control (FDI/FTC) techniques to networked control systems (Fig. 2) should improve safe control and monitoring of such complex automation systems as well as their global reliability, dependability and availability, by dynamically accommodating network performance, reconfiguring network components and adapting the application to the delivered quality of service (Georges *et al.*, 2006).

The huge investment in Ethernet-based industrial communications by the main industrial players (e.g., PROFINet by Siemens, Industrial IP by Rockwell, and Modbus IP by Schneider) is a challenge for researchers, because large distributed systems with new characteristics and new opportunities are being built. These systems must be configured, parameterized, operated and maintained with real-time, safety and security constraints.

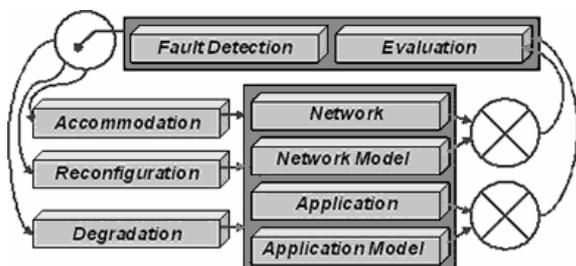


Fig. 2: Networked control systems tolerant to faults⁶

2.3 Forecasts

In future, specific industrial communication techniques and other commercial communication systems such as telecommunication for maintenance and remote access or private networks can become components of these systems. Systems that cross intranet borders or wide area networks are virtual automation networks with new quality-of-service challenges and new management tasks. In detailing real-time constraints, safety and security are the main requirements for the new architectures; technology combinations will require the joint

research efforts of the automation and communication communities to prevent networks becoming the Achilles' heel of embedded and distributed manufacturing automation.

These networked automation issues are challenging the traditional centralized-architecture hierarchical-model control approaches (Table 2, levels 2 and 3) to meet interoperability and agility in manufacturing (Table 2, levels 4 and 5).

Table 2: Capability profile between system architecture feature and the related theoretical and technical modeling framework (Morel *et al.*, 2003)

System Architecture Feature	Theoretical and Modeling Paradigms
5. Intelligent	Kenetics, MAS, HMS
4. Interoperable	Cognitics, Ontology, Object-Oriented
3. Integrated	Systemics, Systems Engineering
2. Hierarchical	System Theory, Automatic Control
1. Isolated	Empiricism, Ad hoc approaches

3 IMS Modeling and Experiments

Intelligence in manufacturing is perceived in various ways ranging from intelligent control and information communication techniques through human intelligence in the operating/engineering loop (Lhote *et al.*, 1999) to agents' self organization.

The area of intelligent systems is challenging—to an extent occasionally verging on controversy—both the research community and the industrial sector to cope with the traditional and centralized automation approaches to meet the high degree of complexity and practical requirements for robustness, generality and reconfigurability in manufacturing control as well as in production management, planning and scheduling.

Among many rationales, trends and experiments, a general consensus exists that holonic manufacturing systems (HMS) should be the unifying technology as well as the product-process engineering (PPE) approach for all product-driven control and management issues required by the customized manufacturing era (Muhl *et al.*, in Morel and Grabot, 2003, Cheng *et al.*, 2004).

3.1 Current key problems

Today, the key problem is the lack of tools and/or platforms to test and validate IMS developments on realistic problems, in terms of both the size of the manufacturing system itself and the thoroughness of the evaluation techniques. Concerning advanced manufacturing control, conceptual designs exist that address the major research issues, at least in principle, for

⁶ (www.strep-necst.org)

instance Valckenaers (in Morel and Grabot, 2003). The complexity of these system designs makes formal proof of their performance and capabilities infeasible and definitely impractical.

Therefore, an environment is required in which the research community can provide and retrieve (emulated) test cases of realistic size and complexity; in other words, research developments must be tested in real-world factories (in emulation) in place of the toy test cases and token evaluation campaigns that remain the norm. Moreover, the evaluation campaign must answer industrial requirements, which typically implies that test runs must cover several months of production. Evidently, IMS systems must be properly designed to allow drawing hard conclusions from test runs; for instance, a manufacturing control system design must randomize parameters and decisions as a default. The IMS network of excellence⁷ has started to make such an environment available for advanced manufacturing control and supply network coordination. Valckenaers *et al.*, in (Panetto *et al.* 2006), describe the development status and roadmap for this research effort which will equip the IMS community with a benchmarking service. Such testing and evaluation platforms will enable researchers to generate solid proofs of concept for their research results with normal levels of development efforts and resources.

Secondly, there is a need for better and deeper understanding of scalability and robustness, typically only achievable through designs that use emergence and self-organization. These designs give up the ability to prescribe explicitly how the system will behave in return for a significant increase in operating range. The analogy in human organizations is to replace explicitly prescribed procedures (cookbook rules) by empowerment of the people performing the work. It is well known that empowerment produces superior results, given adequately skilled personnel. This shift toward empowered elements in an IMS system requires further research for deeper insight on how this shift can be executed and what benefits can be expected. In other words, better understanding of the concepts of emergence and self-organization is necessary, especially in the design of such systems (synthesis of IMS artifacts).

Finally, research must address information handling in sophisticated IMS designs, with traceability as a primary concern. Manufacturing control systems already provide the potential to address this issue, but it should be brought to the

surface, and the need for additional support that transpires must be answered.

3.2 *Recent major accomplishments and trends*

Recently, research on applying multiagent systems in manufacturing has produced many valuable results (Muhl *et al.*, in Morel and Grabot, 2003). However, various obstacles for deployment in industry remain. Marik and Lazansky discuss in this special issue *the industrial applications of agent technology*, and they emphasize that only very few real-life industrial experiments are in use, despite laboratory experiments on the promising MAS and HMS approaches. Often, these obstacles require multidisciplinary solutions, in which, for instance, the manufacturing system design and the manufacturing control both are conceived to offer flexibility, robustness, scalability and cost effectiveness.

Likewise, advanced designs for multiagent manufacturing control have emerged, promising to address many issues. However, a definitive proof of concept requires the developments described above. Initial steps to provide such missing links have been taken already, and key elements of the solution already exist (e.g., suitable emulation technology). In advance of the availability of such a benchmarking service, Mönch addresses in this special issue a *simulation-based benchmarking of production control schemes for complex manufacturing systems* to deal with more specialized but more detailed models for practical purposes.

These advanced designs give up functional decomposition in favor of an object-oriented design approach in which a reflection of the world of interest in the software of the control system plays a prominent early role, much like maps are key elements in solving navigation problems. The PROSA architecture is an illustration of this trend (Van Brussel *et al.*, 1998). The object-oriented approach is extended in a multiagent approach (active objects reflect active entities in the manufacturing system) and by novel coordination mechanisms inspired by insect societies. Through an emergent and self-organizing design, such systems promise robustness and scalability. In contrast to older research based on market mechanisms, it is not necessary to reduce the dimensions of the information in the system, and many tuning problems are avoided. The novel designs postpone the introduction of the decision-making software components until the end. Therefore, the reusability and operating range of the system increases significantly. St Germain addresses in this special issue *an engineering perspective on the supply network control*

⁷ www.ims-noe.org

problem by extending the HMS paradigm for inter- and intra-enterprise logistics issues.

3.3 Forecasts

Significant development can be expected in the foreseeable future in the domain of the *e-manufacturing execution system* (Morel *et al.*, 2003). Some promising studies are addressing the interest in formal techniques for e-MES issues (Qiu *et al.*, 2004), to incorporate shop floor controls formally into plant-wide information-control systems for enabling ‘on the fly’ rescheduling of product routes as well as manufacturing process reconfigurability (Tang and Qiu, 2004). Another reason behind this is an explosion of enabling information technologies among which wireless technology such as radio-frequency identification (RFID) is a prominent example, ensuring state coherence between the physical and information flows all through the product life cycle. For example, in this special issue, Parlikad and McFarlane investigate *the role of this product information in end-of-life decision making*.

This rationale then raises the possibility of a hierarchical, integrated vision of enterprise-wide control for a more interoperable and intelligent system by postulating the customized product as the ‘controller’ of the manufacturing enterprise’s resources (Fig. 3).

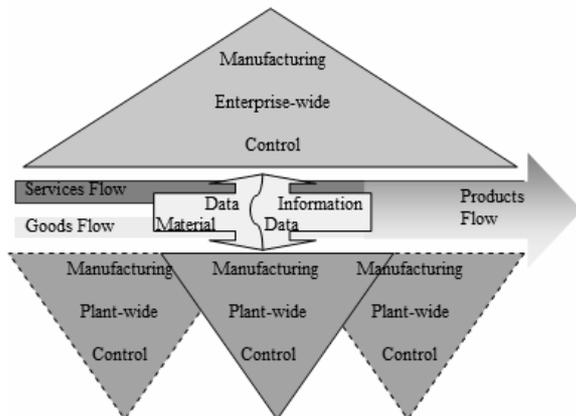


Fig. 3: Product-driven manufacturing enterprise-wide control

Manufacturing execution is a complex task because of the nonlinear nature of the underlying production system, the uncertainties stemming from the production processes and the environment, and the combinatorial growth of the decision space. Schedules and plans, originating from higher levels in a manufacturing organization, can become ineffectual within minutes on a factory floor. Manufacturing is a very dynamic environment, and handling changes and disturbances are high on its list of research

challenges. Moreover, the range of existing manufacturing system types and the performance issues therein, as well as the different kinds of equipment and processes, is very wide. This heterogeneity is challenging as well.

To cope with these challenges, future manufacturing execution system designs must apply the most fundamental and recent insights in self-organizing systems, a topic that is being intensely investigated by the multiagent systems community today (Di Marzo *et al.*, 2004).

To design such self-organizing systems (Table 2, level 5), it is also essential to apply insights from fundamental research (Waldrop, 1992, Valckenaers, in Morel and Grabot, 2003) and to define the related modeling framework, to obtain the required system features.

Important expected progress in the domain is the emergence of manufacturing execution systems that are able to forecast the emerging state of the underlying manufacturing system while preserving the level of decoupling that has made older multiagent manufacturing execution systems robust and configurable (Valckenaers *et al.*, 2004).

These recent and ongoing developments finally promise to deliver the best of both worlds: the planning ability of centralized older solutions and the ability to cope with the real-factory dynamics of the self-organizing multiagent systems.

In addition, enabling technologies are bringing the above research results closer to actual deployment. Tracking technologies such as RFID provide the eyes for the manufacturing execution system. Omnipresent networking and web technologies provide communication and actuation. Modern PLC and industrial PC designs support the deployment of multiagent systems developed in higher-level programming languages. Moreover, the customer calls for traceability as a basic product attribute. Products without a production history are becoming virtually worthless.

Open research issues remain, however. First, the cooperation between high-level planners and schedulers and the manufacturing execution system is virtually unexplored. Secondly, scaling the MES technology to multisite manufacturing coordination and control is in only the initial stages of research.

Furthermore, the development of a comprehensive methodology and theory for design, implementation and deployment is in its infancy. Overall, the future holds a multitude of challenging research activities in this domain.

4 DEPENDABLE MANUFACTURING SYSTEMS CONTROL

There is a growing demand for formalized methods in industrial automation engineering for dependability issues, to control the increasing complexity of software-intensive applications (Fig. 4) and their related ease-of-use techniques (Polzer, 2004). Another issue is to comply with fail-safety legacy certification (Moik, 2003), as safety for people and for industrial investments has become a key factor because of internationally accepted rules.

Johnson addresses in this special issue *the role of formal methods in improving automation software dependability*. He points out the need for verification techniques to check the real software-hardware value-creation chain in industrial automation systems when addressing high levels of the organization (Table 2, levels 3 to 5), so that software dependability cannot affect the correctness of the control design and the reliability of the respective controllers in operation.

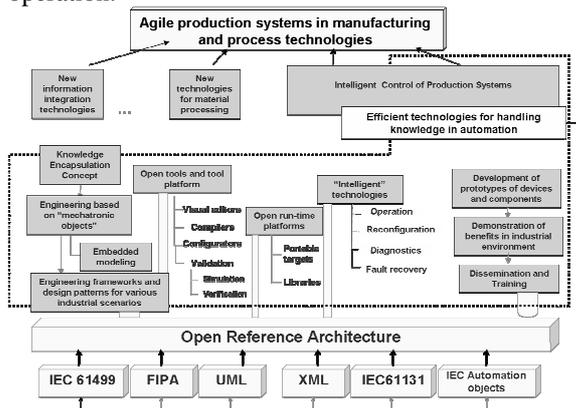


Fig. 4: IMS-OOONEIDA⁸ R&D framework

4.1 Current key problems

A first rationale issue should be to control information and its related communication technology better, as they are problematic in manufacturing plant-wide automation, to prevent dependability concerns in the near future. The increasing use of networked control systems within factories and enterprises can increase or decrease systems dependability, depending on how the networks have been designed and set up. Ethernet-TCP/IP (Transmission Control Protocol/Internet Protocol)-based networked control systems, for instance, ease the access to process data and hence enable new monitoring, diagnosis

and maintenance functionalities. However, a question arises immediately: is the traffic increase coming from these new functionalities compliant with the reactivity constraints required for the application? If not, how can we route this new traffic? Moreover, networked control systems impact security by providing potential means to disturb or to damage systems.

Another current trend is the growing importance of safety- and dependability-related standards when designing industrial controllers. These standards may be domain dependent (such as specific standards for railway transport and power plants) or may cover a wider scope, like the IEC 61508 standard (functional safety of E/E/PE safety-related systems), which introduces a safety life-cycle model and the concept of safety integrity level (SIL). These industrial automation standards recommend the use of formal methods for *a priori* proving high levels of SIL at early steps of system requirements, but without defining how they can be applied.

Finally, dependability becomes a major concern even for managers, because current economic constraints ask for increasing availability while the demand from society to control technological risks better requires accurate safety analysis. As managers focus continually on cost control and often claim that dependability improvement leads to too-expensive systems, development of new design processes that address both cost and dependability concerns is therefore a challenging issue. The work presented in (Papadopoulos and Grante, in Kopacek *et al.*, 2005) combines semiautomatic safety and reliability analysis with multicriteria optimization techniques. This will assist the gradual development of designs that can meet reliability and safety requirements within pragmatic cost and profit constraints, and is a good example of such a process.

Combining *a priori system definition* approaches with *a posteriori system implementation* approaches when addressing formal proofs of system behavior remains an open problem that should be attacked to cope with the increasing vulnerability of nondeterministic automation technologies.

4.2 Recent major accomplishments and trends

The main *dependable manufacturing systems control* concerns remain the following.

- *Dependability analysis must be carried out with a system engineering view*. This amounts to saying that analysis should not focus only on process safety or control software dependability, but should be structured by the automation paradigm (Fusuoka *et al.*, 1983, Pétin *et al.*, 2006)

⁸ (www.ooneida.info)

as stressed for performance-oriented system automation (Fig. 5).

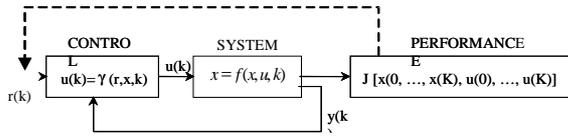


Fig. 5: A closed-loop system model with system performance optimization rather than control performance optimization (Morel, in Erbe, 2003)

- *Dependability must be taken into account, starting with requirements expression and throughout the system life cycle.* This can be achieved by using the semiformal models provided by UML (Unified Modeling Language) and by its Systems Modeling Language⁹ extension (SysML). Starting with the requirements down to the implementation with integrated verification and test steps, the software-driven V model can be applied. This also implies bridging the gap between conventional dependability analysis methods (such as fault tree analysis, failure modes, and effects and criticality analysis) and emerging formal methods for proof-based system engineering (Morel *et al.*, 2004) as well as the gap between industrial practices for dependability assessment and/or improvement (such as simulation techniques and testing) and these formal methods.

Other key issues should be noted:

- the use of formal or semiformal analysis and synthesis methods for design, implementation and validation of system components and communication systems;
- the use of formal or semiformal analysis and synthesis methods on industrial-size examples;
- the impact of networked control systems on manufacturing systems dependability;
- the improvement of fault forecasting methods thanks to formal temporal analysis (introduction of temporal logic in fault forecasting methods);
- the improvement of design methods for fault-tolerant systems thanks to formal methods,

- reconfigurable systems design and mode management; and
- definition of metrics for dependability, safety and security.

The classical methods for dependability improvement have been developed since the 1960s for analyzing physical systems (these methods deal with process dependability) and are based on designers' and users' skills and knowledge. Current manufacturing systems include many processors and software systems and different kinds of networks, and are strongly constrained by production objectives. Their increasing complexity leads us to look for new methods that rely on sound formalisms to enable automatic dependability analysis and to facilitate dependability improvement.

Several research results recently issued by the communities for safety and reliability analysis and for discrete event systems (DES) control seem able to provide solutions to these industrial concerns. Fault forecasting using dynamic or temporal fault-tree analysis, dependability modeling using Bayesian networks, fault-tolerant systems design, formal verification of control software, timed and probabilistic model checking, fault detection and diagnosis of DES, for instance, provide promising solutions for increasing systems dependability.

4.3 Forecasts

Significant progress is to be expected in the formal combination of all these related techniques. However, we must take into account significant, though often antagonistic, concerns. As mentioned in Faure and Lesage (in Kopacek *et al.*, 2001), these methods may be ranked, with a life-cycle criterion, into two categories: offline dependability and online dependability. The purpose of the *offline dependability* methods is to minimize the fault risk during design and implementation, i.e., before the system is used. On the other hand, the objective of *online dependability* methods is to ensure that an implemented and running system is dependable.

4.3.1 Offline dependability

Formal verification and synthesis methods based on DES theory, like model-checking techniques (Berard *et al.*, 1999) and supervisory control theory (Ramadge and Wonham, 1987) seem capable of promising solutions for dependability improvement. They should allow the design *a posteriori* or *a priori* of controllers that comply with the application requirements. Numerous research results based on these two approaches have been published recently. Nevertheless, the current results of these studies

⁹ www.sysml.org

are mainly theoretical and have been generally tested on only small case studies (toy problems). There is therefore a need for new research aimed at making these results on formal methods for DES available to automation engineers.

The key strengths and shortcomings of existing verification methods relative to railway signaling applications are noted in Johnson *et al.* (2005). Morel *et al.* (2004) address the issue of bridging the gap between industrial practices and formal methods. Flordal *et al.* in this special issue apply the Ramadge–Wonham supervisory control theory to the *automatic model generation and plc code implementation for coordination of industrial robot cells*. Such examples of industry-oriented research are addressed by Roussel *et al.* (2004), who develop a specific algebraic synthesis method for industrial controller design, or by Stursberg *et al.* (2005), who apply the timed model-checking tool UPPAAL to verify Sequential Function Chart (SFC) programs.

Moreover, neither of these two approaches (verification and synthesis) is able to provide a global solution. Hence, another interesting prospect is coupling several formal methods to build toolboxes for dependable systems design and implementation. Using formal verification and formal synthesis techniques in a convenient way, for instance, would surely increase the potential of both approaches. Music and Matko (2005), for instance, describe a two-stage method for designing logic controllers. Supervisory control theory is used in the first stage to test the controllability of the specifications and to derive a finite automaton representation of the admissible behavior of the system; in the second stage, reachability analysis is performed on a Petri net model derived from this representation.

All the approaches mentioned above are based upon deterministic modeling; unfortunately, addressing dependability problems requires consideration of nondeterministic behaviors. Hence, research dealing with probabilistic modeling of DES is required. Kwiatkowska *et al.* in this special issue address *controller dependability analysis by probabilistic model checking* for systems that exhibit stochastic behavior.

Meanwhile, the usual fault-forecasting methods must also be improved to cope with the complexity of today's manufacturing systems. Papadopoulos *et al.* (2005) outline a technique that automates the construction of fault trees and FMECAs and explains how this technique can be repeatedly applied to functional and architectural models to enable continuous assessment of evolving designs; this technique is well suited to manufacturing systems based on standard interoperable components and allows reuse of

safety analyses. An improvement of FTA, named deductive cause–consequence analysis (DCCA), is presented in Ortmeier *et al.* (2005). DCCA allows rigorous proof of whether a failure at the component level is the cause for a system failure. This enables designers to prevent flaws when designing fault trees.

Finally, bridging the gap between fault forecasting methods and DES formal methods is a challenging issue. Industrial users will accept formal methods only if they are integrated within a computer-aided framework for dependability that should include and automate existing industrial techniques, such as FTA and FMECA. To reach this objective, Barragan and Faure (2005), for instance, propose a method that can state the formal properties of a logic controller, a prerequisite for formal verification using model checking, from a fault-tree analysis, taking into account both the controlled process and the controller.

4.3.2 Online dependability

Several studies of DES fault detection and diagnosis, reconfiguration techniques and fault-tolerant control, as well as of DES identification have delivered promising results that look useful for dependability improvement when operating a system.

Lafortune *et al.* (2001) outline methodologies for fault detection and isolation based on the use of discrete-event models that have been successfully used in a variety of technological systems ranging from document processing systems to intelligent transportation systems. Genc and Lafortune (2005) present a new distributed algorithm for online fault detection and isolation of discrete event systems modeled by Petri nets.

Identification of DES might be particularly considered as a prerequisite for fault detection and diagnosis. Klein *et al.* (2005), for instance, focus on the identification of large-scale discrete-event dynamic systems for fault detection. The properties of a model for fault detection are discussed, and metrics to evaluate the accuracy of the identified model are defined. An identification algorithm that allows setting the accuracy of the identified model is also presented.

Finally, diachronic integration between fault-forecasting methods, providing some formal models of faults, are built up during this step, and diagnosis is also a challenging issue.

5 Education and Training

Nof (in Panetto *et al.*, 2006) emphasizes that e-manufacturing is highly dependent on the efficiency of collaborative man–man and man–machine e-work. E-manufacturing, and

consequently collaborative e-work, is addressing in industry the need for agile workforces in competitive organizations, while in training bodies, it is addressing the difficulties faced by high-level trainers and trainees when learning about complex systems paradigms (Table 2).

Any operational system emerges in real life from an ad hoc combination of formal, informal and intuitive issues by combining top-down and bottom-up approaches.

The learning complexity of such holistic paradigms imposes on both research and academic training an appropriate project system that reproduces a realistic systems engineering context (Fig. 6).

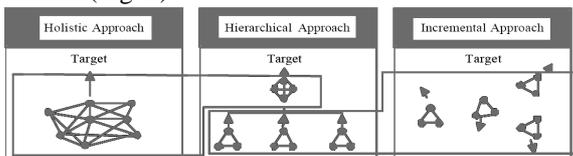


Fig. 6: Large-scale project engineering approaches (Rumpe and Scholz, 2002)

In one approach, we could apply a normative document-driven process for engineering a system¹⁰ such as ISO/IEC 15288 or the model-driven system definition, development and deployment approaches (Table 2, levels 3 and 4) within a computer integrated manufacturing (CIM) context¹¹.

A complementary approach could be to adapt the extreme programming-like (XP) approach currently applied in agile software development, to facilitate face-to-face learner-to-learner and teacher-to-learner collaborative e-work, reproducing complex engineering situations with lower-level methods (Table 2, levels 4 and 5).

Bruns and Erbe present in this special issue such an e-learning low-cost evolution of previous CIM training concepts. It allows trainers and trainees to enter a mixed situation with an idealized computer simulation to understand the stepwise abstraction and concretization of technical system complexity. The proposed *learning environment* merges onsite and remote components into a cooperative learning process to bridge reality and virtuality as addressed by the infotronics world.

6 Conclusion

Many other issues should be debated to anticipate the next automation of manufacturing

systems besides those presented in this special issue (Dolgui *et al.*, 2006).

One challenging approach could be to explore with more holism the appropriate balance between the increasing complexity of software-intensive systems (Fischer, 2006), ranging from embedded micro-systems to macro-systems of systems, and a more human-centered automation (Mayer and Stahre, 2006) for safety or ecoefficiency purposes.

Another challenging approach could be to explore others modeling artifacts such as the promising System of Systems (Chen and Clothier, 2003) to cope with the high degree of complexity required to deploy plant-wide information control systems in enterprise.

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¹⁰ www.incose.org

¹¹ www.aip-primeca.net

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