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. This achievement of the Integration-in-Manufacturing paradigm based on centralized/distributed hardware/software automation architectures is shifting by the Intelligence-in-Manufacturing paradigm addressed by the IMS industry-led R&D initiative. The remaining goal is to define and to experiment the next generation of manufacturing systems capable to cope with the high degree of complexity of meeting agility over flexibility and reactivity in customized manufacturing. This introducing paper summarizes these key problems, trends and accomplishments for manufacturing plant control before to emphasize for practical purposes some rationales and forecasts in deploying automation over networks, HMS and its related agent-based technology, as well as in applying formal methods to ensure dependable control of these manufacturing systems. Copyright © 2005 IFAC

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1. MANUFACTURING PLANT AUTOMATION CONTEXT

The manufacturing enterprise is intensively deploying a host of hardware/software automation/information technologies in order to face the changing societal environment pulled by the increasing customization of both goods and services as 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 in order to meet industry-led B2M (Business-to-Manufacturing) issues (Panetto and Goncalves, 2006).

\(^1\) www.mesa.org; www.omg.org/mda ;
\(^2\) IEC62264, 61499, 61131 ; www.opcfoundation.org ; www.mimosa.org ; www.isa.org

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The resulting automation model (fig. 1) is a wide network of automata which is challenging researches and developments in order to achieve synchronic integration (in time) of shop-floor process-controls in large (robotics, assembly, machining, …) into plant-wide information-control systems and diachronic integration (through time) of products life-cycle over the manufacturing chain, as addressed by the IIM (Integration in Manufacturing) paradigm.
Despite web-enabled technologies are strengthening distributed automation in manufacturing (Banaszak and Zaremba, 2003), only a form of technical intelligence that goes beyond simple data through information to knowledge is embedded into manufacturing systems components and within the products themselves will play a prominent role as the pivotal technology that makes it possible to meet agility in manufacturing over flexibility and reactivity, as addressed by the shifting IIAM (Intelligence in Manufacturing) paradigm. This complexity of efficiently deploying interoperability and autonomy for manufacturing plant control and production management issues is challenging the industry-led international IMS\(^3\) initiative in order to define, to develop and to deploy the next generation of open, modular, reconfigurable, maintainable, and dependable manufacturing systems.

The IFAC CC5 on Manufacturing and Logistics systems (Ollero, et al., 2002)(Nof, et al., 2006) and the IFAC TC 5.1 on Manufacturing Plant Control contribute to raise up the related scientific challenges on Intelligent Manufacturing Systems (Monostori, et al., 2003)(Morel and Grabot, 2003), Intelligent Assembly and Disassembly (Borangi, 2003) as well as on Information Control Problems in Manufacturing (Kopacek, et al., 2005).

This special issue deals with some current key problems/applications, recent major accomplishments/trends and main research-development forecasts related to information control in the field of networked manufacturing automation (section 2), IMS modelling and experiments (section 3) and dependable control of discrete systems (section 4).

Among many others rationale issues which should be debated, the conclusion of this special issue focus mainly on the learning complexity of such holistic paradigms in Education and Training.

2. NETWORKED MANUFACTURING AUTOMATION

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

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

Among these interoperability issues between e-manufacturing applications, (Neumann) addresses what is going on communication in industrial automation in order to control the communication problems which are inferred by this increasing impact of the world-wide distribution of Internet on the manufacturing automation domain.

2.1. Current key problems

Embedding a distributed technical intelligence (data/information processing, storage and communication) into field automation has been largely experimented in order to enable actuation and measurement systems interoperability as well as to ensure control, maintenance and technical management system integration (Iung et al., 2001). Among many rationales to assess and to predict the performance degradation (Leger and Morel, 2001) of a process, a machine or a service is to merge on-site and remote infotronics components in closed Device-to-Business loop in order 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 in order to enable the prophylactic of when the performance is becoming unacceptable, the diagnostic of why the performance is degrading and the decision of what maintenance action to perform as well as the performance benchmarking coming from similar operating Watchdog Agents™ (Lee, in Kopacek et al., 2005).

Another major technological challenge of 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 in order to easily accommodate the requirements imposed by new applications and services. Vertical communication in the control level and horizontal communication between the factory hierarchy has to be managed additionally.

\(^3\) www.ims.org
Finally, the efficient use of these promising mechatronics, infotronics and communication technologies is highly dependent of dealing with the complexity to intelligently combine a host of existing techniques for a global performance rather than a local one. These engineering issues require field device metamodels to integrate the devices in the entire engineering life cycle of the automation systems (Die-drich, et al., 2001). UML, the de-facto industrial Unified Modelling Language, is the candidate for designing distributed automation architectures in a collaborative and pluridisciplinary way as there are several so called UML profiles on the road. Special profiles for real time, safety/dependability, ..., have to be evaluated carefully, such as:

- Profile for Scheduling Schedulability, Performance, and Time Specification.
- Profile for Modelling Quality of Service and Fault Tolerance Characteristics and Mechanism.

2.2. Recent major accomplishments & trends

Networked Controlled Systems should integrate all new technologies such as wireless networks, embedded systems, nomad components and electronics tags in order to enable to meet new requirements such as mobility, modularity, control and diagnosis decentralisation and/or distribution, autonomy, redundancy, quick and easy maintenance.

As a major industrial communication challenge of the related multilevel communication architectures is to unify plant networking with Ethernet, the resulting automation challenge is to guarantee the same deterministic features that those of more specific fieldbuses currently applied in shop floor manufacturing.

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

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

The huge investment in Ethernet based industrial communication of main industrial players (e.g. PROFInet by Siemens, Industrial IP by Rockwell, Modbus IP by Schneider, ...) are a challenge for the research because large distributed systems with new characteristics and new opportunities are built. These systems have to be configured, parameterised, operated and maintained with real time, safety and security constraints.

4 http://www.omg.org/docs/formal/03-09-01.pdf
5 http://neptune.irit.fr/Biblio/02-01-02.pdf

Fig. 2: Networked Control Systems Tolerant to faults (www.strep-necst.org)

2.3. Forecasts

In future, specific industrial communication means and other commercial communication systems such as telecommunication for maintenance and remote access or private networks can become components of the systems. These systems crossing intranet borders or crossing Wide Area Networks are Virtual Automation Networks with new quality of services and new management tasks. In detail real time constraints, safety and security are the main requirements for the new architectures and technology combinations requiring joint research efforts of automation and communication communities in order to prevent networks to become the Achille’s heals of embedded and distributed manufacturing automation.

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

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-organisation.

The area of intelligent systems is challenging - occasionally verging on controversy - the research community as well as the industrial sector in order 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 HMS (Holonic Manufacturing System) should be the unifying technology as well as PPE (Product-Process Engineering) 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, both in terms of size of the manufacturing system itself and the thoroughness of the evaluation campaign itself. Concerning advanced manufacturing control, conceptual designs exist that address the major research issues at least in principle, for instance (Valckenaers, in Morel and Grabot 2003). The complexity of these system designs makes formal proof of their performance and capabilities infeasible and definitely unpractical.

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 need to be tested on real-world factories (in emulation) in order to remedy with toy test cases and token evaluation campaigns as it remains the norm. Moreover, the evaluation campaign must answer industrial requirements, which typically implies that test runs must cover several months of production. Evidently, the IMS designs need to 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 Excellence has started to make such an environment available for advanced manufacturing control and supply network coordination. (Valckenaers et al., in Panetto and Goncalves, 2006) describes the development status and roadmap for this research effort in order to equip the IMS community with a benchmarking service. Such testing and evaluation platforms will enable researchers to generate solid proof-of-concepts for their research results with normal levels of development efforts and resources.

Secondly, there is a need for better and deeper understanding of scale-ability and robustness, typically only achievable through designs that use emergence and self-organization. These designs give up the ability to explicitly prescribe 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 (cooking book 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 element in an IMS system need further research, producing 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 are needed, especially from the perspective of designing such systems (synthesis of IMS artefacts).

Finally, research needs to 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 this need to be brought to the surface, and the needs for additional support that transpire must be answered

3.2. Recent major accomplishments & trends

Recently, research on applying multi-agent 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) state the industrial applications of the agent technology and emphasize that only very few real-life industrial experiments are in use despite laboratory experiments of the promising MAS and HMS approaches. Often, these obstacles require multi-disciplinary solutions, in which for instance the manufacturing system design and the manufacturing control both are conceived to offer flexibility, robustness, scale-ability and cost-effectiveness.

Likewise, advanced designs for multi-agent 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 link have been taken already and key elements of the solution already exist (e.g. suitable emulation technology). On standby of the availability of such a benchmarking service, (Mönch) addresses 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 favour 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 multi-agent 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 scale-ability. 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 et al.) address an engineering perspective on the supply network control problem by extending the HMS paradigm for inter and intra-enterprise logistics issues.

3.3. Forecasts

Significant development is to be expected in the foreseeable future is the domain of the e-Manufacturing Execution System (Morel, et al., 2003). Some promising works are addressing the interest of formal techniques for e-MES issues (Qiu et al., 2004) in order to formally incorporate shop floor controls into plant-wide information-control systems for enabling ‘on the fly’ rescheduling of product routes as well as manufacturing processes.

6 www.ims-noe.org
reconfigurability (Tang and Qiu, 2004). Another reason behind this is an explosion of enabling information technologies among which wireless technology like RFID is a prominent example allowing to ensure the state coherence between the physical flows and the information ones all along the product life cycle; As example in this special issue, (Parlikad and McFarlane) investigate the role of this product information in end-of-life decision making.

The rationale issue is then to put into question the hierarchical/Integrated vision of the Enterprise-wide control for a more Interoperable/Intelligent one by postulating the customized product as the ‘controller’ of the manufacturing enterprise resources (fig. 3).

Fig. 3: Product-driven Manufacturing Enterprise-wide Control

Manufacturing execution is a complex task because of the non-linear 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, are known to become ineffectual within minutes on a factory floor. Manufacturing is a very dynamic environment and handling changes and disturbances is 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 need to apply the most fundamental and recent insights in self-organising systems, a topic that is intensely investigated by the multi-agent systems community today (Di Marzo et al., 2004).

To design such self-organising systems (table 2, level 5), it is also essential to apply insights from fundamental research (Waldrop, 1992; Valckenaeers, in Morel and Grabot, 2003) and to define the related modelling framework in order to meet the required system features.

Important progress in the domain, which can be expected, is the emergence of manufacturing execution systems that are able to emergently forecast the state of the underlying manufacturing system while preserving the level of decoupling that has made older multi-agent manufacturing execution systems robust and configurable (Valckenaeers et al., 2004).

These recent and ongoing developments finally promise to deliver the best of both worlds: the planning ahead in time of centralised older solutions and the ability to cope with real-factory dynamics of the self-organising multi-agent systems.

In addition, enabling technologies bring 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 multi-agent systems developed in higher-level programming languages. Moreover, customer requirements impose demands that render products with a trace of their production history worthless.

Open research issues remain however. First, the cooperation amongst high-level planners and schedulers and the manufacturing executions systems is virtually unexplored. Secondly, scaling the MES technology to multi-site manufacturing coordination and control only is in the initial stages of research.

Furthermore, the development of a comprehensive methodology and theory for the 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 formalised methods in industrial automation engineering for dependability issues in order to control the increasing complexity of software-intensive applications (fig. 4) and their related ease-of-use techniques (Polzer, 2004). Another issue is to check with fail-safety legacy certification (Moik, 2003) as safety for human beings and for industrial investments become key factors because of international accepted rules.
(Johnson) addresses in this special issue the role of formal method for improving automation software dependability. He points up the need of verification techniques in order to check the real software/hardware value creation chain in industrial automation systems when addressing high level of organisation (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.

4.1. Current key problems

A first rationale issue should be to better control Information and its related Communication Technology which is rushing about all directions in Manufacturing Plant-wide Automation in order 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 the fashion in which networks have been designed and set-up. Ethernet TCP/IP 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 it is not the case, how to route this new traffic? Moreover that kind of networked control systems impacts security for providing potential means to disturb or to damage the systems.

Another current trend is the growing importance of safety/dependability-related standards when designing industrial controllers. These standards may be domain dependant (specific standards for railway transport, power plants, ...) or may cover a wider scope, like the IEC 61508 standard (Functional safety of E/E/PE safety/related systems) that introduces a safety life-cycle model and the concept of SIL (Safety Integrity Level).

At last, dependability becomes a major concern even for managers, because current economical constraints ask for increasing availability whilst the demand on the part of society to better control technological risks requires accurate safety analysis. As managers focus continuously to cost control and claim often 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) that combines semi-automatic safety and reliability analysis with multi-criteria optimization techniques to assist the gradual development of designs that can meet reliability and safety requirements within pragmatic cost and profit constraints is a good example of such a process.

4.2. Recent major accomplishments & trends

Main Dependable Manufacturing Systems Control concerns remain the following:

- Dependability analysis must be carried out with a system engineering view. This amounts to say that we are not focusing only on process safety or on control software dependability, but that our works are structured by the automation paradigm (Fusukoaka, 1983)(Pétin et al. 2006) as stressed for performance-oriented system automation (fig. 5)

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

- Dependability must be taken into account as from requirements expression and all along the system life-cycle. This can be achieved by using semi-formal models that are provided by UML and by its SysML7 extension for Systems Engineering. Starting with the requirements down to the implementation with integrated verification and test steps along the software driven V model can be applied. This implies also to bridge the gap between conventional dependability analysis methods (fault-tree analysis, FMECA, ...) and emerging formal methods for Proof-based System Engineering (Morel et al., 2004) as well as between industrial practices for dependability assessment and/or improvement (simulation techniques, test, ...) and these formal methods.

Others key issues should be pointed:

- Use of formal or semi-formal analysis and synthesis methods for design, implementation and validation of system components and communication systems,
- Use of formal or semi-formal analysis and synthesis methods on industrial size examples,
- Impact of networked control systems on manufacturing systems dependability,
- Improvement of faults forecasting methods thanks to formal temporal analysis (introduction of temporal logic in faults forecasting methods),
- Improvement of design methods for fault-tolerant systems thanks to formal methods,
- Reconfigurable systems design; mode management,
- Definition of metrics for dependability, safety and security.

The classical methods for dependability improvement (FMECA (Failure Modes, Effects and Criticity Analysis), FTA (Fault Tree Analysis, ...) have been developed since the 60's for analyzing physical systems (these methods deal with process dependability) and are based on designers and users skills and knowledge. The increasing complexity of current manufacturing systems, that include lots of processors and software, different kinds of networks, and that are strongly constrained by production objec-

7 www.sysml.org
4.3. Forecasts

Significant progress is to be expected in the formal combination of all these related techniques that implies to take into account significant, though often antagonist 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: off-line dependability and on-line dependability. The purpose of the Off-line 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 the On-line dependability methods is to ensure that an already implemented and running system is dependable.

4.3.1 Off-line 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 able of bringing promising solutions for dependability improvement for they allow to design a posteriori or a priori a controller that complies with the application requirements. During the last years, numerous research results based on these two approaches have been published. Nevertheless current results of these research works are mainly theoretical and have been generally tested on small-sized case studies (toy problems). There is therefore a need for new research works aiming at making available for automation engineers these results on formal methods for DES.

The key strengths and shortcomings of existing verification methods relative to railway signaling application needs are noted in (Johnson, et al., 2005). (Morel et al., 2004) addresses the issue of bridging the gap between industrial practices and formal methods. (Fjordal et al.) 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 researches are addressed in (Roussel et al., 2004) that develop a specific algebraic synthesis method for industrial controllers design, or in (Stursberg et al., 2005) that applies the timed model-checking tool UPPAAL to verify SFC (Sequential Function Chart) programs.

Moreover none of these two approaches (verification and synthesis) is able of providing a global solution. Hence, another interesting prospect is coupling several formal methods so as to build toolboxes for dependable systems design and implementation. Using in a convenient way formal verification and formal synthesis techniques for instance would surely increase the potentialities of both approaches. (Music and Matko, 2005) for instance describes a two stages method to design 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 approaches mentioned above are based upon deterministic modelling; unfortunately addressing dependability problems requires to consider non-deterministic behaviours. Hence, focus must be put on researches dealing with probabilistic modelling of DES. (Parker et al.) address in this special issue the controller dependability analysis by probabilistic model checking for systems that exhibit a stochastic behaviour.

Meanwhile, usual fault-forecasting methods must also be improved to cope with the complexity of today manufacturing systems. (Papadopoulos et al., 2005) outlines a technique that automates the construction of fault trees and FMEAs and explains how this technique can be repeatedly applied on 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 to re-use safety analyses. An improvement of FTA, named deductive cause-consequence analysis (DCCA) is presented in (Ortmeier et al., 2005). DCCA allows to rigorously prove whether a failure on component level is the cause for system failure or not. This enables to prevent flaws when designing fault-trees.

At last, bridging the gap between fault forecasting methods and DES formal methods is a challenging issue. Industrial users will accept formal methods indeed 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 proposes a method enabling to state 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 On-line dependability

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

(Lafortune et al., 2001) outlines 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) presents a new distributed algorithm for on-line 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 focuses on the identification of large-scale discrete-event dynamic systems for the purpose of 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 which allows setting the accuracy of the identified model is also presented. At last, 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. CONCLUSION

(Nof, in Kopacek et al., 2005) 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, are addressing in industry the need for agile workforce in competitive organizations and in training bodies the difficulties 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 approaches with bottom-up ones. Learning such complexity with more holism requires an appropriate learning environment reproducing a system engineering realistic context (fig. 6).

5. CONCLUSION

A way can be to apply a normative document-driven process for Engineering a System8 or/and Model Driven System Definition, Development and Deployment approaches (table 2, levels 3 & 4) within a CIM-like context9. A complementary approach can be to adapt XP-like approach currently applied in agile software development in order to facilitate face-to-face learner-to-learner teacher-to-learner collaborative e-work reproducing complex engineering situations with lower means (table 2, levels 4 & 5).

(Erbe et al.) present such e-learning low-cost evolution of previous CIM training concept enables to put trainers and trainees in a mixed situation over idealized computer-simulation to get the stepwise abstraction and concretization of technical system complexity. The proposed learning environment merges on-site and remote components into a cooperative learning process in order to bridge reality and virtuality as addresses by the infotronics world.

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