CARV 2007

Evolvable Production Systems in a RMS Context: Enabling Concepts and Technologies

J. Barata[1], M. Onori[2], R. Frei[1], P. Leitão[3]

Abstract: The goal of this paper is to describe the research on Evolvable Production Systems (EPS) in the context of Reconfigurable Manufacturing Systems (RMS), and to briefly describe a multiagent based control solution. RMS, Holonic and EPS concepts are briefly described and compared. Novel inspiration areas and concepts to solve the demanding requirements set by RMS, such as artificial life and complexity theory, are described. Finally, the multiagent based control solution is described as the underlying infrastructure to support all future development in EPS, using concepts such as emergence and self-organisation.

Keywords: Reconfigurable Manufacturing Systems, Multiagents, Evolvable Production Systems, Control Solution

1 Introduction

The goal of this paper is two fold, to describe the research on Evolvable Production Systems (EPS) in the context of Reconfigurable Manufacturing Systems (Mehrabi

[1] New University of Lisbon /UNINOVA - Quinta da Torre, Monte da Caparica, 2829-516 Caparica, Portugal, Tel. +351-212948535, E-mail: jab@uninova.pt

[2] KTH, Department of Production Engineering Brinnelvagen, Stockholm, 100 44 Stockholm, Sweden, Tel. +46-87906637 E-mail: onori@iip.kth.se

[3] Polythecnic Institute of Bragança - Quinta de Sta Apolónia, Apartado 1134, 5301-857 Bragança, Portugal, Tel. +351-273303003, E-mail: pleitao@ipb.pt

et al., 2000, Koren et al., 1999), and to briefly describe a multiagent based control solution applied to the NovaFlex assembly cell, which was developed according to EPS principles.

In the first part of this paper the requirements needed by current manufacturing systems as defined in previous RMS research works are highlighted, and their impact on the control architecture requirements are discussed. In fact several control architectures have been proposed in the past to address many of the issues highlighted by RMS. However, in many cases they have not completely addressed the set of requirements defined by RMS research work, in particular the issues of granularity of modules (manufacturing components), avoiding programming when the system is changed, and diagnosability.

A fundamental work to provide control architectures to solve RMS requirements is holonic manufacturing (Bussmann and McFarlane, 1999, Babiceanu and Chen, 2006, Van Brussel et al., 1998, Gou et al., 1998, Tharumarajah et al., 1996), which uses an approach based on the work of Arthur Koestler (Koestler, 1989) about systems sciences and the notions of parts and wholes. However, the authors believe that to properly solve the requirements needed for agile and reconfigurable manufacturing systems it is fundamental to develop biologically inspired solutions that use principles from biology, complexity theory, swarm intelligence, chaos theory, selforganisation and emergence. EPS uses these principles to address current manufacturing challenges, or saying it in another way EPS uses a biologically inspired approach to solve RMS requirements. EPS fulfil the majority of the established RMS requirements and even go a step further by being modular at a finer granularity, which allows truly process-specific system design. EPS are not only a conceptual framework like most of the cited approaches. EPS offer a practical solution by providing mechanisms for fast reconfiguration at mechanical as well as control level, using multi-agent-technology for modelling and implementation. EPS open the doors for the production systems of the future: based on today's technology, it aims at implementing advanced concepts such as self-organisation, self-diagnose and self-healing. Coping with emergent behaviour will be fundamental, and taking profit of emergent capabilities will open considerable potential for new solutions.

Because the approach towards a fully biologically inspired solution and in particular the issue of selforganisation and emergence is difficult, a stepwise approach has been devised in developing EPS control solutions. Therefore, an approach is being made in which the different constituents of the system are considered as modules with intelligence. This means that every manufacturing component at different levels of granularity (from entire workstations to unit or components such as grippers or even sensors) are considered as intelligent entities (with computational power). The paper will then describe a multiagent based approach applied to a manufacturing cell composed of several conveyors, pallets, and two robots, each equipped with several grippers and a holding device, in which basic principles of emergence are present.

By providing a discussion of EPS and its importance in RMS research, and describing a control solution architecture to solve RMS requirements the authors believe that this paper could provide relevant scientific work. It is fundamental to understand that its focus is mainly on the control side. The main idea is describing how new manufacturing requirements impose new type of control architectures and how the proposal being developed in the framework of EPS can help solving these requirements.

2 RMS, Holonic, and EPS

The main issue to be addressed in this section is describing how Evolvable Production Systems are related to the established concepts of Holonic Manufacturing and RMS.

As defined in (ElMaraghy, 2006) RMS incorporates principles of modularity, integrability, flexibility, scalability, convertibility, and diagnosability. These principles impose strong requirements to the control solution. In particular, centralized approaches become completely unsuited due to its intrinsic rigidity. Decentralised solutions must be considered that take into account the fundamental requirements of plugability of components, which includes the aspects related to dynamic addition and removal of components as well as adaptation in the sense that the system do not need to be reprogrammed whenever a new module is added or removed. This is a fundamental aspect behind any control solution approach to solve the defined requirements. Moreover, diagnosability also demands a decentralized approach, in particular if the manufacturing system is considered as a set of manufacturing components, each with diagnosis capability. The overall diagnosis of the system is obtained considering all the diagnosis information obtained from the individual modules. Once again, the ideal situation is to consider that the overall system diagnosis did not need to be reprogrammed whenever the components are changed. Due to these requirements, a particular and relevant aspect in the system being considered is the intelligent nature of its components, i.e., each component is considered has having computational power that will support individual diagnosability, dynamic plugability of components, and adaptation to working conditions.

Therefore, the major challenge in the control solution is how to guarantee proper coordination and execution in a system in which both its components and working conditions can be dynamically changed. This is a challenge that needs a completely new approach and this is why in the context of EPS a solution based on concepts inspired from the Complexity Theory and Artificial Life is being developed. The next section covers what concepts from non traditional manufacturing research domains are being used to create truly dynamic control solutions.

Nevertheless, in the context of this paper it is important to clarify what are the big differences between the approach being proposed here and Holonic Manufacturing. The genesis of holonic manufacturing was very much a biological inspired approach and it was very close to the concepts of bionic and fractal (Tharumarajah et al., 1996). However, succeeding implementations along the years have been more and more away from the original inspiration, and, in many aspects, the system became more hierarchical than a real distributed one. With effect, the control approach to be developed in the context of EPS wants to go back to the basics, that is to say relying hardly on the original idea of considering each component as a distributed intelligent unit that aggregate in order to create a complex system. In this context, concepts such as emergence and self-organisation become more and more important to be applied to new generation control solutions. Interestingly enough other researchers such as Tharumarajah are proposing a self-organisation view in manufacturing enterprises (Tharumarajah, 2003). However, successful implementations of these new concepts within shop floor are still very few.

Considering what was stated above, one may view Evolvable Production Systems (EPS) as a development of the Holonic Manufacturing Systems (HMS) approach; however, a closer looks reveals that, although there are similarities in the exploitation and implementation phases, the paradigms differ quite substantially in their perspective (or trigger issue), and that only EPS achieves fine granularity. By granularity it is considered the level of complexity of the component that compose a manufacturing system. For instance, when a line is composed of several cells and these cells are modules that can be plugged in and out, this is considered thick granularity. If, on the other hand, the components that can be plugged in or out are grippers, sensors, or pneumatic cylinders, this is considered fine granularity. This issue is in fact a very important one in terms of distinguishing the paradigms.

The main difference in the EPS paradigm is that it was created from a more dynamic, industrially-relevant perspective (trigger issue): EPS is mainly concerned with what occurs in a production system when a production change-over is called for; that is, whenever the current production system needs to undergo some change in its physical, control, or productivity layout. Such changes occur at ramp-up, product change-over, or demand surges. This is where the biological inspiration to EPS first makes itself apparent: it is change that drives the adaptability/evolution of the EPS systems, not the current or known scenarios. Furthermore, as will be detailed later, the adaptability is dictated by real evolvability principles such as "survival-of-the-fittest" at algorithm level. This biological approach becomes even more evident when one studies the way modularity is achieved within EPS. In most approaches, modularity is set by either known mechanical subdivisions, or by taking the classical subdivisions that exist within manufacturing; for example, in reconfigurable assembly, the modules are most often set by the transport/handling/joining/placing/packaging processes. There is no biological link and the RMS and HMS paradigms tend to try to achieve a general, top-level solution. EPS is radically different in this respect as it will focus on the predicted and unpredictable changes that may occur within a very limited product range(genus). The first solution will be limited and specific, and may, if successful, gradually be applied to the associated product family(species). Hence EPS is not a generic solution but a specific approach that may be adopted by other "species" if its evolutionary capabilities denote a high rate of success.

Furthermore, EPS takes a hybrid and not top-down approach to the definition of its modules. The EPS modules are defined by precise sub-processes that have been identified for a given product range: the taxonomy of the sub-processes is very detailed and therefore results in fine granularity. This is a low-level approach, and gives modules with very optimised performance characteristics: process-oriented modules (Maraldo et al., 2006). Note that since it is specific, and focuses on the given evolutionary demands of a product range and its exact sub-processes, it may also be closely linked to product design issues (discussed later). This is unique among current paradigms.

The third way in which one may associate EPS with biological systems is based on how its adptability/evolvability is designed: based on many, process-specific elements/modules, the system control will be based on multi-agent systems that will autonomously capture emergent properties and act appropriately. The EPS systems will consist of finely granular solutions, with each module and/or unit possessing its own processing power. When these modules come together to form systems, cells or workstations, the aggregate skills of the units/modules will be greater than the sum of the individual skills: the emergence of new skills is precluded. Emergence, however, will also occur during the operational life-cycle of the modules, and will inevitably raise unwanted skills as well. Therefore, coping with emergent behaviour is a central issue within EPS.

Comparing EPS with RMS become simple in the sense that EPS are an answer to the requirements defined by RMS. Of course many research works being done in the framework of RMS can be comparable to EPS. The big difference to these research works is the approach and the level of granularity being considered and addressed.

3 Enabling Research Domains and Concepts

The main issue to be addressed in this section is describing the areas in which EPS control systems are getting inspiration to solve the requirements for adaptability at fine granularity. Numerous scientific domains investigating phenomena which EPS also exhibit have emerged in the last few years, which can provide helpful tools and valuable theoretical background to cope with the complexity of manufacturing systems.

Complexity Theory

Complexity Theory looks for simple causes leading to complex behaviors (Delic and Dum, 2006). Complex systems are spatially and/or temporally extended non-linear systems with many strongly-coupled degrees of freedom. They are composed of numerous in themselves often simple elements and are characterized by collective properties. EPS consist of numerous equipment modules which are connected to each other and have multi-lateral interactions. Each of them has some degrees of freedom, which are constraint by other system parts. Together, the modules form a system with the desired global behavior.

Chaos Theory is often considered as a part of Complexity Theory, focusing on nonlinear aperiodic dynamics, where the phenomenon of chaos stands for the cases when future outcomes are arbitrarily sensitive to tiny changes in present conditions (Gell-Mann, 1995). Manufacturing systems often exhibit sensitivity to specific conditions and to disturbances. Certain factors lead to system breakdown while others have no significant effect. It is difficult to predict the critical circumstances and to cope with them.

Artificial Life

Taking natural life and its characteristics as an example, scientists attempt to create life-like behaviors with the capability of evolution on computers and other “artificial” media. EPS are very similar to artificial living systems. They have a modifiable structure, will exhibit some kind of self-organization, can adapt to their environment, and react to stimuli. They are capable of evolving according to the circumstances, namely in terms of equipment states, and can incorporate newly available technology. As any living organism, they will include efforts to keep themselves in a constant well-functioning state through self-surveillance and self-management – at least to a certain degree.

The dynamics of swarm-building living organisms as well as the application of the concepts to Artificial Life are studied within the scope of Swarm Theory. Indirect ways of communication, namely stigmergy, have been learned from ant societies: information in the form of volatile pheromones is deposited in the environment and thus reduces or avoids direct communication between too many peers. Mechanisms similar to those found in fish shoals and bird flocks can be used by mobile robots for coordination with their fellows. The robots' autonomy and their capacity of collaboration are fundamental. Being reactive and proactive devices, they often include reasoning capabilities.

Agentified modules in EPS can be seen like the members of a swarm: their coordination can be based on similar strategies. Even if their mechanical properties are diverse, from a software point of view, they have similar or identical characteristics. They can participate in a swarm (respectively a coalition) or withdraw from it, without disturbing the rest of the group, and thus permit true and immediate Plug&Produce functionality.

Autonomic Computing

Although at another level than the other areas described above, Autonomic Computing is a fundamental concept for EPS. The vision of Autonomic Computing (Kephart and Chess, 2003) refers to the tendency of computers to become ubiquitous. Forming large networks and having complex and multiple interactions, they become increasingly difficult to manage. As a consequence, software will be designed to take care of itself. User interaction will be minimized and reprogramming avoided. As already mentioned EPS are very much based on the ideal of having computer power in any module. As EPS address fine granularity this means a CPU almost everywhere. It is very important to emphasise that the more modules of fine granularity include computational power the more is necessary to find new ways of coordination and automatic plugability, which is exactly what EPS want to address. This trend of computational power everywhere can also be detected by the effort being done by Schneider that is developing a Device Profile Web Service (DPWS) able to run on tiny devices (Colombo et al., 2005).

Agents

Depending on the context, an agent can be a human person, an association, an animal, or a piece of software, eventually connected to some hardware. The fundamental characteristics are identity, intelligence and the ability to act and react in order to persecute goals. Agents have at least a certain degree of autonomy and can compete or collaborate with others.

There are numerous successful experiences with agent-based systems in industry (Shen and Norrie, 1999, Parunak, 2000, Marik and McFarlane, 2004, Monostori et al., 2006). Rockwell Automation even develops agent-based systems where the agents run inside the PLC itself (Mařík et al., 2005) instead of on separate computers.

The next two topics: emergence and self-organisation are fundamental in the context of the work being developed in EPS. In areas such as biology and artificial life, emergence and self-organization have been discussed for many years and accordingly, definitions exist. Also for Multi-Agent Systems, these topics have been investigated (Di Marzo Serugendo et al., 2006, Brueckner et al., 2005).

Self-Organization

Reasons for implementing self-organization in EPS are to minimize and facilitate user interaction, i.e. to hide complexity and increase system autonomy. Building and configuring a system composed of numerous entities with multi-lateral interactions is a highly complex task; the more autonomy the system has, the easier it gets for the user. Production systems tend to have many components of diverse nature which interact in many coupled ways. Agents need the capacity of organizing their collaboration themselves, in different forms and compositions, according to the needs, without passing through a central coordination point.

Self-organization is robust and adaptive with regard to its environment. In presence of perturbations and change, the system is capable of maintaining its organization and functionality. This means in practice that the control system should be capable of handling problems and if necessary finding alternative production ways. In natural systems, the “target behavior” is an attractor and the system will again converge towards it. A major challenge in manufacturing applications is to let the system self-organize and at the same time, determine its behavior. Different from natural self-organized systems, artificial systems respectively EPS may require a kind of leader, a broker or (eventually human) decision maker. The control influence of this authority may be punctual in time and scope, e.g. at important strategic points.

Emergence

Complex systems most often consist of at least two different levels: the macro-level, considering the system as a whole, and the micro-level, considering the system from the point of view of the local components. Local components behave according to local rules and based on preferably local knowledge; a representation of the entire system or knowledge about the global system functionality is neither provided by a central authority nor reachable for the components themselves. They communicate, interact with each other and exchange information with the environment. From the interaction in this local world emerge global phenomena, which are more than a straight-forward composition of the local components’ behaviors and capabilities.

Typically, there is a two-way interdependence: not only is the global behavior dependent on the local parts, but their behavior is also influenced by the system as a whole.

Emergent phenomena are scalable, robust, and fault-tolerant, i.e. insensitive to small perturbations and local errors as well as component failure, thanks to redundancy. They exhibit graceful degradation, meaning that there is no total break-down because of minor local errors.

4 Multiagent Based Control Approach

The goal of this section is to briefly describe a multiagent based control solution that was developed to control an industrial like assembly cell: NovaFlex. Due to lack of space only a very brief description is possible.

To successfully implement all the concepts that have been described in the previous sections a stepwise approach was envisaged in order to be able to obtain sound practical results that will smooth the transition to industrial implementation. Therefore the multiagent based control approach being described should be regarded as one step in the direction of an ideal. It should be considered as a foundation infrastructure over which all future developments will take place. The main point in this implementation is the transformation of each module or manufacturing component into an agent, which then becomes an abstraction of the component including its functionalities and enhanced interaction skills (social skills). The basic architecture is depicted in Fig. 4.

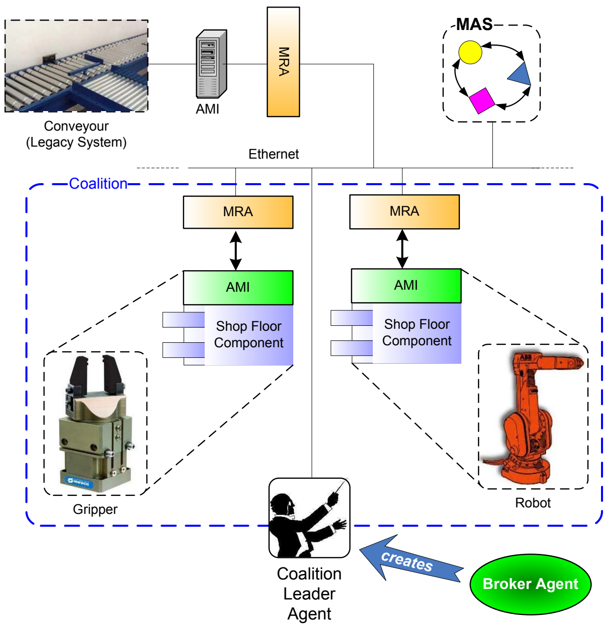

Fig. 1. Multiagent basic architecture

The basic agents that compose the architecture are the MRA – Manufacturing Resource Agent, the AMI – Agent Machine Interface, the Broker Agent and the Coalition Leader Agent.

The fundamental aspect behind this architecture is the notion of coalition of agents. In fact, looking to a shopfloor it is quite easy to grasp the idea that a system is a composition of manufacturing components that somehow are aggregated and cooperate to solve the problem they were designed to solve. Hence, this approach considers that a system is then a coalition of agentified manufacturing components

(MRAs). The problem is how to agentify the manufacturing components and how the coalition.

Another relevant aspect of this architecture is the concept of skill, which are nothing else then descriptions of the components' abilities or functionalities. Taking into consideration, for instance the component robot, the skills offered by the robot agent, when participating in a coalition, are the skill movePTP (joint move), or moveWC (world coordinates). Therefore each agent will be characterized by its set of skills, which will then be used by the broker when helping creating the coalitions. Skills are also used whenever agents are requested to perform some actions, since what they are asked for is to perform one of the skills they have offered.

AMI

An *AMI* is an agent that connects the MRA to its physical controller by offering to the MRA the services (functionalities) existing in the physical component. The components are integrated in the agent's framework using a software wrapper to hide the implementation details. The *AMI* receives requests from the *MRA* and then calls the wrapper to execute the requested service. AMIs exist mainly due to support legacy equipment because it is foreseen that in the future each manufacturing component can include an agent itself and therefore it will not be needed to create a software wrapper to support the connection of legacy controllers to the agent world.

MRA

The *MRA* can be defined as a manufacturing component extended with agent skills, which corresponds to its agentification in order to be able to participate in a society of agents (system).

The MRAs share many of their behaviours or functions. Of course, depending on the agent type, there are some differences. All of them have the interaction ontology java classes in order to allow accurate information exchange (created in *Protégé* and transformed into java classes using *Ontology Bean Generator* plugin). They possess methods to query the shop floor equipment ontology database for essential information as well as catalogue specifications, such as the skills offered by each agent. After the MRA starts, it composes a *DF* entry annunciating its skills in order the other agents can discover them and make use of it. The *MRAs* only react to *FIPA Request Protocol* compliant messages. When the arriving message involves a subsequently execution request to *AMI*, the request is then forwarded to its corresponding AMI.

Broker and Coalition Leader Agents

A coalition is an aggregated group of agentified manufacturing components interacting in order to generate combined functionalities that, in some cases, are more complex than the simple sum of their individual capabilities (Barata, 2005). A coalition is able to execute complex operations that are composed of simpler operations offered by coalition leaders. Every *MRA* can join a coalition, sharing its individual skills, however the components' selection responsibility is totally from the user that had defined it, and each *MRA* does not have performance goals to achieve, neither value system implemented nor contracting negotiation skills.

The broker agent will create, change, and terminate shop floor's coalitions, whenever this will be required by shopfloor needs and it will be executed interacting with a *CoalitionLeader*. This agent is the agent that will lead the coalition and it will be responsible to get all the requests to the coalition. Whenever a coalition must be created the *CoalitionLeader* is created and the broker starts its interaction with it in order to fulfill the desired shopfloor requirements. A fundamental aspect of the *CoalitionLeader* agent is its ability to deal with complex skills, which as the name indicates are compositions of basic skills. The skills supplied by each MRA agent are considered basic skills in the sense that the leader can ask the MRA to perform it. However there are skills that can only be obtained by the interaction between different MRAs, which are then called complex. Complex skills are then a representation of aggregated skills. The advantage of this approach is that coalitions can be always represented as aggregation of skills. If a coalition has a certain type of members then it will be able to perform the actions associated to the skills brought in by its members but also other actions associated to the complex skills that were able to create out of the basic ones. Therefore different types of systems (coalitions) can be created without the need to reprogram, since the leader knows how to generate those complex skills. In the future the intention is to use and study mechanisms in order that these complex skills emerge automatically from the interaction among the coalition members. At this stage, the generation of skills is implemented using rules described in the ontology. Whenever the leader is created these set of rules is inherited and it will be able to generate complex skills whenever its coalition grows or shrinks.

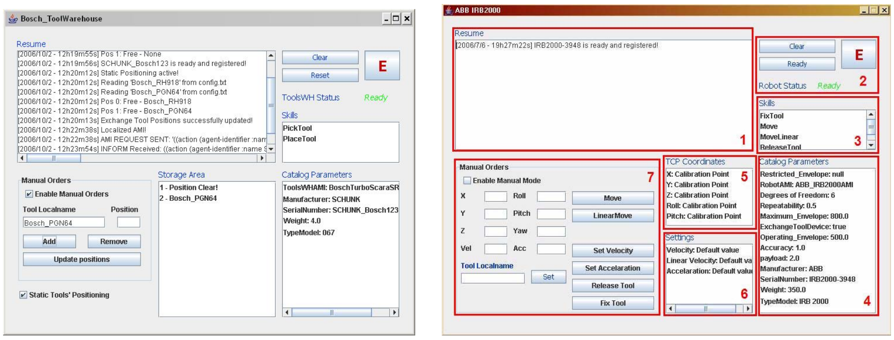

Fig. 2. Examples of two agent's GUI

Fig. 2 shows the user interface for the agent robot and toolwarehouse. The different parameters and possible commands can be seen.

5 Conclusions

The authors are strongly convinced that control architectures able to solve the requirements defined by RMS can only be achieved using a distributed agent based approach with concepts inherited from artificial life and complexity theory. This is mainly due to the fact that these requirements demand architectures in which the global manufacturing system is composed of many heterogeneous intelligent controllers that can be plugged in or out without reprogramming, and without reinitiating the other components. An important aspect that must be taken into account is that developing a control system becomes more a collaborating problem rather than developing a specific algorithm for a pre-determined situation. Rather than being interested in optimality the goal is to find ways to allow cooperation between the modules in a way that solve the goals required by the system. Therefore, concepts such as emergence or self-organisation seems to be very adequate.

The first agent based implementations have proved the adequateness of this paradigm to develop distributed solutions in which intelligent modules can be added or removed without reprogramming, which is a very important point. On the other hand, agents can also be easily used to support further implementations using emergence and self-organisation. However, implementation results still need to be achieved.

6 References

BABICEANU, R. F. & CHEN, F. F. (2006) Development and Applications of Holonic Manufacturing Systems: A Survey. *Journal of Intelligent Manufacturing,* 17**,** 111-131.

BARATA, J. (2005) *Coalition Based Approach For ShopFloor Agility,* Amadora - Lisboa, Edições Orion.

BARATA, J., SANTANA, P. & ONORI, M. (2006) Evolvable Assembly Systems: A Development Roadmap. IN DOLGUI, A., MOREL, G. & PEREIRA, C. E. (Eds.) *INCOM 2006 - 12th IFAC/IFIP/IFORS/IEEE/IMS Symposium on Information Control Problems in Manufacturing.* St Etienne - France.

BRUECKNER, S. A., DI MARZO SERUGENDO, G., KARAGEORGOS, A. & NAGPAL, R. (Eds.) (2005) *Engineering Self-Organising Systems,* Berlin Heidelberg, Springer.

BUSSMANN, S. & MCFARLANE, D. C. (1999) Rationales for Holonic Manufacturing. *Second International Workshop on Intelligent Manufacturing Systems.* Leuven, Belgium.

COLOMBO, A. W., JAMMES, F., SMIT, H., HARRISON, R., MARTINEZ-LASTRA, J. & DELAMER, I. (2005) Service-Oriented Architectures for Collaborative Automation. *IECON'05 - IEEE Industrial Electronics Conference.* Raleigh, NC, USA.

DELIC, K. A. & DUM, R. (2006) On the Emerging Future of Complexity Sciences. *ACM Ubiquity,* 7.

DI MARZO SERUGENDO, G., GLEIZE, M.-P. & KARAGEORGOS, A. (2006) Self-Organisation and Emergence in MAS: An Overview. *Informatica,* 30**,** 45-54.

ELMARAGHY, H. A. (2006) Flexible and Reconfigurable Manufacturing Systems Paradigms. *International Journal of Flexible Manufacturing Systems,* 17**,** 261-276.

GELL-MANN, M. (1995) What is Complexity? *Complexity.* www.santafe.edu/~mgm/complexity.pdf ed., John Wiley and Sons, Inc. .

GOU, L., LUH, P. B. & KYOYA, Y. (1998) Holonic Manufacturing Scheduling: Architecture, Cooperation Mechanism, and Implementation. *Computers in Industry,* 37**,** 213-231.

KEPHART, J. O. & CHESS, D. M. (2003) The Vision of Autonomic Computing. *IEEE Computer,* 0018-9162/03**,** 41-50.

KOESTLER, A. (1989) *The Ghost in the Machine,* London, Arkana.

KOREN, Y., HEISEL, U., JOVANE, F., MORIWAKI, T., PRITCHOW, G., ULSOY, A. G. & VAN BRUSSEL, H. (1999) Reconfigurable Manufacturing Systems. *CIRP Annals,* 48.

MARALDO, T., ONORI, M., BARATA, J. & SEMERE, D. (2006) Evolvable Assembly Systems: Clarifications and Developments to Date. *CIRP/IWES 6th International Workshop on Emergent Synthesis.* Kashiwa - Japan.

MARIK, V. & MCFARLANE, D. C. (2004) Industrial Adoptation of Agent-Based Technologies. *IEEE Intelligent Systems,* 1542-1672/04**,** 22-30.

MAŘÍK, V., VRBA, P., HALL, K. H. & MATURANA, F. P. (2005) Rockwell automation agents for manufacturing. *AAMAS.* Utrecht, NL, ACM Press NY, USA.

MEHRABI, M. G., ULSOY, A. G. & KOREN, Y. (2000) Reconfigurable Manufacturing Systems and their Enabling Technologies. *International Journal Manufacturing Technology and Management,* 1**,** 113-130.

MONOSTORI, L., VÁNCZA, J. & KUMARA, S. R. T. (2006) Agent-Based Systems for Manufacturing. *CIRP Annals,* 55.

PARUNAK, H. V. D. (2000) Agents in Overalls: Experiences and Issues in the Development and Deployment of Industrial Agent-Based Systems. *International Journal of Cooperative Information Systems*.

SHEN, W. & NORRIE, D. H. (1999) Agent-Based Systems for Intelligent Manufacturing: A State-of-the-Art Survey. *Knowledge and Information Systems, an International Journal,* 1**,** 129-156.

THARUMARAJAH, A. (2003) A Self-organising View of Manufacturing Enterprises. *Computers in Industry,* 51**,** 185-196.

THARUMARAJAH, A., WELLS, A. J. & NEMES, L. (1996) Comparison of the bionic, fractal and holonic manufacturing system concepts. *International Journal Computer Integrated Manufacturing,* 9**,** 217-226.

VAN BRUSSEL, H., WYNS, J., VALCKENAERS, P., BONGAERTS, L. & PEETERS, P. (1998) Reference Architecture for Holonic Manufacturing Systems: PROSA. *Computers in Industry,* 37**,** 255-274.