Smooth Migration from the Virtual Design to the Real Manufacturing Control

Paulo Leitão
Polytechnic Institute of Bragança,
Campus Sta Apolónia, Apartado 1134,
5301-857 Bragança, Portugal
pleitao@ipb.pt

J. Marco Mendes
Faculty of Engineering - University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
marco.mendes@fe.up.pt

Armando W. Colombo
Schneider Electric Automation GmbH,
Steinheimer Str. 117, D-63500
Seligenstadt, Germany
armando.colombo@de.schneider-electric.com

Abstract- *The Virtual manufacturing concept is based on the use of computational resources during the design of products and manufacturing systems, reducing the ramp-up time to market and the costs for the system's design, operation and reconfiguration. Combined with emergent paradigms for manufacturing control, such as multi-agent systems and service-orientation principles, and using a formal language to describe the system behavior, e.g. Petri nets, a truly and complete virtual production environment is achieved. This paper discusses this powerful approach to the virtual design and production environment driven by formal models, allowing users to design and deploy collaborative and re-configurable automation applications in a faster and cost-effective fashion. A special attention is devoted to the process of migration from the virtual environment to the real world, aiming to reduce the transition time and increasing the efficiency of the process.*

I. INTRODUCTION

Today's marketplace is characterized by an increasing global competition, demanding highly customized products, shrinking product lifetimes and increasing the products complexity. In this scenario, industries need to address quickly the customers' needs by manufacturing the desired products at the right time and at competitive costs, under the penalty of no longer being competitive. A new class of reconfigurable systems is required, being the traditional centralized, top-down, rigid and static control replaced by the decentralized control over distributed autonomous, cooperative and intelligent entities. Multi-agent systems [1], Holonic manufacturing systems [2-3] and more recently Service-oriented Architectures [4] are emergent paradigms that address the referred requirements.

Several implementations of applying the referred emergent paradigms were reported in the literature (see [5-6] and the references therein) but in spite of their promising potential, their industrial adoption is being very slow. Among other reasons, an issue that contributes for this weak adoption is the missing of formal, mature, structured and integrated engineering frameworks to support the specification, design, verification and implementation of collaborative (agent-based or service-oriented) production control applications, in an easy, modular and rapid manner. Aiming to address this weakness, High-level Petri nets formalism [7] is used in this work as the formal language to specify and validate service-oriented and agent-based applications, taking advantage of its powerful mathematical foundation. In fact, the use of High-level Petri nets allows achieving a formal approach that covers the complete life-cycle of the development process, from the requirements-analysis through the design-validation and implementation of collaborative automation systems and their control systems in an integrated manner [8].

During the development life-cycle, the simulation of the control applications assumes a crucial role, allowing the verification of the correctness of the achieved solution and even testing various "what-if" scenarios to continuously improve/optimize it during the design phase. High-level Petri nets formalism is suitable to execute the simulation, taking into account the system specifications and considering the time parameter associated to transitions. It supports the debug of the system's behavior by easily reproducing abnormal conditions (or at least, conditions that cannot be easily created in real world). The information extracted from the temporal evolution of the High-level Petri nets control model reflects the temporal sequence of the system operation, being easy to check the system compliance with the specified performance indexes, discover cyclic evolution and existence of bottlenecks.

Integrating this formal approach to describe and validate the system's behavior with 2D/3D software tools, a truly and interactive virtual production environment is achieved. This virtual engineering environment uses intensively computational resources to perform realistic design analysis and verification under different scenarios and conditions, and generates feedback in real time.

Using virtual environments to emulate the real world and to support the simulation, it is important to guarantee an easy and smooth migration of the control applications from the virtual environment to the real world. Among others, it is important to guarantee that the control application models behave in a similar manner when deployed into the industrial controllers to run in the real world. If, during the migration process, the designed behavioral models need to be significantly adjusted, the results achieved during the simulation process do not reflect the real system behavior. Additionally, a smooth migration can also imply benefits in terms of reconfigurability, since a higher performance in the migration process may decrease the costs and time associated to perform the re-configuration/adaptation process.

This paper discusses the advantages of using virtual production environments to support the simulation and verification during the design phase. The behaviors are described by the introduction of a formal and structured approach to support the specification and validation of automation systems using the High-level Petri nets as formal language. Integrating the powerful capabilities of High-level Petri nets to support formal verification and simulation with 2D/3D software tools, a computational framework is achieved supporting users to create a virtual design and production environment for the convenient development of automation systems and their supervisory control. This virtual and formal environment permits to achieve an easy and smooth migration from the virtual to the real production environments.

The rest of the paper is organized as follows. Section II overviews the virtual manufacturing concept and analyses the requirements for a smooth migration. Section III discusses a formal and integrated approach, using High-level Petri nets, to support the virtual design of automation systems and the smooth migration to the real world. Section IV presents an experimental case study scenario to illustrate the proposed concepts. At last, Section V rounds up the paper with the conclusions.

II. Virtual Design of Production Systems

The virtual design of production systems aims to provide a computational environment allowing users to develop applications in an emulated real world. As the term “virtual” suggests, these environments can be created, simulated or carried on by means of a computer. In fact, informatics and computational resources play crucial role to provide mechanisms for the visualization and simulation of models describing the system behavior.

A. Virtual Design Environments

Virtual Manufacturing is a concept that has been used by some companies to improve their processes, introducing more quickly new products in the market. In spite of the several definitions founded in the literature, see [9-12], it can be briefly defined as the use of computer models and simulations to model and design manufacturing processes for the purpose of analyzing and understanding them. The strategy is to create an integrated environment, composed by several software tools and systems, aiming to generate a new method to develop products and systems.

Three paradigms of Virtual Manufacturing can be identified [11]: design-centered, production-centered and control-centered. Probably, the most well-known application area of Virtual Manufacturing is the design-centered, where Computer Aided Design (CAD) and Computer Aided Engineering (CAE) software tools are widely used. As an example, the use of Finite Element Analysis (FEA) during the design of the Boeing 373 airplanes to improve the skin quality after the final installation, allowed to minimize the waviness and to increase the fuel economy of the plane, leading to saves of more than 2 million dollars per year. Another well-known example is the use of robotic simulation and off-line programming capabilities. However, in the context of this work, the focus is the production-centered and especially the control-centered Virtual Manufacturing, which uses additional simulations to control models and actual processes allowing seamless simulation for optimization during the actual production cycle [11].

As stated by Cachapa et al. [13], a computational simulation is an attempt to model a real-life situation on a computer so that the behavior of the system can be verified. Simulation has been commonly used to study the behavior of real world manufacturing systems to gain better understanding of underlying problems and to provide recommendations to improve those systems [14]. Being the observation of real systems very expensive and sometimes cumbersome, a simulation model is an easier way to identify bottlenecks and to enhance system performance in terms of productivity, queues, resources utilization, cycle times and lead times [14].

The advantages of using the simulation of the system through the use of virtual production environments (i.e. connecting virtual equipment to the control application) are mainly the following [15]:

- A complete virtual factory automation system model can be built, including the logic control that can be simulated before to be implemented in the physical factory plant.
- The complete system or partial pieces of the system (e.g. lines, cells or equipments) can be debugged and verified without the need to use the (real) physical devices.
- It is easier to reproduce abnormal conditions and to debug with conditions that cannot be easily created in the real world (for example introducing “what-if” scenarios). Especially, dangerous tests in the real world can be done safely in this virtual world.
- The data can be reused for operator training and maintenance, and the simulations can be repeated as many times as necessary to the correct understanding and tuning of the system control or as a feasible study to reuse logic control to other systems.
- The control strategies can be improved/optimized using iterative simulation scenarios and before its practical realization.

Fig.1 illustrates the virtual and real manufacturing environments, with special focus to the iterative process till reaching the correctness and maturity of the solution, using information technologies as the basis platform. After the complete verification of the correctness of the system behavior in the virtual environment, the designed system is migrated to run in the real world, e.g. connecting to the real physical devices.

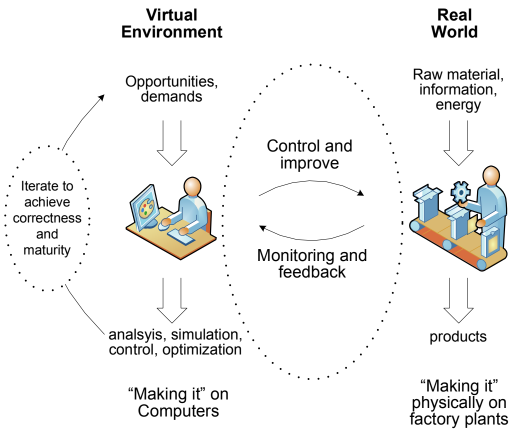

Fig. 1. Virtual and Real Manufacturing Environments (adapted from [16]).

B. *Migration from the Virtual to the Real World*

The migration process is well known within people and animals, representing respectively, the movement from one country or region to another and the movement, usually periodically, from one region or climate to another for feeding and breeding. The migration of birds is one typical example of seasonal migration. In the context of this work, the concept of migration concerns to the movement of a production control application from the virtual environment to the real world, considering hardware and software technologies.

The achievement of an easy and smooth migration from the virtual environment to the real world requires the accomplishment of the following main requirements:

- *Accuracy*: the virtual model should be "calibrated" to represent exactly the real world, namely in terms of layout and device disposition, but also in terms of structural and behavioral control aspects, considering the environment context founded in the real world.
- *Hardware representation*: the hardware constraints should be taken into consideration during the virtual simulation, i.e. virtual devices should emulate correctly the functionalities of the physical relatives, e.g. showing a correct mapping of the sensors and actuators connected to the industrial controllers I/Os.
- *Integration*: the deployment mechanism should simplify the migration of the control solution to the real world, considering interfaces allowing integrating various industrial controllers available in the market.
- *Re-configuration*: the use of model-driven approaches in the development of control solutions allows simplifying the re-configuration capability by reducing the complexity and costs in the deployment phase.

A pertinent question is how existing software tools and approaches to develop collaborative automation solutions address the smooth migration problem, fulfilling the described requirements.

The use of 2D/3D software tools allows creating virtual environments for production systems, presenting generally some limitations in terms of migration. As an example, the Delmia Automation tool from Dassault Systèmes provides a 3D environment where virtual systems can be modeled and controlled, being part of a 3D Product Lifecycle Management (PLM) which supports the product lifecycle from product design to planning and realization [17]. Delmia Automation tool already enables the validation of the control logic in a simulation environment and the programming of various Programmable Logic Controllers (PLCs), but the migration to the real world still presents some obstacles:

- The validation is achieved by the simulation of the model but a validation using formal languages is missing.
- The deployment into industrial controllers is strongly dependent of the developed interfaces, requiring more integration and interoperability compatibilities.
- It is not prepared to accommodate multi-agent systems and service-oriented automation ecosystems

Other software tools present even more limitations in terms of validation and migration processes.

In terms of existing approaches to develop automation control solutions, a comparison is illustrated in Fig. 2.

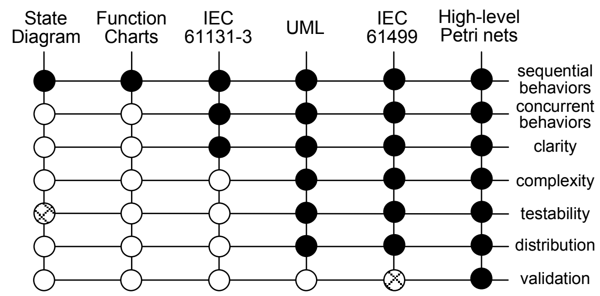

Fig. 2. Comparison of Modeling Methods for Automation Applications.

It is clear that State Diagrams, Function Charts and IEC 61131-3 modeling approaches present several drawbacks to model and validate efficiently collaborative automation systems. IEC 61499 allows analyzing models of control systems and proves their properties, but it requires the use of external languages, such as Prolog and Net Condition/Event Systems [18]. In fact, only Petri nets allow simulating the behavior model and consequently formally verifying the system specifications, using its own formalism. This capability to support the simulation and verification of the system correctness permits to achieve a sooth migration from the virtual design to the real control environment.

III. Formal and Integrated Approach for Smooth Migration

As previously referred, the development of production control systems is usually carried out manually and not derived from a model-like description of the production system. The correctness of such design can only be validated in the implementation phase, presenting high rates of misunderstanding and mistakes, and, as a consequence, it is very expensive [8].

A. *High-level Petri nets Approach*

The approach proposed in this work considers the High-level Petri nets as the formal language for the description of the behavioral models of the production system. Being a formal method to describe and validate certain typical relationships, such as concurrency and parallelism, synchronization, resource sharing, mutual exclusion, monitoring and supervision [19], High-level Petri nets are suitable for the formal specification and validation of production control systems. Using the mathematical foundation associated to High-level Petri nets, the analysis, validation and simulation can be performed: the first ones using the functional algebra theory, e.g. analyzing the T- and P- invariants, and the other one by means of a token game (simulation of the Petri net according to its rules) considering the time parameter associated to the transitions.

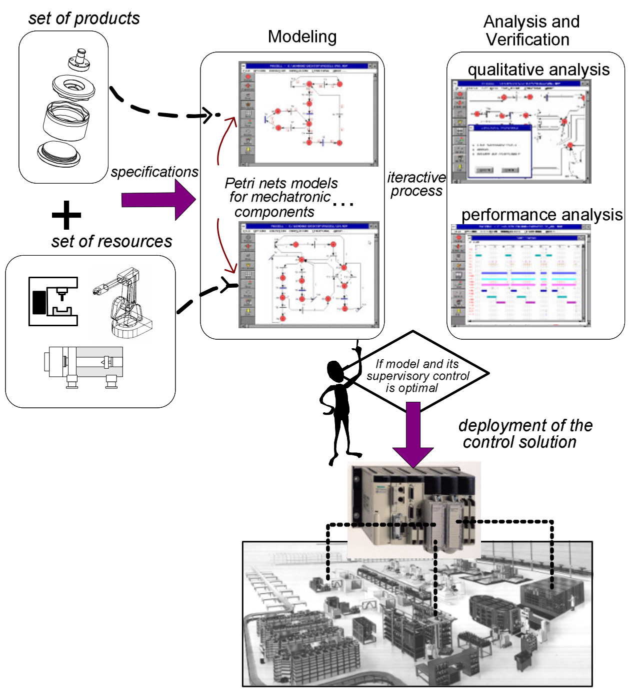

Fig. 3. Design of Collaborative Automation Systems using the High-level Petri nets formalism [8].

The proposed High-level Petri nets engineering methodology provides a catalogue of services that simplifies the development life-cycle of collaborative automation systems, from the design to the operation and re-configuration [8], as illustrated in the Fig. 3. It simplifies the definition and formal specification of an “encapsulation process” in industrial collaborative production systems. The dynamic behavior of collaborative (agent-based or service-oriented) control units is formally modeled and validated using High-level Petri nets, which ensure a rigorous specification due to its powerful mathematical foundation. As an example, when dealing with service-oriented systems, the services are associated to transitions that can be stepwise refined to get more detailed models.

Once the control system is designed and simulated, being its specification verified in the virtual environment, it is required to set the system into operation by migrating the control solution to the real world. The methodology introduces as innovation the integration of modeling, analysis and validation processes, leading to a reduction of the development costs and time effort, supporting also the adaptation and re-configuration needs.

B. *Continuum Development Tools*

The application of Petri nets can range typical from systems with predictable behavior to more complex ones with distributed participants. In any case, system engineering and associated tools are required to facilitate the developer's intervention. From the Petri nets side, the practical usage is limited by the lack of computer tools which would allow handling large and complex nets in a comfortable way [20]. Therefore, the Continuum Development Tools has being developed according to the described engineering approach to provide a user-friendly environment for several engineering tasks of service-oriented/multi-agent automation systems. It covers the specification and configuration of automation systems, the analysis and simulation, and also the operation of the system.

As an example, Fig. 4 represents a screenshot illustrating the simulation of the control logic for an automation system, represented using a Petri net model.

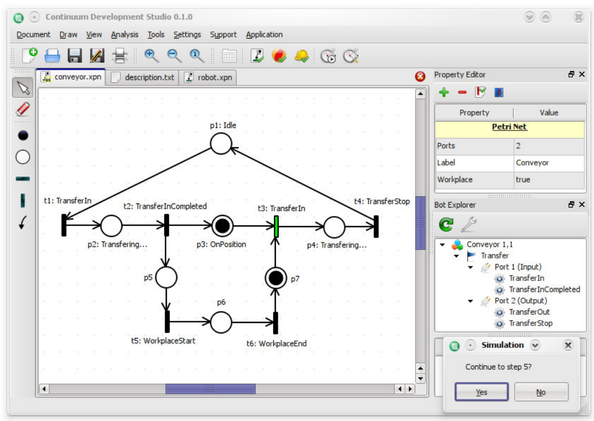

Fig. 4. Main GUI of the Continuum Development Tools.

The integration of 2D/3D visualization tools, such as Delmia Automation and Arena, with the High-level Petri nets based service-oriented engineering framework establishes a complete support for the development life-cycle, offering the possibility to experiment in a virtual 2D/3D environment the production system, helping to achieve maximum production efficiency, lower cost, better quality and short time to market.

The resulted virtual simulation is driven by the High-level Petri nets based logic control engine provided by the Continuum framework. In the proposed engineering framework, the simulation process is executed iteratively, modifying and adjusting the production control system parameters, till reaching the correctness of the control system behavior. The validation and simulation of the control system during the design phase, allows reducing significantly the costs and the number of mistakes detected in the operation phase.

After the complete verification of the correctness of the virtual production system behavior, the production control system is ready to be migrated from virtual environment to the real world, as illustrated in Fig. 5.

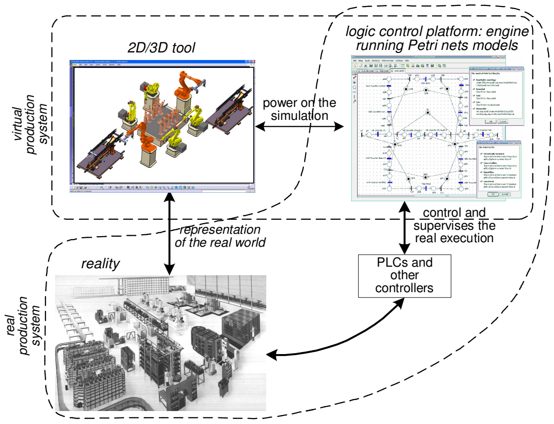

Fig. 5. Migration from Virtual to Real World using the High-level Petri nets Formalism.

For this purpose, the Continuum platform deploys the control models into industrial controller devices, such as PLCs and microcontrollers, which will run the control solution in the real production systems.

Aiming to support a smooth migration, the proposed engineering framework provides the capability to export the control logic models (described in High-level Petri nets) using XML (eXtended Markup Language) language. The XML-like control logic model can then be easily read and understood by the industrial controllers without any additional customization or parameterization, increasing the integration and compatibility aspects.

As an example, the Delmia Automation tool is used to export information, expressed in XML, about the virtual devices (e.g. their connections), being that information used by the Continuum platform (that contains the model classes) to connect and aggregate the devices. Delmia Automation and Continuum were integrated with the SOA4D version of DPWS (Device Profile for Web Services) [21] to permit the conversation between different software pieces and devices via service-orientation.

IV. Experimental Case Study Scenario

Aiming to illustrate the feasibility of the proposed concepts, an experimental case study was considered. It is based on the FlexLink™ Dynamic Assembly System (DAS) 30, comprising several unidirectional and cross conveyors arranged in a closed-loop configuration, and two lifters connecting the upper and lower systems, as depictured in Fig. 6. When circulating in the system, a pallet is faced with several decision points, as the one illustrated in the figure. The decision point represents a fork in the paths of the work-piece, upon which it can either continue straight on to the end lifter, or turn in the direction of one of the two workstations.

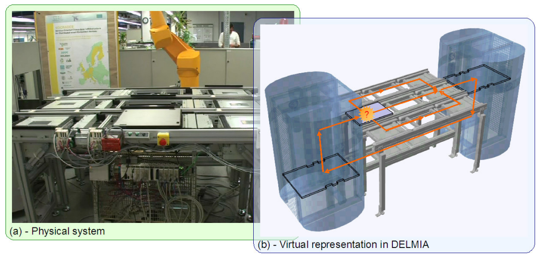

Fig. 6. Physical and Virtual Representation of the Case Study Scenario.

The objective was to develop a service-oriented control application for the experimental system using High-level Petri nets for the behavior description, composition and coordination, and the Delmia Automation tool as a 3D software tool to represent virtually the devices, offering virtual services that encapsulate their functionalities.

The production cell was initially designed using the Delmia Automation software tool, being the devices assembled in the model and properly configured. For this purpose, it was used autonomous DPWS-enabled smart devices [13], representing conveyors, cross-tables and lifters, composing virtual devices that offer their functionalities as services being hosted in the Delmia Automation software tool. At this moment, the system is ready for emulation being necessary to develop the control solution that will drive the virtual production system.

The service-oriented control system was developed using the Continuum platform, with the behavioral models of each device, i.e. lifters and unidirectional and cross conveyors, being described using High-level Petri nets. A synthesized High-level Petri nets behavioral model has been composed from the individual behavioral models according to the layout of the virtual production cell, using the information about the device connections provided by the Delmia Automation tool. The connection of the models is done through specific interfaces (ports), which, when connected, drive the correct collaboration between the two connected components. The configuration of the models with DPWS properties allows the embedded High-level Petri nets engine to discover and invoke the virtual services that were hosted in the Delmia Automation software tool.

The achieved virtual system offering virtual services combined with the High-level Petri nets control models constitutes the virtual production system that can be simulated. When the simulation starts, each virtual device will automatically initialize, launching and configuring an unique Web service interface and start waiting for control commands. At this point, services are available and any compliant application can search in the network and use them.

The execution of the simulation is performed by running the High-level Petri nets models, i.e. running the token game. A virtual pallet representing the work-piece is added to the system so that the model can react to control commands and changes in the environment. When executing a High-level Petri nets model inside the Continuum platform, the status of the High-level Petri nets model is made visible in the graphical Petri nets editor, giving information about the current marking and the enabling- and the firing-modes of the executed Petri nets model. At this stage, alternative simulations can be performed in the virtual environment by changing the system parameters, introducing the degradation of the conveyors and including more virtual pallets that leads to the increase of the traffic congestion.

In spite of being an early prototype experimentation, some important concepts were observed, namely, that complex systems can be easily modeled, analyzed and simulated in a truly virtual environment, that combines 2D/3D simulation software tools and the High-level Petri nets computational environment. A demonstration video including this approach can be seen at http://www.youtube.com/watch?v=0aRRvqEln2I.

Important to this work is the reference that the transition to the real system is done in such a way that the control models, previously analyzed in the virtual environment, remain the same, being not necessary the re-engineering of the control system. In the experimental case, a PC was used to host the control application running with the real devices. Moreover, the use of Web services between the control applications and the virtual/real equipment facilitates not only the communication, but also the integration of these virtual/real scenarios. These observations allow to conclude, in a preliminary stage, that the control solution was smoothly migrated from the virtual environment to the real environment.

V. CONCLUSIONS

This paper discusses the use of virtual engineering environments to support the fast, easier and structured design of production control systems, taking special attention to the requirements for an easy and smooth migration from the virtual to the real production system.

Aiming to achieve a formal and structured framework for the development of collaborative automation systems, the proposed approach considers the use of High-Level Petri nets to drive the system's behavior (both in virtual and real worlds), making easier and reducing the effort in the transition from the design and analysis phases done in the virtual environments to the real-time operation phase. In fact, taking advantage of the powerful mathematical foundation associated to the Petri nets formalism, a rigorous specification, analysis and verification of the system correctness can be performed during the design phase and before to deploy the control solution into practice. The simulation procedure can be combined with the integration with 2D/3D software tools, allowing an easy and user-friendly interaction during the design and simulation processes.

The proposed concepts were illustrated using the Continuum platform to develop the service-oriented control application for the experimental case study, emulated in the Delmia Automation tool and hosting virtual services.

ACKNOWLEDGMENT

The authors would like to thank the European Commission and the partners of the EU IST FP6 “Service-Oriented Cross-layer infrastructure for Distributed smart Embedded devices” (SOCRADES) project, the EU FP6 “Innovative Production Machines and Systems” (I*PROMS) Network of Excellence, and the ICT FP7 “Cooperating Objects” (CONET) Network of Excellence, for their support.

REFERENCES

[1] Wooldridge, M., “*An Introduction to Multi-Agent Systems*”, John Wiley & Sons, 2002.

[2] Koestler, A., “*The Ghost in the Machine*”, Arkana Books, London, 1969.

[3] Leitão, P., Restivo, F., “ADACOR: A Holonic Architecture for Agile and Adaptive Manufacturing Control”, *Computers in Industry*, 57 (2), 2006, pp. 121-130, Elsevier.

[4] Jammes, F. and Smit, H., “Service-oriented Paradigms in Industrial Automation”, *IEEE Transactions on Industrial Informatics*, 1(1), 2005, pp. 62–70.

[5] Leitão, P., “Agent-based Distributed Manufacturing Control: A State-of-the-art Survey”, to appear in the *International Journal Engineering Applications of Artificial Intelligence*, 2009, Elsevier.

[6] Babiceanu, R. and Chen, F., “Development and Applications of Holonic Manufacturing Systems: a Survey”, *Journal of Intelligent Manufacturing*, nº 17, 2006, pp. 111-131.

[7] ISO/IEC 15909, 2000. High-level Petri Nets - Concepts, Definitions and Graphical Notation. Final Draft International Standard ISO/IEC 15909.

[8] Leitão, P. and Colombo, A.W., “Petri net based Methodology for the Development of Collaborative Production Systems”, Proceedings of the 11th IEEE International Conference on Emerging Technologies and Factory Automation, 2006, pp. 819-826.

[9] Iwata, K., Onosato, M., Teramoto, K., and Osaki, S., “A Modelling and Simulation Architecture for Virtual Manufacturing Systems”, *Annals of the CIRP*, 44 (1), 1995.

[10] Bowyer A., Bayliss, G., Taylor, R., and Willis, P., “A Virtual Factory”, *International Journal Shape Model*, 2(4), 1996, pp. 215-226.

[11] Lin, E., Minis, I., Nau, D. and Regli, W., “*Virtual Manufacturing User Workshop*”, Lawrence Associates Inc., July, 1994.

[12] Marinov, V., “What Virtual Manufacturing is?”; http://bosphorus.eng.emu.edu.tr/vmarinov/VM/VMdef.htm, 2000.

[13] Cachapa, D. Colombo, A. Feike, M. and Bepperling, A., “An Approach for Integrating Real and Virtual Production Automation Devices Applying the Service-oriented Architecture Paradigm”, Proceedings of the 12th IEEE International Conference on ETFA, 2007, pp. 309-314.

[14] Ali, S. A., Seifoddini, H. and Sun, H., "Intelligent Modeling and Simulation of Flexible Assembly Systems", Proceedings of the 37th Conference on Winter Simulation Conference, 2005, pp. 1350-1358.

[15] Leitão, P., Mendes, J.M., Bepperling, A., Cachapa, D., Colombo, A.W. and Restivo, F., “Engineering Tools for the Integration of Service-oriented Production Systems”, to appear in the Proceedings of the 13th IFAC Symposium on Information Control Problems in Manufacturing, Moscow, Russia, 2009.

[16] Saadour, M. and Sandoval, V., “Virtual Manufacturing and its Implications”, Virtual Reality and Prototyping, June, 1999.

[17] ARC Advisory Group, “DELMIA V5 Automation Platform: Merging Digital Manufacturing with Automation”, ARC White Paper, February 2006.

[18] Vyatkin, V. and Hanisch, H.-M., “A Modeling Approach for Verification of IEC 61499 Function Blocks using Net Condition/Event Systems”, Proceedings of the 7th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA´99), 1999, pp. 261-270.

[19] Murata, T., “Petri nets: Properties, Analysis and Applications”, *IEEE*, vol. 77, 1989, pp. 541-580.

[20] Suraj, Z., Fryc, B., Matusiewicz, Z. and Pancerz, K., “A Petri Net System -an Overview”, *Fundamenta Informaticae*, 71 (1), IOS Press Amsterdam, The Netherlands, January 2006, pp. 10 -119.

[21] Microsoft, 2006. Devices Profile for Web Services. Avail. at http://schemas.xmlsoap.org/ws/2006/02/devprof/