Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnline Papers Online CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 51-2 (2018) 266–271

Petri Net Model of a Smart Factory in the Frame of Industry 4.0

Juan-Ignacio Latorre-Biel*. Javier Faulín. Angel A. Juan***. Emilio Jiménez-Macías******

** Institute of Smart Cities. Public University of Navarre. Spain*
(e-mail: juanignacio.latorre@unavarra.es).
*** Institute of Smart Cities. Public University of Navarre. Spain.*
(e-mail: javier.faulin@unavarra.es).
**** Internet Interdisciplinary Institute. Dept. of Computer Science.*
Open University of Catalonia. Spain (e-mail: ajuanp@uoc.edu).
***** Dept. of Electrical Engineering. University of La Rioja. Spain*
(e-mail: emilio.jimenez@unirioja.es).

Abstract: Industry 4.0 advocates an intensive use of information and communication technologies in manufacturing facilities for achieving sustainability and success in a market with exigent and informed consumers willing personalized products and services. Three main concepts of the Industry 4.0 paradigm are addressed: cyber-physical systems, the Internet of Things, and virtualization. A Petri net model of a smart factory regarding the Industry 4.0 paradigm is proposed as virtualization for decision making support. Enhanced computing and communication capabilities of machines and products allow implementing the approach of mass customization. Any product is associated to a sequence of services, being able to request them to the appropriate machines. The formalism of the object Petri nets has been chosen, where a token net is associated to the product and a system net to the facility. The resulting model can be considered for analysis, performance evaluation, and decision making support.

Keywords: Petri nets, Industry 4.0, modeling and simulation, decision support system, smart manufacturing.

1. INTRODUCTION

Industry 4.0, or the fourth industrial revolution as it has also been named, implies significant changes in manufacturing. The reduction in the cost of electronic devices that can provide with sensing, communication, and computing capabilities to production devices allows boosting field data harvesting and device network connectivity to the Internet. In this context, machines and products may become cyber-physical systems, which can process data and participate in decentralized decision making (Basile et al., 2016). Additionally, connectivity to the Internet, in the frame called Internet of Things (IoT), allows sending data from the production process and devices to distributed servers, also connected to the Internet, and interpret it through big data and cloud computing algorithms.

Virtualization is another characteristic of Industry 4.0. It can be achieved by the development of simulation models of a factory, where different management and design strategies can be tested before putting them into practice and for helping in real time decision making.

Decision making in complex systems has been carried out extensively in different application fields using virtualization based on several approaches, such as:

a) Discrete event simulation (Baruwa et al. 2015; Bergero and Kofman 2014; Latorre-Biel et al., 2013a).

b) Heuristic and metaheuristic algorithms for searching in the solution space (Angel et al. 2015; Mujica-Mota 2015; Latorre-Biel et al. 2017).

c) Choice of an appropriate formal language to represent a model of the system of interest (Latorre-Biel et al. 2016; 2013b; 2011a).

d) Development of simplified and efficient models for describing a system of interest (Bourdil et al. 2016; Latorre-Biel et al. 2015; 2011b; 2010).

e) Other features, for example using an agent-based approach (Bruzzone et al. 2015), sequencing decisions (Latorre-Biel et al. 2014a), or solving optimization problems with disjunctive constraints (Latorre et al. 2014b; c).

The present paper provides with a contribution for the development of a Petri net (PN) model of a manufacturing facility in the frame of industry 4.0. This model fits into all the categories of virtualization presented in the previous paragraphs, since it allows simulation, it can be included in an optimization problem with metaheuristic-guided search and disjunctive constraints, and uses an adequate formalism for the construction of an efficient model and is able for implementing an agent-oriented perspective. Additionally, the main features of cyber-physical systems, applied to

10.1016/j.ifacol.2018.03.046

products with computing, sensing, and communication capabilities, can be described by the proposed model.

PNs present a widespread application in modelling automated and flexible manufacturing facilities (Silva, 1993).

In the smart manufacturing facility described in this contribution each particular product is manufactured following the order of a customer, which collaborates in the design of the product by adjusting some of its features in a website or mobile app. This information of the fabrication of the product purchased by the customer is sent directly to the production line; thus, configuring the list of services that will be required by the product during its manufacturing process. Sensors, computing capacity, and communication allow the product to know where it is and to find the appropriate machine to ask for a certain service, such as machining, assembly, addition of a given raw material, etc. Once all services are completed, the product is packed and delivered.

Industry 4.0 and smart factories have been the focus of several research papers. For example, Dunke and Nickel (2015) propose a simulation-optimization approach for dealing with some information and communication technologies of industry 4.0. PNs have also been implemented in Industry 4.0 and smart factories. For example Long et al. (2016) present some application examples dealing with machine availability and self-organization. Zhang et al. (2016) propose a PN model for handling exceptions, while Kahloul et al. (2016) implement reconfigurable object PNs for designing reconfigurable manufacturing systems. Mendes et al. (2010) deals with a service-oriented approach in a production facility by PN composition.

The main contribution of this paper consists in the development of a PN model of a smart factory using the formalism of object PNs to represent the subtleties of the Industry 4.0 manufacturing approach.

The rest of the paper is organized as follows. Section 2 introduces the object PNs. Section 3 describes the chosen smart factory, while section 4 discusses its PN model. Last section is devoted to the conclusions.

2. OBJECT PETRI NETS

The paradigm of the PNs has been considered to represent a smart factory in the frame of Industry 4.0 (see figure 1). In particular, some tokens in the considered PN model of a smart factory may represent products (see figure 2), while others may model resources (see figures 3). In the frame of Industry 4.0, products might store, process, and communicate data; hence, experiencing different states depending on their production status. It is natural to represent products showing a dynamical behaviors as PNs themselves.

Object PNs, developed under the paradigm of nets-within-nets, can describe tokens as PNs. Moreover, these token PNs, or object PNs as they are also called, can synchronize their evolution between them and with diverse production equipment, which is appropriate for modeling products in the context of Industry 4.0. These synchronization processes can be performed by different interaction mechanisms.

Token nets represent the value of the state variables of a PN modeling the smart factory, called system net, in the form of tokens of the system net places.

The set of a system net and its object nets associated to it as tokens is called object net system. An introduction to this topic can be found in Valk (2004).

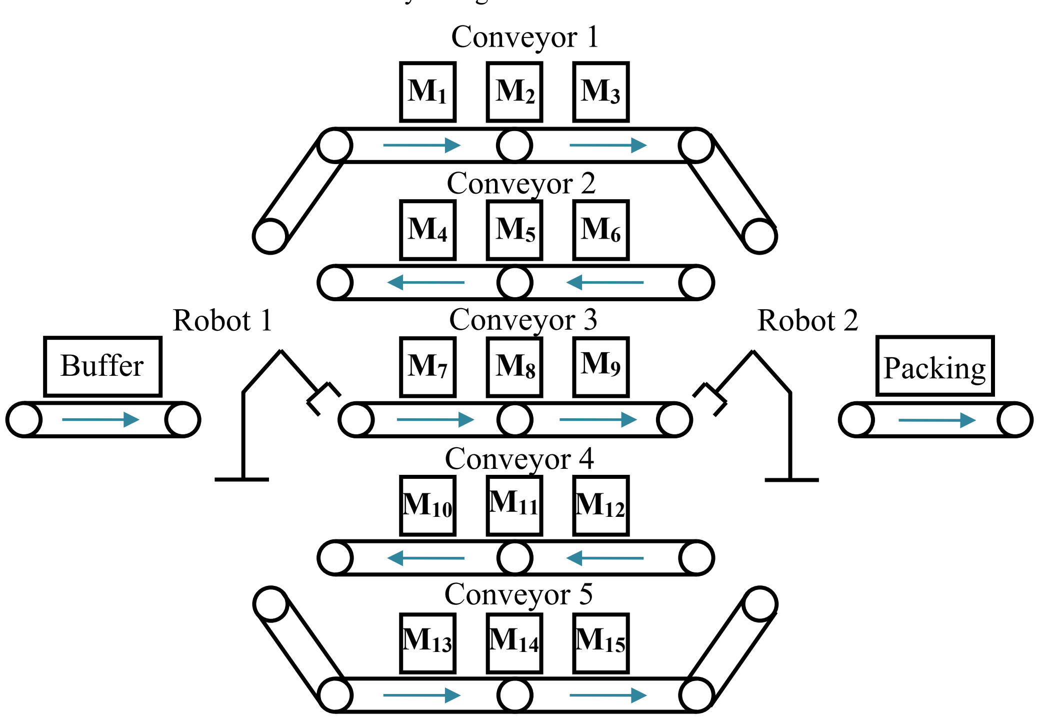

Fig. 1. Layout of the manufacturing process.

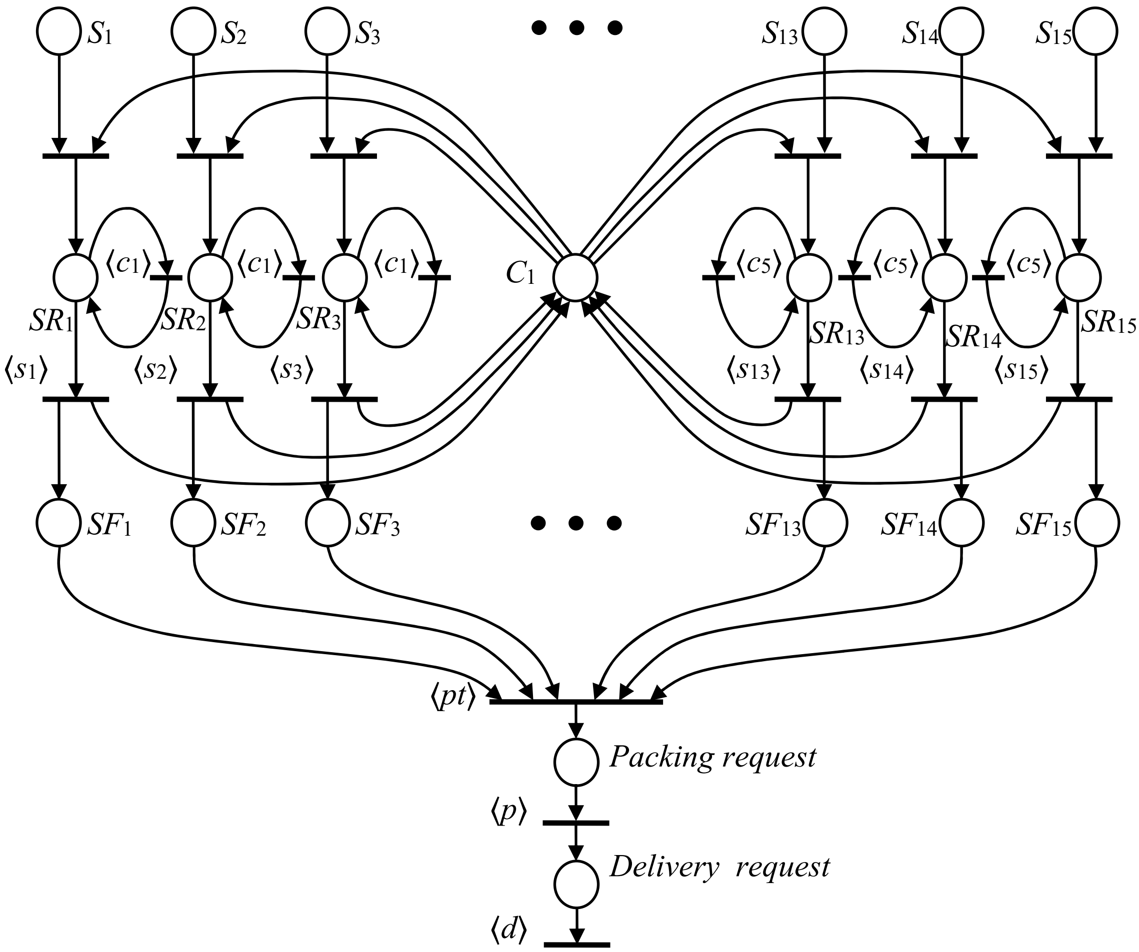

Fig. 2. Token net representing a single product.

The transitions of a token net and a system net that are synchronized (interact) can be labeled by a common symbol, such as <name>. The marking of a token net is constituted by black tokens. However, the marking of a system net can be composed by token nets, as well as by black tokens. A place presents an associated token type: object nets or black tokens.

3. APPLICATION CASE

In the application case of this paper, the following emerging technologies have been considered:

a) Cyber-physical systems, since products and machines present computing, sensing, and communication capabilities.

b) IoT, since communication between products and machines allows decentralized decision making.

c) Virtualization, since a model of the production process is developed for decision making support.

The application case can be associated to a company offering a product that can be configured by the user in a website or mobile application software; hence, this information proceeds directly to the manufacturing facility. It is not required an order of fabrication from a management level of decision, but the information of the product acquired by the user is added to the waiting orders queue. Hence, it is possible to arrive to the concept of batch one or mass customized products. Under this approach, it is possible to manufacture simultaneously a large amount of different products.

The considered smart manufacturing facility counts on a number of machines that can perform different actions to the products. Each product requests services to one or several machines, with the purpose of manufacturing the final product. These services can be requested via the IoT and thanks to the capabilities of communication and information storage associated to the products or to their bases or containers. An example is a food product that can be configured by different combinations of a certain number of raw materials. Each machine supplies one specific raw material.

In the present example 15 machines are considered. In order to convey the products, 2 robots and 6 conveyor belts are considered. Five of the conveyor belts transport semi-finished products to the production machines.

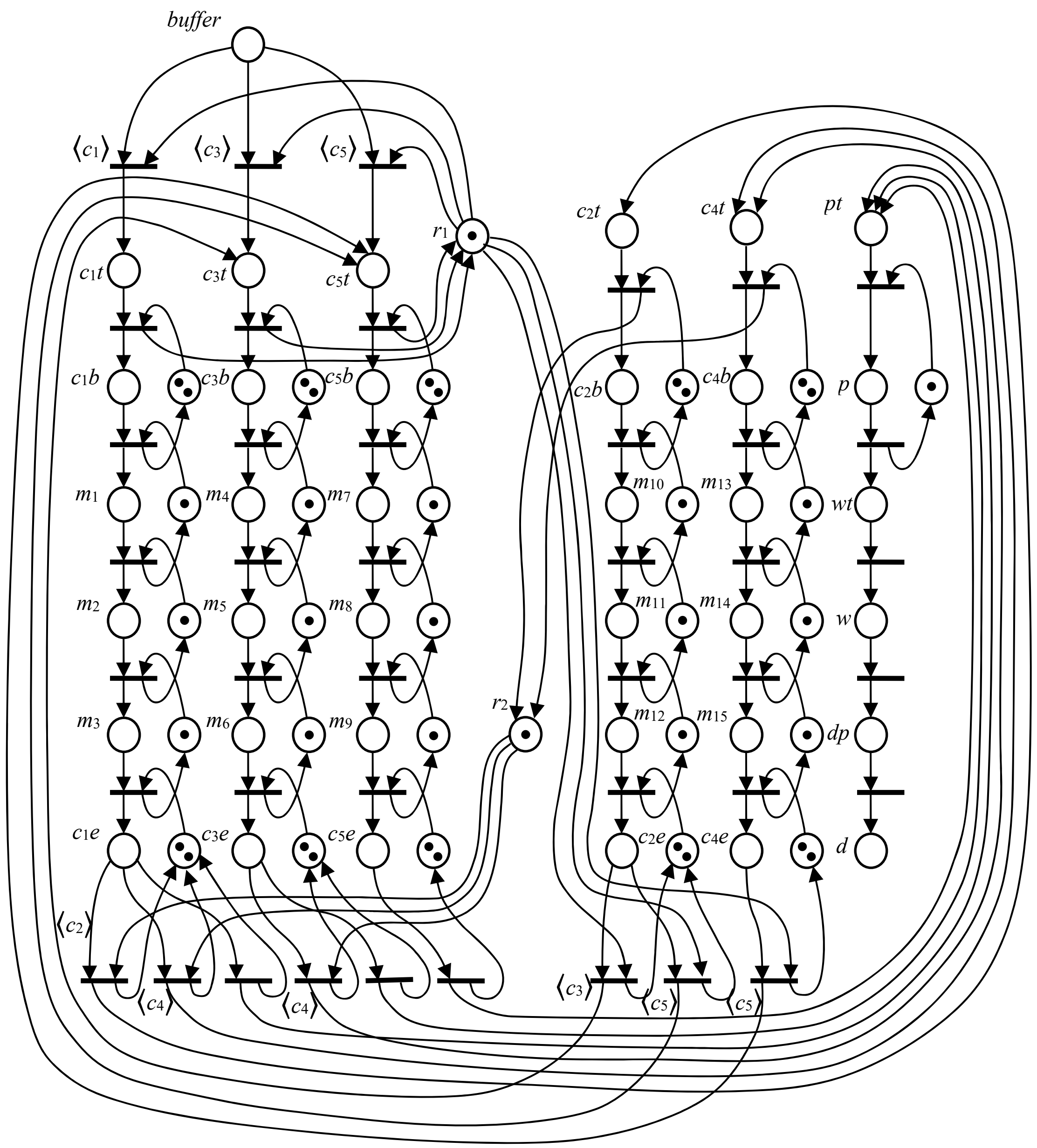

Figure 3. System net representing the manufacturing facility.

Each conveyor belt moves products for reaching three of the production machines. Robot 1 loads conveyor belts 1, 3, and 5 and unloads conveyor belts 2 and 4, and also the buffer of bases or containers for individual products. Each one of this bases or containers holds the product during the manufacturing process and may contain computing and communication capabilities. Moreover, robot 2 loads conveyors 2 and 4 and final conveyor to the packaging station and unloads conveyors 1, 3 and 5. Figure 1 shows a representation of the layout of the factory.

This case can be easily generalized for more machines at every conveyor and for more conveyors.

4. MODEL OF A SMART FACTORY

The model of the smart factory described in the previous section and developed with the formalism of the object PNs is composed of:

a) Token net. It is a PN model of a single product, which can request different services along its manufacturing process. Every active product is modeled by a different token net.

b) System net is the PN model of the manufacturing facility. Black tokens in some places represent products. The communication between system net and tokens nets allows requesting services.

Figure 2 shows the net structure of a token net. The first row of places $\{S_1, S_2, \ldots, S_{15}\}$ represents the list of services required by the product modeled by this PN. 15 production machines provide services; hence, also 15 places represent the 15 potential service requests.

The second row of places, $\{SR_1, SR_2, \ldots, SR_{15}\}$, represents the service that is active at a certain instant. Place C_1 guarantees that a single service is requested at a given time. A strategy for assigning priorities to the output transitions of C_1 consists of giving more priority to the service with smallest ordinal number: the highest priority corresponds to S_1 and the lowest to S_{15}.

The third row of places $\{SF_1, SF_2, \ldots, SF_{15}\}$ is for services already performed. After all services have been performed, packing and delivery services are requested.

The initial marking of one of these token nets requires a token in C_1 and 15 additional tokens in row S_i , representing requested services, and row SF_i , representing non-requested services.

Figure 3 represents a Petri net model of the smart factory represented in figure 1 and plays the role of system net in the frame of an object Petri net. Their tokens are, in fact, Petri nets called token nets (see figure 2).

This system net is a Petri net model composed of the following subsystems:

a) Buffer of bases or containers for holding the product along the manufacturing process. This subsystem is represented by the place *buffer*.

b) Robots, which allow loading and unloading the conveyor belts of the buffer and the different machines (conveyors 1 to 5 in figure 1).

c) Conveyor belts that give access to the different machines: conveyor 1 to machines 1 to 3; conveyor 2 to machines 4 to 6; conveyor 3 to machines 7 to 9, conveyor 4 to machines 10 to 12; and conveyor 4 to machines 13 to 15. Every conveyor is described by 6 places: transport to conveyor (c_it), initial section of the conveyor (c_ib), machines accessible from this conveyor (m_i, m_j, m_k), final section of conveyor (c_ie).

d) Final stages of packing (places transport to packing –*pt*– and packing –*p*–), storage (places transport to warehouse –*wt*– and warehouse –*w*–), and delivery (delivery preparation –*dp*– and delivery –*d*–).

It is convenient to notice that there are some structural conflicts in the token net as well as in the system net represented in figure 2 and 3, respectively. In particular, Petri net in figure 2, presents a structural conflict in the output transitions of place 1. This structural conflict will become actual conflict in the case that more than 1 service is requested by the product to be manufactured. A solution to this conflict can be obtained by assigning the highest priority to the transition associated to the lowest ordinal service and reducing the priority as the ordinal of the service increases.

Furthermore, there are two structural and actual conflicts in the output transitions of both robots. A deterministic priority assignment policy should be applied to the transitions involved in both conflicts, with the purpose that all services requested by the different products are satisfied as soon as possible. In order to achieve this objective, it is necessary to minimize the transportation time of every product.

The interaction between the token nets and the system net is performed through some synchronized transitions, labeled with specific names between the symbols "⟨⟩".

In particular, some transitions are labeled with $\{\langle c_1\rangle, \langle c_2\rangle, \langle c_3\rangle, \langle c_4\rangle, \langle c_5\rangle\}$ in both, the token net and the system net. These transitions represent the activation of a transport request by a product to one of the five conveyors. This request is performed in a place that also represents the request of a specific service in a particular machine. As a consequence, the same place presents an additional output transition labeled $\langle s_i\rangle$, where $i = 1, \ldots, 15$. In order to avoid a more complex representation of the system net, figure 3 does not represent the transitions that interact with the ones belonging to the token nets, labeled $\langle s_i\rangle$. However, a complete representation of the system net should include a transition that is an output and input node of each place labeled m_i. This transition should be labeled $\langle s_i\rangle$.

Finally, transitions labeled $\langle pt\rangle$, $\langle p\rangle$, and $\langle d\rangle$ represent in the token nets and the system net the request of transportation to the packing station, the packing operation, as well as the delivery process respectively.

5. CONCLUSIONS

This paper has proposed the use of the formalism of object Petri nets as very appropriate for modeling a smart factory in the context of Industry 4.0. A token net is able to represent any product, whose state may change along the production process as long as it requests services to the production equipment for completing its manufacturing.

A system net is able to represent the manufacturing facility, more conventionally regarding the modeling of flexible manufacturing systems previous to the Industry 4.0 paradigm. However, this model describes a manufacturing facility, whose layout has been defined finding a compromise between complexity in the transportation means of the products and keeping the possibility that any product can visit any of the production machines. This layout is a consequence of the need for batch size 1 production, also called mass customization.

This model should be put to the test for obtaining a deeper insight in the behavior of a smart factory by means of simulation, as well as structural analysis. As a consequence, better strategies for the success of profitable as well as social and environmentally concerned manufacturing can be developed.

REFERENCES

Angel A.J., Faulin J., Grasman S.E., Rabe M., and Figueira G. (2015). A review of simheuristics: Extending metaheuristics to deal with stochastic combinatorial optimization problems. Operations Research Perspectives, 2: 62–72.

Baruwa O.T., Piera M.A., and Guasch A. (2015). Deadlock-Free Scheduling Method for Flexible Manufacturing Systems Based on Timed Colored Petri Nets and Anytime Heuristic Search. *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 45(5):831-846.

Basile, F., Chiacchio, P., and Coppola, J. (2016). A cyber-physical view of automated warehouse systems. *In proceedings of the 2016 IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 407-412. Fort Worth, TX, USA, August 21-24, 2016.

Bergero F. and Kofman E. (2014). A vectorial DEVS extension for large scale system modeling and parallel simulation. *SIMULATION: Transactions of The Society for Modeling and Simulation International* 90(5):522-546.

Bourdil P.A., Berthomieu B., Dal Zilio S., and Vernadat F. (2016). Symmetry reduction for time Petri net state classes. *Science of Computer Programming*, 132(2): 209–225.

Bruzzone A., Garro A., Longo F., and Massei M. (2015). An Agent-Oriented Perspective on System of Systems for Multiple Domains. In Rainey L.B. and Tolk A. (eds.) *Modeling and Simulation Support for System of Systems Engineering Applications*, pp.185-217. Wiley.

Dunke F. and Nickel S. (2015). Simulation-based Optimisation in Industry 4.0. Markus Rabe & Uwe Clausen (eds.) *Simulation in Production and Logistics 2015*. Fraunhofer IRB Verlag, Stuttgart.

Kahloula L., Bourekkachea S., and Djouanib K. (2016). Designing reconfigurable manufacturing systems using reconfigurable object Petri nets. *International Journal of Computer Integrated Manufacturing*, 29(8): 889–906.

Latorre-Biel J.I., Faulin J., and Juan A.A. (2017). Enriching Simheuristics with Petri net models. *In Proceedings of the 2017 Winter Simulation Conference*, pp. 2475-2486. Washington, Dec. 2017.

Latorre-Biel J.I., Jimenez-Macias E., Perez-de-la-Parte M., Saenz-Diez J.C., Martinez-Camara, E., and Blanco-Fernandez J. (2016). Compound Petri nets and alternatives aggregation Petri nets: Two formalisms for decision-making support. *Advances in Mechanical Engineering*, 8(11): 1-12.

Latorre-Biel, J.I., Jiménez-Macías, E., Blanco-Fernández, J., Martínez-Cámara, E., Sáenz-Díez, J.C., and Pérez-Parte, M. (2015). Decision Support System, Based on the Paradigm of the Petri Nets, for the Design and Operation of a Dairy Plant. *International Journal of Food Engineering*. 11(6): 767-776.

Latorre-Biel J.I., Jimenez-Macias E., and Perez-Parte M. (2014). Sequence of decisions on discrete event systems modeled by Petri nets with structural alternative configurations. *Journal of Computational Science*, 5(3): 387-394.

Latorre-Biel J.I., Jimenez-Macias E., Perez de la Parte M., Blanco-Fernandez J., and Martinez-Camara E. (2014). Control of Discrete Event Systems by Means of Discrete Optimization and Disjunctive Colored PNs: Application to Manufacturing Facilities. *Abstract and Applied Analysis.* 2014(2014): 1-16.

Latorre-Biel, J., Jiménez-Macías, E., and Blanco-Fernández, J. (2014). Optimal Design of an Olive Oil Mill by Means of the Simulation of a Petri Net Model. International Journal of Food Engineering, 10(4), pp. 573-582.

Latorre-Biel, J.I. and Jiménez-Macías, E. (2013). Modelling, analysis, and simulation of manufacturing processes with alternative structural configurations by parametric Petri nets. *Advanced Science Letters*, 19(2): 665-669.

Latorre J.I. and Jiménez E. (2013). Petri nets with exclusive entities for decision making. *International Journal of Simulation and Process Modelling*. 8(1): 66-73.

Latorre-Biel, J.I. and Jiménez-Macías, E. (2011). The exclusive entities in the formalization of a decision problem based on a discrete event system by means of Petri nets. *In Proceedings of the 23rd European Modeling and Simulation Symposium, EMSS 2011*, pp. 580-586. Rome(Italy), Sep. 2011.

Latorre-Biel, J.I., and Jiménez-Macías, E. (2011). Matrix-based operations and equivalente classes in alternative Petri nets. *In Proceedings of the 23rd European Modeling and Simulation Symposium, EMSS 2011*, pp. 587-592. Rome(Italy), Sep. 2011.

Latorre-Biel, J.I.; Jimenez, E.; and Perez, M. (2010) Coloured Petri nets as a formalism to represent alternative models for a discrete event system. In Proceedings of the 22th European Modeling and Simulation Symposium, EMSS 2010, pp. 247-252. Fes, Morocco, October 2010.

Long F., Zeiler P., and Bertsche B. (2016). Modelling the production systems in industry 4.0 and their availability with high-level Petri nets. *IFAC-PapersOnLine*, 49-12 (2016) 145-150.

Mendes J.M., Leitão P., Restivo F., and Colombo, A.W. (2010). Composition of Petri Nets Models in Service-oriented Industrial Automation. *In Proceedings of the 8th IEEE International Conference on Industrial Informatics (INDIN)*, pp. 578-583. July 2010, Osaka, Japan.

Mujica-Mota M. (2015). Check-in allocation improvements through the use of a simulation–optimization approach. *Transportation Research Part A Policy and Practice*, 77: 320-335.

Silva M. (1993) Introducing Petri nets. In: Di Cesare F (ed.) *Practice of Petri nets in manufacturing,* pp.1–62. Chapman & Hall. London.

Valk R., (2004). Object Petri Nets. Using the Nets-within-Nets Paradigm. In Desel J., Reisig W., and Rozenberg, G. (eds.), *Advances in Petri Nets: Lectures on Concurrency and Petri Nets*, volume 3098 of Lecture Notes in Computer Science, pp. 819-848. Springer-Verlag, 2004.

Zhang Y., Wang W., Wu N., and Qian C. 2016. IoT-Enabled Real-Time Production Performance. Analysis and Exception Diagnosis Model. *IEEE Transactions on Automation Science and Engineering*, 13(3): 1318-1332.