AUTOMATIC DESIGN BASED ON THE PETRI NETS PARADIGM

Juan-Ignacio Latorre-Biel[(a)], Emilio Jiménez-Macías [(b)]

[(a)] Public University of Navarre. Deptartment of Mechanical Engineering, Energetics and Materials.
Campus of Tudela, Spain
[(b)] University of La Rioja. Industrial Engineering Technical School.
Department of Electrical Engineering. Logroño, Spain

[(a)]juanignacio.latorre@unavarra.es, [(b)]emilio.jimenez@unirioja.es

ABSTRACT
From ancient times, it has been a dream of human beings the automation of the hardest works to prevent humans from the inconveniences of these tasks. Not only dangerous, remote and repetitive tasks but also mechanical operations that require high precision, speed or repeatability have been automated. The industrialized modern society requires an efficient and sustainable use of the available resources for producing goods and services for the consumers. For achieving this objective, the manufacturing facilities and equipment, chain supplies and products themselves should be designed for verifying certain specifications. In this paper, the design process of a product, such as a production plant, chain supply or a good produced for the final customers is addressed under the light of the modeling paradigm of Petri nets in order to automatize some of the stages of this operation.

Keywords: product design, Petri nets, automation, decision support system

1. INTRODUCTION

From ancient times, it has been a dream of human beings the automation of the hardest works to prevent humans from the inconveniences of these tasks. Not only dangerous, remote and repetitive tasks but also mechanical operations that require high precision, speed or repeatability have been automated.

Along the last decades, a research effort has been devoted to the physical activities and also to the intellectual work performed by humans. The advantages of this approach are many, especially in situations where it is necessary to make difficult decisions due to the influence of a large amount of information, the consideration of systems with complex behavior, etc.

The industrialized modern society requires an efficient and sustainable use of the available resources for producing goods and services for the consumers. For achieving this objective, the manufacturing facilities and equipment, chain supplies and products themselves should be designed for verifying certain specifications.

A global environment for the manufacturing, distribution, commercializing, recycling, and waste management produces a network of interrelations of multiple actors that makes difficult the decision process in the design of such systems.

For this reason, the development of decision-support systems constitutes a great help in the development of efficient manufacturing facilities, chain supplies and final products. In this paper, the design process of a product, such as a production plant, chain supply or a good produced for the final customers is addressed under the light of the modeling paradigm of Petri nets in order to automatize some of the stages of this operation.

1.1. The paradigm of the Petri nets

The design process involves multidisciplinary work teams, where managers, research and development engineers, sale executives, production engineers, procurement technicians, financial experts, etc. share information, knowledge, a common objective, and should make the best decisions.

The different professional and academic background of the staff involved in the design process make difficult the interchange of information with the accuracy that a critical process, such as the design of a product or a service, requires. However, a fluid interchange of information between design teams and between the members of any of these teams is crucial to develop a successful design process.

A formal language to represent the information concerning the design alleviates the different tasks, where professionals belonging to diverse sectors are involved. Petri nets is a paradigm very well suited for performing this role, since its formal nature and the different interpretations and levels of abstractions allow representing a system in its design process, as well as in the different stages of its life cycle (Silva and Teruel 1997 and Silva and Teruel 1998).

In particular, several Petri net formalisms have been developed for the design process of a discrete event system: alternative Petri nets, compound Petri nets, alternatives aggregation Petri nets, and disjunctive coloured Petri nets (Latorre *et al*. 2011b; Latorre *et al*. 2011d; Latorre *et al*. 2010e).

Moreover, a formal language, such as the ones based on Petri nets, allows the development of a deep analysis of the system in process of being designed, i.e validation, verification, performance measurement by steady state analysis or simulation.

For this reason, the modeling of the system, by means of Petri nets, may be helpful, not only in the task of representing the system formally and without ambiguity, but also in the process of designing a system free of flaws and optimal according to the criteria set up in the decision problem of choosing the best alternative solution.

1.2. The Petri nets in the design of discrete event systems

Petri nets have been broadly used for the representation of systems in different stages of the design process of a discrete event system and in different technological and industrial sectors. Several are the authors, who have reported applications of this formal language to different case-studies or have developed general or specific methodologies to increase the reliability, automation, and efficiency of certain steps in product and service design.

For example, (Silva and Teruel 1998) surveys and illustrates the utilization of Petri nets in several stages of the life cycle of modern manufacturing systems. Different types of manufacturing systems and usual problems that may arise in the design and operation of these systems are addressed, such as their modeling and control. One of the goals of this reference consists of proving the utility of the paradigm of the Petri nets as the sole formalism to be used during the whole life cycle of the system.

Furthermore, a specific formalism belonging to the family of the Petri nets is considered in (Horváth *et al.* 2000). In this paper it is proposed the application of advanced Petri-net (APN) as a means for modelling design processes together with the decision patterns of designers. According to the reference, the in-process decisions made by designers strongly influence both the process of designing and the manifestation of the designed artefact. An APN is a bi-layer allocated architecture with linked, bipartitioned, directed, and attributed multi-graphs. The case study that presents the conceptualization and design process of a product is described to illustrate the adequacy of APN technique for simultaneous modelling of design actions and decisions.

A more general point of view is given by (Girault and Valk, 2001). This article illustrates the progress in the development and application of formal methods based on Petri net formalisms. It contains a collection of examples arising from different fields, such as flexible manufacturing facilities, telecommunication networks and workflow management systems. The book covers the main phases in the life cycle of the design and implementation of a discrete event system. Some of the stages taken into account are specification of the system, the model checking techniques for verification, analysis of properties, code generation, and execution of appropriate models.

A more specific approach is provided in (Zimmerman *et al.* 2001). In this paper it is described the Petri net based design engine TimeNET, which is a software tool intended for the efficient design and operation of complex manufacturing systems, integrating modeling, analysis and control methodology. The independent modeling of structural and functional system parts by means of coloured stochastic Petri nets is suggested. TimeNET contains a library of common submodels for this purpose, which includes some parameters, such as processing times or buffer capacities. Qualitative analysis, as well as different evaluation techniques for an efficient performance prediction is implemented: direct numerical analysis, approximated analysis and simulation. The evaluation of different control strategies is also considered. An application example is given to illustrate the use of the mentioned tool and methodology.

Moreover, (Rust *et al.* 2003) introduces a high level Petri net model for real-time systems with dynamically changing structure. The reference describes a load balancing algorithm, implemented as a part of the model itself, for dynamically allocate tasks to computing devices. A design process composed of the modeling, analysis and partitioning and synthesis, is proposed. The high-level Petri net is extended with constructs for self-modification, leading to a self-modifying net, where the transitions are labeled with rules for net transformations and their firing imply a modification in the current net.

The following reference, (Carmona *et al.* 2004), focuses on the application of the Petri nets in designing asynchronous circuits from, for example, specifications in hardware description languages. The described methods avoid using full reachability state space for logic synthesis. On the contrary these methodologies, include direct mapping of Petri nets to circuits, structural methods with linear programming, and synthesis from unfolding prefixes using boolean satisfability problem solvers.

A different approach is considered by (Lorenz *et al.* 2007), which addresses the synthesis problem for P/T-nets from a behavioral description. According to this methodology, the behavior is given in terms of a finite partial language, as a finite set of labeled partial orders (LPOs). The computed net is a finite representation of the so called saturated feasible net whose places correspond to regions of the given partial language.

An industrial application is presented in (Gradišar and Mušič, 2007), which describes the application of timed Petri nets and the existing production data to the algorithmic modeling of manufacturing systems. Production-data management systems provide information concerning the structure of a production facility and the products that can be produced. The Petri net is built directly following a top-down approach, from the bill of materials and the routings. This reference describes a timed Petri net simulator developed in Matlab and an application example aimed at the scheduling of an assembly system.

With a similar industrial application, but a different modeling methodology, (Lee and Jeong, 2008) addresses the modeling of a manufacturing system by means of the paradigm of the Petri nets under a bottom-up approach. The presented methodology focuses as well in the design of a controller with deadlock prevention policy. This reference follows a hierarchical procedure that considers a resource model, a process model and a controller. An example is given with the purpose of illustrating the methodology presented in the article.

Furthermore, a different formalism belonging to the family of the Petri nets is considered in (Staines, 2009). This paper describes the modeling, analysis and evolution of a reduced coloured Petri net for fault diagnosis and recovery in embedded and control systems. The reduced coloured Petri net is a compact form of a coloured Petri net having complex token types based on sets containing the structured information for error handling. This approach can reduce the size of the coloured Petri net because information is put in the token by means of the folding of places and transitions. This approach is illustrated with an example of a control system.

An approach outside of the industrial field is presented in (Bergenthum et al., 2009). The authors address the modeling of a business process by means of the Petri nets paradigm as a step in a methodology for decision making. This methodology starts collecting scenarios from domain experts to create a behavioral specification. The reference presents an algorithm for the synthesis of a Petri net, based on refinements, which leads to a model of small size.

In the paper (Latorre et al., 2009) a methodological approach for designing DES is described. The design process from the combinatorial creation of complete solutions for the DES in process of being designed to the choice of the best one for the aimed application is addressed in this methodology. The classic approaches of divide and conquer and the methodology based on the formalism of the alternatives aggregation Petri nets are compared. Some propositions on the alternative aggregation Petri nets are stated, among them the equivalence of the optimization problem based on a set of alternative Petri nets and the one based on an alternative aggregation Petri net constructed from the others.

A large amount of examples can be found in (Labadi and Chen, 2010). This survey stresses the advantages of Petri nets as modeling and analysis tools for the specific field of logistics systems. The paper is organized as a review of the scientific literature on the topic. The reference is focused on the most recent developments in the application of Petri net based approaches for modeling, qualitative or structural analysis, performance evaluation, and the subsequent optimization.

The main objective of the previous references consists of the development of tools, methodologies, or formalisms that may help in the process of design discrete event systems.

This help may consist on a systematic approach, an environment that ease the development of models of systems, automatic procedures to solve design problems from different type of specifications, the development of new formalisms that allow representing the model of the system in several stages of its life cycle, the improvement of the verification and validation of models of the system in process of being designed, the application of design techniques to different application fields.

In the following, the general procedure of designing a product or a service will be addressed. It will be considered all the important stages, from the gathering of relevant data, obtained from the market, competitors, new technologies, or former design projects, to the beginning of the manufacturing process of the final product.

Section 2 will address the general procedure of designing a product, while in section 3, the problem of automatizing some of the stages involved in the design process are considered. Some conclusions are presented in section 4, as well as some general research lines for the future, related to the automation of the process of designing a product.

2. STAGES OF THE DESIGN PROCESS

In a general case, it is possible to structure the steps involved in the design process of a product or service in four different stages.

These stages are usually developed in a sequential manner, bur a process of concurrent engineering may lead to the parallelization of some of them. In fact, some of the steps that compose every one of the mentioned four stages can be developed concurrently by different multidisciplinary teams, which work with the same objectives.

The four mentioned stages are detailed in the following:

2.1. Investigation and definition

This step consists of finding the need that the product or service is aimed to satisfy, as well as analyzing different sources of information for helping in the creative process of developing solutions.

These sources of information may include customers, products sold by the competitors (analyzed by reverse engineering), solutions from other sectors or markets, new technologies, patents, reports, journals, exhibitions, social networking, previous design projects, or a creative process itself.

In this phase of the design, the specifications of the system should be stated in the design brief and the product design specification. Petri nets is a formal paradigm well suited for this task.

2.2. Design and development (conceptualization)

This second stage consists on using the information gathered in the previous phase to create partial solutions able to solve specific subproblems in the design process.

Examples of these kinds of subproblems in product design may be the design of the mechanical components, the electric design, the aesthetic design, or the industrial design. Once this task has been concluded, it is possible to afford the process of generating complete solutions by mixing appropriatedly the mentioned partial solutions.

Every one of the obtained solutions consists of an alternative system, which can be chosen as a definitive design.

In fact, the process of combining the different subsystems in diverse ways to obtain complete alternative solutions to the design problem can be stated as a combinatorial process. As a consequence, the generation of complete alternative solutions can aim to count on the largest and most varied range of feasible solutions to select the most promising one. It is not unusual, that this process implies a different problem: the combinatorial explosion, where a huge number of complete solutions can be constructed from a relatively small amount of partial solutions.

This important phase leads to the configuration of the solution space of the design problem. In order to state the decision problem, it is necessary to define more elements than the solution space.

One important component of the decision problem is the model of the system in process of being designed. A classical approach for the modeling of the system consists on developing a different model for every one of the complete solutions developed for the design process. When using the paradigm of the Petri nets as modeling formalism, the different models are called alternative Petri nets (Latorre *et al*. 2011a). In a situation, where a huge number of alternative solutions arise, the idea to develop an independent model for every alternative solution is unaffordable by standard methodologies.

Fortunately, other compact formalisms have been developed to represent a system in process of being designed (Latorre *et al*. 2011b). These type of models allow the automation of the decision process in a single step and ease the development of methodologies to construct automatically the complete solutions for a design process from a set of partial solutions.

Other important element of the decision problem is the objective function, usually based on performance measurements of the model of the system. These performance measurements can be calculated by the simulation of the behavior of the system under a set of scenarios, which are chosen from an expected operation of the system.

To complete the statement of the decision problem, some additional constraints can be added. They may be related to restrictions in the operation of the system in process of being designed.

Once the decision problem is stated, a methodology to solve the decision problem can be afforded leading to the best solution for the product design process as outcome.

The solution of the decision problem usually requires the evaluation of the quality of the complete alternative solutions by means of simulation and the evaluation of the objective function.

In this phase, due to the problem of the combinatorial explosion it may be necessary a previous step of selecting the most promising solutions to be evaluated.

2.3. Planning and production

This stage requires the creation of a production plan and the development of a prototype. Depending on the type of product that is being designed, it may not be possible to develop a prototype and the closest activity to this operation is the development of a model of the system in a formal language, such as the Petri nets. For example, this is usually the case when a manufacturing facility is designed.

On the other hand, the production plan can be developed in parallel to the previous stage in a process called concurrent engineering. Thanks to this approach, it is possible to reduce considerably the time delay from the conception of the idea to design a new product and the start of its manufacturing.

2.4. Evaluation

This step consists of a test of the prototype in order to decide if all the expected specifications are met. Due to the fact that a prototype is not always developed in the design process of a product, this stage of evaluation may be included in the decision process of step 2.

Once the design process of a product has been finished, it is ready to be produced. Consequently, the following stages of the product design are the manufacturing, quality control and storage, distribution, selling, and set up, where some of these steps can be skipped according to the type of product (or service) offered to the customers.

3. AUTOMATION OF THE DESIGN PROCESS

There are, of course, variations on the previous sequence of stages that may alleviate the development of diverse phases of the design process.

For example, if the solution space developed in the second phase is not exhaustive enough or the selection of solutions to be analyzed performed in the third stage is not large enough, it is possible to perform an iterative process of refining a good solution by searching in its vicinity in the solution space, that is, modifying local features that improve the overall quality of the solution. The triggering of this iterative process consistS of an evaluation process, such as the one described in the fourth stage of the design process.

The first stage of the design process has received little attention from the research community of modeling and simulation based on the paradigm of Petri nets. In fact, different computer-based tools are available for obtaining information from the market and other sources, in order to detect needs of the potential customers and know alternative solutions for satisfying the needs. Additional information about the regulations and additional constraints are used for developing a set of specifications for the solutions to be chosen.

The second stage begins with a data-intensive process of gathering information of alternative products already existing in the market, products with similar specific features, commercial subsystems, and other sources in order to construct new solutions.

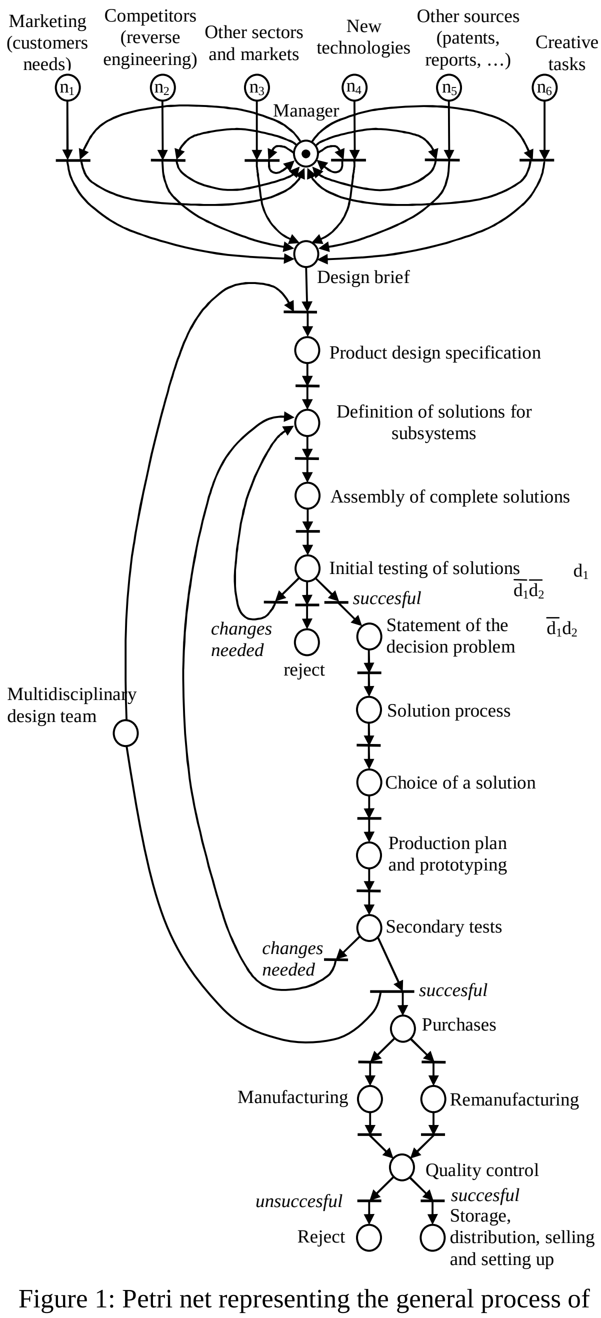

Figure 1: Petri net representing the general process of product and service design.

This process of constructing new solutions from the gathered data is, in part, a combinatorial problem, since partial solutions can lead to adequate solutions to the current design problem. This stage consists in building up the solution space by solving a constraint satisfaction problem, since the valid solutions should verify the specifications defined in the previous stage.

Most of these stages can be alleviated by the use of the paradigm of the Petri nets. However, this particular stage of building up different alternative solutions may show an intensive use of Petri nets in a modeling process, as proven by the bibliography. The different modeling approaches developed for Petri nets lead to the building of formal models. The qualitative analysis techniques, which are applicable to Petri net models, allow developing correct models.

The evaluation of the quality of the different alternative solutions may be afforded by means of formal methods, based on the calculation of performance parameters by means of steady state analysis or simulation. If it is required a previous stage of selecting a subset of the solution space, it is possible to apply different techniques. One of the successful methodologies based on a probabilistic search are the use of metaheuristics to guide the search of the best solutions, in combination with the calculated performance parameters.

In order to obtain the best solution it is possible to construct an objective function with the performance measurements calculated in the previous step and choosing the one that provides with the highest value. This stage and the previous one can be completely automated (Latorre *et al*. 2011b).

4. CONCLUSIONS

In this paper, the automation of the design process of a system is discussed. The diverse stages in the design process are presented and the different degrees of automation, achieved by different authors, are reviewed. Moreover, an approach to automatize a large amount of steps, belonging to different stages in the design process, proposed by the authors of this paper, is described.

Future research lines should afford the detailed analysis of the stages of the design process that have been less analyzed by means of the formalism of the Petri nets, such as the stage of investigation and definition. These stages use to be the ones considered as more creative. Hence, the complete automation of the design process might require a better understanding of the underlying brain processes related to the creative processes.

ACKNOWLEDGMENTS

This paper has been partially supported by the project of the University of La Rioja and Banco Santander (grant number API12-11) ‘Sustainable production and productivity in industrial processes: integration of energy efficiency and environmental impact in the

production model for integrated simulation and optimization'.

REFERENCES

Bergenthum, R.; Desel, J.; and Mauser, S. "Synthesis of Petri Nets for Business Process Design". Fundamenta Informaticae - Application of Concurrency to System Design archive Volume 95 Issue 1. IOS Press Amsterdam, The Netherlands. January 2009.

Carmona, J.; Cortadella, J.; Khomenko, V.; and Yakovlev, A. "Synthesis of Asynchronous Hardware from Petri Nets". In Desel, J.; Reisig, W. and Rozenberg, G. (Eds.): Lectures on Concurrency and Petri Nets: Advances in Petri Nets, volume 3098 of Lecture Notes in Computer Science, pages 345-401. Springer-Verlag, 2004.

Girault, C. and Valr, R. (Eds.) "Petri Nets for System Engineering: A Guide to Modeling, Verification and Applications". Springer-Verlag, 2001.

Gradišar, D. and G. Mušič. "Production-process modelling based on production-management data: a Petri-net approach". International Journal of Computer Integrated Manufacturing, Vol. 20, No. 8, pp. 794-810, 2007.

Horvath, I.; Vergeest, J.S.M.; and Van der Vegte, W.F. "Modeling design processes and designer decisions with advanced petri-nets". In Lehoczky, L. and L. Kalmar (Eds.), International Computer Science Conference (pp. 81-90). University of Miskolc. Miskolc, Hungary. 2000.

Labadi, K. and Chen, H. "Modelling, analysis and optimisation of supply chains by using Petri net models: the state-of-the-art". International Journal of Business Performance and Supply Chain Modelling. Vol. 2. Nos. 3/4. 2010.

Latorre, J.I., Jiménez, E., Pérez, M., Blanco, J., "The problem of designing discrete event systems. A new methodological approach," Proceedings of the 21st European Modelling and Simulation Symposium (EMSS 09). Puerto de la Cruz, Spain, vol. 2, pp. 40-46, September 2009.

Latorre, J.I., Jiménez, E., Pérez, M., "Coloured Petri Nets as a Formalism to Represent Alternative Models for a Discrete Event System". Proceedings of the 22nd European Modelling and Simulation Symposium (EMSS 10). Fez, Moroco, pp. 247-252, October 2010.

Latorre, J.I., Jimenez, E., Pérez, M., Blanco, J. and Martínez, E. "The optimization problem based on alternatives aggregation Petri nets as models for industrial discrete event systems". M&S Optimization Applications in Industry and Engineering. The Society for Modeling & Simulation International. 2011.

Latorre-Biel, J.I., Jiménez-Macías, E., Pérez, M., " The exclusive entities in the formalization of a decision problem based on a discrete event system by means of Petri nets ". Proceedings of the 23rd European Modelling and Simulation Symposium (EMSS 11). Rome, Italy, pp. 580-586, September 2011.

Lee. J.; and Jeong, I. J. "Design of Petri nets based controllers for the synthesis of manufacturing systems", Proceedings of SKISE Spring Conference, May 15, 2008.

Lorenz, R.; Bergenthum, R.; Mauser, S.; and Desel, J. "Synthesis of petri nets from finite partial languages". Proceedings of the 7th International Conference on Application of Concurrency to System Design (ACSD), pages 157–166, 2007.

Rust, C.; Stappert, F.; and Schamberger, S. "Integrating Load Balancing into Petri-Net based Embedded System Design". The European Simulation and Modeling Conference (ESMC 2003), 1st October 2003.

Silva, M., Teruel, E. "Petri nets for the Design and Operations of Manufacturing Systems", European Journal of Control, 3, 82–199, 1997.

Silva, M.; and Teruel, E. "DEDS Along their Life-Cycle: Interpreted Extensions of Petri Nets". IEEE International Conference on Systems, Man and Cybernetics. San Diego, USA. 1998.

Staines, A.S. "A Compact Colored Petri Net Model for Fault Diagnosis and Recovery in Embedded and Control Systems". International Journal of Computers. Issue 2, Volume 3, 2009.

Zimmermann, A.; Freiheit, J.; Huck, A. "A Petri net based design engine for manufacturing systems". In: International Journal of Production Research, Vol. 39, No. 2, pages 225-253. 2001.

AUTHORS BIOGRAPHY

Juan Ignacio Latorre, Ph.D. in Industrial Engineering, has developed his professional career in the industry and in educative institutions. He is assistant professor in the Department of Mechanical Engineering, Energetics and Materials in the Public University of Navarre (Spain). His main research interests are factory automation, simulation and modeling of industrial processes and formal methodologies to solve decision problems based on DES. His main research activities have been performed with the modeling, simulation and optimization research group of the University of La Rioja (Spain) in the field of decision-support systems based on models of DES.

Emilio Jiménez is a Professor in the Electrical Engineering Department at the University of La Rioja, where he leads the modeling, simulation and optimization group. His main research interests include factory automation, modeling and simulation of industrial processes and formal methodologies to solve decision problems based on DES.