SEQUENCE OF DECISIONS ON DISCRETE EVENT SYSTEMS WITH STRUCTURAL ALTERNATIVE CONFIGURATIONS

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ABSTRACT
The management of certain systems, such as manufacturing facilities, supply chains, or communication networks implies assessing the consequences of decisions, aimed for the most efficient operation. This kind of systems usually shows complex behaviors where subsystems present parallel evolutions and synchronizations. Furthermore, the existence of global objectives for the operation of the systems and the changes that experience the systems or their environment during their evolution imply a more or less strong dependence between decisions made at different time points of the life cycle. This paper addresses a complex problem that is scarcely present in the scientific literature: the sequences of decisions aimed for achieving several objectives simultaneously and with strong influence from one decision to the rest of them. In this case, the formal statement of the decision problem should take into account the whole decision sequence, making impractical the solving paradigm of "divide and conquer". Only an integrated methodology may afford a realistic solution of such a type of decision problem. In this paper, an approach based on the formalism of the Petri nets is described, several considerations related to this problem are presented, a solving methodology based on the previous work of the authors, as well as a case-study to illustrate the main concepts.

Keywords: Petri nets, sequence of decisions, metaheuristic, discrete event system, alternatives aggregation Petri nets, optimization

1. INTRODUCTION
Real and complex systems, regarded as discrete event systems, may require a decision making process to be useful for certain applications, such as industrial manufacturing, supply chain, computer systems, and communication networks. The decisions may be more or less difficult to take, regarding to the system itself, the considered application, and the objectives to be achieved. For allowing the decision making, the discrete event system should present one or several freedom degrees or undefined characteristics leading to an undefined discrete event system (Latorre et al, 2011c).

These undefined characteristics may belong to the behavior or to the structure of the system. Several solving methodologies can be considered. In order to develop a more or less general procedure for solving the decision-making problem it is convenient to represent the decision-making problem in a formal language.

Moreover, simulation consists of a technique for trying to foresee the future behavior of the system, under specific initial conditions, that can cope with a broad range of systems and configurations. The result of this formalization of the decision problem is usually an optimization problem, including a model of the system able to perform simulations (Latorre *et al*. 2011c).

1.1. The paradigm of the Petri nets
Different formal languages can be chosen for modeling a given discrete event system. For example, it may be considered queuing networks, finite state machines or automata, Petri nets, or generalized semi-Markov processes (Moody and Antsaklis 1998).

In this case, the paradigm of the Petri nets has been chosen for several reasons. First of all, an undoubted advantage of Petri nets is the double graphical and matrix-based representation. This particular feature of the Petri nets make them very intuitive and powerful, for structural analysis as well as for performance evaluation and simulation.

A second interesting characteristic of the Petri nets is their natural way to represent complex behaviors that include parallelism and synchronizations (Silva 1993), and for the body of knowledge in the field of the Petri nets, which has been developed in the last decades (Balbo and Silva 1998).

The undefined characteristics of the original discrete event system can be expressed in the resulting model by means of undefined parameters, leading to the concept of undefined Petri net (Latorre *et al*. 2011a). The parameters of a Petri net can play different roles and, subsequently, may be classified accordingly into different types, such as structural, marking, transition-firing, or interpretation parameters.

An overview of different approaches for solving an optimization problem based on an undefined Petri net can be found in (Latorre *et al*. 2011b).

1.2. Optimization processes

The mentioned approaches range from series of optimizations for certain initial conditions chosen manually, including a partial automation of the search for the optimal values associated to the non-structural parameters to the methodology proposed in (Latorre *et al*. 2011b), where a single search for all types of parameters is afforded.

This approach based on a single optimization process has been presented for a decision that corresponds to an instant in the evolution of the discrete event system. This instant may be related to a stage in the design process of the system or a change in the configuration of the freedom degrees of the system or in the freedom degrees themselves.

The optimization process can be solved for the mentioned decision problem focused on an instant in the operation of the DES and a solution can be obtained, where all the undefined parameters will take specific values (Latorre et al. 2010). Once a solution for the undefined parameteres has been obtained, it is necessary to perform a backwards translation from the undefined parameters to the undefined characteristics of the original discrete event system or freedom degrees, in order to solve the decision problem stated on the original system and not on its model.

The rest of the paper is organized as follows. The section 2 is focused on the statement of the problem aimed to obtain a sequence of decisions based on a discrete event system. The section 3 outlines some approaches aimed to solve the mentioned problem aimed to afford a sequence of decisions. Sections 4 and 5 describe two case studies, while section 6 draws the conclusions and future research lines. The article is completed with a section of acknowledgements and the bibliography.

2. SEQUENCE OF DECISIONS

Some real situations in the design and operation of an undefined discrete event system might lead the decision maker not to a single decision, where some freedom degrees can be specified, but to a sequence of decisions.

This sequence of decisions can be afforded by means of separated optimization processes, following the paradigm of “divide and conquer” or by means of a single optimization.

Examples of this kind of complex problems are the scheduling of tasks, the planning of operations, the routing of conveying parts, and in general the control of the equipment in a manufacturing facility (Piera and Mušič 2011; Bai *et al*. 2010; Ramirez *et al*. 1993).

It is very usual that this kind of problem requires making a sequence of decisions related to transition-firing parameters. The mentioned parameters, which are the ones that usually appear in this kind of problem, are the priority of firing the transitions involved in conflicts, which arise during the operation of the system.

In order to clarify the concept of undefined parameters and the different types of them, which will be considered in this paper, the following considerations are presented.

2.1. Undefined parameters

The Petri net model of a discrete event system is a formal and quantitative representation of the structure and behavior of the original system. The parameters that configure the Petri net can be classified according to their function in the model. Any of these parameters can be undefined ones, giving place to an ambiguity or non-determinism that can be solved by means of an appropriate decision.

Definition 1. Parameter of a Petri net.

Any numerical variable of a Petri net model or its evolution.

□

Definition 2. Undefined parameter.

Any numerical variable of a Petri net model or its evolution that has not a known value but it has to be assigned as a consequence of a decision from a set of at least two different feasible values. The value assigned to the undefined parameter after a decision must be unique.

□

Definition 3. Defined parameter.

Any parameter of a Petri net that is not undefined (see **definition 2**).

□

Notice that a decision that chooses a feasible value for an undefined parameter transforms the parameter into a defined one.

The undefined parameters of a Petri net can be classified according to their function in the model. A non-exhaustive classification, but useful for many the abbreviations and extensions of the ordinary Petri nets is the following:

Definition 4. Structural parameter.

Numerical value for any element in the input or output incidence matrices of a Petri net. The elements of the incidence matrices determine the weight of the arcs that link the nodes of the Petri net (places and transitions).

□

An example of structural parameters arises from the different manufacturing strategies of the case study presented in (Latorre *et al*. 2009). The flow of parts and information (production request) in the manufacturing facility is modelled by weighted arcs between nodes of the Petri net. Different strategies imply diverse weights in some elements of the incidence matrices; hence, before choosing a manufacturing strategy, some structural parameters are undefined ones.

Definition 5. Marking parameter**.**

Number of tokens in a particular place of the Petri net in the initial state of its evolution. In the case of a high-level (coloured) Petri net it includes the attributes (colour) of every token.

□

Definition 6. Transition-firing parameter**.**

Priority of firing a transition involved in a structural conflict or time of firing an enabled transition in the case of free speed firing.

□

Priority is a concept related to priority Petri nets, where the inherent non-determinism related to actual or effective conflicts is solved by associating priorities to the transitions of the net.

In a structural conflict, there is an ordering for firing the involved transitions, which are taken from the priority relation. These priorities determine which transition should be fired when an actual or effective conflict arises. For more information on the different type of conflicts see, for example, (David and Alla 2005).

On the other hand a free speed firing is a topic usually related to the performance improvement of a system by not firing a transition immediately after it becomes firable (maximal speed) but at the time when, for example, the performance of the system is the best that can be achieved.

An example of undefined parameters related to effective conflicts can be found in a case study described in (Latorre *et al*. 2010). In this example, an optimal sequence of decisions for controlling the operation of a manufacturing facility is searched, as well as a series of decisions related to the design of this system.

Definition 7. Interpretation parameters.

Events, logic conditions, time delays or outputs associated to any node (place or transition) of a certain Petri net.

□

Notice that this kind of parameter might be called synchronization parameters as well.

It is interesting to take into account that the undefined transition firing and interpretation parameters include the usual controllable parameters considered in the classic control theory of DES.

2.2. Outcome of the decision process.

Following with the considerations presented in the previous sections, there are different possibilities to cope with the problem mentioned in the introduction of this section 2.

One possibility consists of giving a sequence of decisions that optimize the objective of the operation of the system.

It is also possible to provide with a summary of this information in the form of a scheduling for the different machines, a best production mix or sequence of manufacturing, a fixed priority associated to a given transition, a preferred dispatching rule, etc (Mušič 2009, Zimmerman *et al*. 2001).

Another common way to afford this type of problem consists of developing a supervisor, for example in the form of a complementary Petri net model, which is able to prevent the system to reach certain states, such as deadlocks.

In general, it is possible to state that the amount of computational resources required to solve a decision problem depends on the size of the solution space. For real applications, this size is usually very large, no matter if the problem consists of a single decision, giving values to a set of undefined parameters, or a sequence of decisions.

2.3. Methodology for solving sequences of decisions and parameters of the PN

The usual methodologies for solving sequences of decisions may be different regarding the undefined parameters present in the model of the system. Usual undefined parameters in the case of scheduling, planning, or routing are undefined transition-firing parameters, in particular priorities associated to the firing of the transitions involved in conflicts (Piera and Mušič 2011).

However, other type of undefined parameters can be obtained as a result of the translation into a formal language of the undefined characteristics or freedom degrees of the original undefined discrete event systems.

In industrial applications an example in the use of undefined marking parameters can be found when the model of the feeding process of raw materials in a factory is afforded.

Furthermore, undefined interpretation parameters, such as the delay time associated to an enabled transition to become firable are less usual, but may also be considered to model different layouts of the same machines in a manufacturing facility, which imply diverse conveying time for the parts, when moved from a given machine to another one.

Finally, undefined structural parameters can be associated to the design of a discrete event system or a modification in its structure once the system is in operation (Latorre et al., 2009).

2.4. Parameters that vary over time

The research performed on systems whose parameters vary over time, as is the case of taking a sequence of decisions to modify the values of certain undefined parameters of the Petri net, has been focused mainly on specific topics of the field.

Furthermore, many researches have been devoted to solving efficiently the conflicts that arise in the evolution of a Petri net, for example to perform the scheduling of tasks in a manufacturing facility.

On the other hand, different formalisms for modeling systems with a changing structure have been developed and deeply studied, such as graph grammars, reconfigurable Petri nets, or sel-modifying Petri nets (Ehrig *et al*. 2008; Llorens and Oliver 2004; Badouel and Oliver 1998; Valk, 1978) respectively.

However, these formalisms are not specially defined for solving sequences of decisions or single-decision problems.

Other formalisms, such as a compound Petri net, a mixed set of alternative compound and simple Petri nets, an alternatives aggregation Petri net, or a disjunctive coloured Petri net have been developed for the decision making and can easily be applied for solving sequences of decisions. See for example (Latorre *et al*. 2011c).

3. SOLVING APPROACHES

A sequence of decisions can be required for an undefined discrete event system or, expressed in other language, for its formal counterpart: an undefined Petri net. The undefined Petri net is associated to a set of undefined parameters, also called controllable ones (Latorre et al, 2011c). Two main approaches can be taken into account for making the sequence of decisions.

3.1. The paradigm of "divide and conquer"

On the one hand, the approach of "divide and conquer" may afford the solution of the problem by means of a decomposition of the set of decisions, made for assigning values to specific parameters, into different groups associated to diverse optimization problems.

A natural criterion for grouping the decisions into optimization problems is time. The evolution of the system may require making decisions at certain time points, as a consequence of significant changes in one or several of the elements that define the formal statement of a decision problem: an optimization problem.

The start-up of the operation of an undefined discrete event system requires taking decisions according to the solution of the formal representation of the decision problem: an optimization problem. If one or several elements of this optimization problem are modified, the best solution for the original problem may not be the best for the modified problem or even it might not be a feasible solution. For this reason a new decision problem should be stated and solved.

A given point in time that requires making decisions may be associated to different conditions in the environment of the discrete event system. This situation may happen, for example, in an industrial facility, due to a change in the cost of raw materials, or a variation in the demand.

Furthermore, a change in the system itself may also require making a decision. For example if a machine breaks down or stops its production, or the value assigned as a consequence of a decision to a given undefined parameter is not a feasible value anymore, it is necessary to take the appropriate decision to return as soon as possible to a normal operation of the discrete event system.

This approach of "divide and conquer" may be useful in case that the decisions in the sequence are independent among them, in the sense that at a certain decision is reactive to a given change in the environment or the system itself and has the purpose of maximizing the objective function, disregarding future decisions.

This situation might arise when the changes in the environment or the system are unforeseen, as happens with the breakdown of a machine or a change in the demand of the manufactured products.

As a consequence, different methodologies, available in the scientific literature, can be applied to solve the required decision making for achieving the objective of the operation of the discrete event system under the new conditions (Piera and Mušič 2011; Latorre *et al*. 2011c; Bai *et al*. 2010; Mušič, 2009; Zimmerman *et al*. 2001; Moody and Antsaklis 1998; Ramirez *et al*. 1993.

3.2. Single-process approach

A second approach for making sequences of decisions consists of stating and solving a single optimization problem. In the statement of this problem, undefined parameters might arise, not only in the model of the system but also in the other elements of the optimization problem, such as the objective function.

This single optimization problem might present a very large solution space, in fact a family of solution spaces, one for every decision, which should be explored in the same solving process.

An approach like this may be more convenient than the "divide and conquer" paradigm, previously mentioned, when the decisions of the sequence are programmable, for example if it is possible to decide the time point and the order of the changes in the environment or the system itself.

In these cases, it is clear that the decisions to be made influence strongly one another, and for this reason it is convenient to make every decision in relation to the others from the same sequence and in relation to the global objective of the operation of the discrete event system.

4. EXAMPLE OF THE PREVENTIVE MAINTENANCE

The industrial field provides with several examples of problems, where a sequence of decisions should be made and it is possible to decide the moment and the order of a series of changes in the environment or the system itself, which lead to the need of a sequence of decisions to keep the system under an efficient operation.

4.1. Programming of the preventive maintenance.

The first of the examples consists in the preventive maintenance programming of the machinery of a manufacturing facility.

This problem requires making the decision of using efficiently the available maintenance resources for minimizing the cost, the time required for the maintenance operations, and the loss of production if the manufacturing facility does not stop the production during the maintenance process.

In this last kind of problem, where the manufacturing facility is in production when the preventive maintenance is already in progress, the structure of the discrete event system changes accordingly to the machines that are stopped for maintenance, while the rest of them are producing.

4.2. Choice of a formalism appropriate for simulation

A methodology based on the simulation of a selected number of feasible configurations requires an appropriate model for the alternative structural configurations, which the factory may have. In order to include this feature in the model of the system, a formalism including a set of exclusive entities is a natural and easy way to represent the original discrete event system.

In particular, a compound Petri net, an alternatives aggregation Petri net, or a disjunctive coloured Petri net are examples of appropriate models for this kind of system. In this kind of models, a sequence of decisions to specify the order of stopping and maintaining the different machines is associated to a sequence of decisions that choose one after another a subset of the exclusive entities related to the model (Latorre-Biel *et al*. 2011c).

4.3. Solving methodology

A test of the most promising of these sequences, for example by means of a search in the solution space guided by a metaheuristic, may lead to the optimal sequence for the maintenance operations. Every maintenance operation will require a decision on the investment of resources. This assignment of maintenance resources will determine the duration of each maintenance operation and the different time points for their beginning.

The methodology presented in this paper to solve this problem includes the following steps:

1. Determine the model of the discrete event system in complete operation.

2. Obtain the diverse alternative structural configurations that correspond to the different maintenance operations that imply to stop different machines.

3. Construct a compact model including all the different alternative structural configurations.

4. Determine the rest of the elements of the optimization problem, including the objective function, which should reward the objectives of the manufacturing process, as well as the goals of the maintenance operations. One critic specification of the problem consists of the completion of all the maintenance operations.

5. Apply a metaheuristic for finding a good solution, that would include the order an type of maintenance operations, their time points, the maintenance resources invested in the operations, and the configuration of the freedom degrees of the remaining manufacturing equipment for producing efficiently during the maintenance operations.

4.4. Structural modification

In fact, this kind of problem can be rewritten as a problem for deciding the structural variation of a Petri net model at certain time points for achieving optimally a goal at the end of the time period, when the structure of the model remains constant or is modified for other reasons, different from the preventive maintenance operations.

An easier version of the previous problem appears when the achievement of two of the objectives, to reach a maximal yield from the manufacturing operations and to obtain a maximal efficiency in the maintenance operations are disengaged in time.

This situation arises when the manufacturing facility stops the production operations in certain periods of time and the duration of the stops can be devoted to the maintenance operations. The usual time for these operations of preventive maintenance are the holidays, weekends, and nights, depending on the manufacturing facility under study.

5. ANOTHER EXAMPLE

A second example of this kind of problem can be found in the change of production in certain manufacturing facilities where this process implies an investment of time and resources.

In these kind of factories it is common that in a certain period of time, different changes of the final products manufactured are performed to obtain a stock of a range of different type of products for satisfying the demand and, perhaps, to store a certain amount of them in the warehouse.

The modification in the production mix may imply a change in the structure of the Petri net model, related to the layout of the manufactured parts or the information required to organize de manufacturing operations.

6. CONCLUSIONS

In this paper, the general problem of defining a sequence of decisions in the design or operation of a discrete event system is afforded. This general problem requires the consideration of a changing structure of the model of the system. Whereas diverse formalisms based on the Petri net paradigm have been developed for representing a variable structure in a Petri net, the problem of deciding what is the optimal evolution for this variation has not been solved yet.

In this paper, some considerations on the statement and solution of this kind of problem have been presented and outlined based on the previous work developed by the authors.

Nevertheless, there already are many issues to be researched before a general statement of this kind of problem can be considered completely solved.

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

Bai, Q., Ren, F., Zhang, M. and Fulcher, J., 2010. Using colored petri nets to predict future states in agent-based scheduling and planning systems. *Journal of Multiagent and Grid Systems - Advances in Agent-mediated Automated Negotiations archive*. Volume 6 Issue 5,6. IOS Press Amsterdam.

Badouel, E., Oliver, J., 1998 Reconfigurable nets: a class of high level petri nets supporting dynamic changes with workflow systems. *Research Report* No. 3339, INRIA (Institut national de recherche en informatique et en automatique),.

Balbo, G. and Silva, M. (editors), 1998 *Performance Models for Discrete Event Systems with Synchronizations: Formalisms and Analysis Techniques.* Editorial Kronos, Zaragoza, Spain,.

David, R., Alla. H., Discrete, 2005 *Continuous and Hybrid Petri nets*. Springer,

Ehrig, H., Hoffmann, K., Padberg, J., Ermel, C., Prange, U., Biermann, E. and Modica, T., 2008. Petri Net Transformations. In: Vedran Kordic, ed. *Petri Net. Theory and Applications*. I-TECH Education and Publishing, Vienna,

Latorre, J.I., Jiménez, E., Pérez, M., 2009 Decision taking on the production strategy of a manufacturing facility. An integrated methodology, *Proceedings of the 21st European Modelling and Simulation Symposium* (EMSS 09). Puerto de la Cruz, Spain, vol. 2, pp. 1-7.

Latorre, J.I., Jiménez, E., Pérez, M., 2010 A genetic algorithm for decision problems stated on discrete event systems. *Proceedings of the UKSim 12th International Conference on Computer Modelling and Simulation*, pp. 86-91. Cambridge, United Kingdom.

Latorre-Biel, J.I., Jiménez-Macías, E., Pérez, M., 2011. 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.

Latorre, J.I., Jiménez, E., Pérez, M., 2011. Simulation-Based Optimization for the Design of Discrete Event Systems Modeled by Parametric Petri Nets. *Proceedings of the UKSim 5th European Modelling Symposium on Mathematical Modelling and Computer Simulation* (EMS2011), pp. 150-155. Madrid, November.

Latorre, J.I., Jiménez, E., Pérez, M., 2011 Petri nets with exclusive entities for decision making. *International Journal of Simulation and Process Modeling, Special Issue on the I3M 2011 Multiconference*. Inderscience Publishers.

Llorens, M. and Oliver, J., 2004. Structural and Dynamic Changes in Concurrent Systems: Reconfigurable Petri Nets. *IEEE Transactions On Computers*, Vol. 53, No. 9.

Moody, J.O., Antsaklis, P.J., 1998. *Supervisory Control of Discrete Event Systems Using Petri Nets*. Kluwer Academic Publishers, Boston.

Mušič, G., 2009. Petri net based scheduling approach combining dispatching rules and local search. *Proceedings of the 21st European Modelling and Simulation Symposium* (EMSS 09). Puerto de la Cruz, Spain, vol. 2, pp. 27-32.

Piera, M.A. and Mušič, G. 2011. Coloured Petri net scheduling models: Timed state space exploration shortages. *Mathematics and Computers in Simulation*. Elsevier.

Ramírez, A.; Campos, J.; Silva, M., 1993 On Optimal Scheduling in DEDS. *Proceedings of the 1993 IEEE International Conference on Robotics and Automation Atlanta*, USA, pages 821-826.

Silva, M., 1993. Introducing Petri nets. In: Di Cesare, F., ed. *Practice of Petri Nets in Manufacturing*, pp. 1-62. Ed. Chapman&Hall.

Valk, R., 1978. Self-Modifying Nets, a Natural Extension of Petri nets. *Proceedings of Icalp'78. Lecture Notes in Computer Science*. Vol 62. Pages 464-476.

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