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MANUFACTURING SYSTEMS ANALYSIS AND DESIGN. QUALITATIVE VERSUS QUANTITATIVE TECHNIQUES IN A PETRI NET SETTING

BY

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Abstract. The paper discusses and illustrates by examples the role of Petri net (PN) models in the analysis and design of flexible manufacturing systems (FMSs). Qualitative techniques use untimed PN models in developing control strategies that ensure good behavioral properties of FMSs. Timed PN models serve for a refined approach where quantitative information is incorporated in the model. The case study presented herein proves the utility of a Petri net simulator with appropriate facilities for the selection of the most adequate policy in controlling a production flow.

Key words: flexible manufacturing systems, deadlock, Petri nets, simulation, performance analysis.

2010 Mathematics Subject Classification: 93C65, 37M05.

1. Introduction

Flexible Manufacturing Systems (FMSs) have become prominent in modern industry because the user can simply modify, according to his needs, either the physical or the logical structure of the system [1]. An FMS consists of a number of resources (machines, buffers, conveyors, fixtures, etc.) used to concurrently process different types of parts. A given resource may be used in common in the production processes of several part-types (*parallel sharing*), and/or may be used multiple times during the production process of a given part-type (*sequential sharing*). Failure to suitably assign shared resources can have serious effect on system performance resulting in a *deadlock* state, when the FMS ceases to operate.

Deadlock free operation is an important behavioral property of FMSs and represents a major objective of their control. In order to analyze the deadlock phenomenon it is necessary to have models of FMSs able to describe dynamics characterized by concurrency, synchronization, parallelism, mutual exclusion and conflict. *Petri Nets* (PNs) are a graphical and mathematical modeling tool [2], [3], capable to capture both the static and the dynamic characteristics of discrete event systems. Thus, PNs offer an effective framework for modeling FMSs where the deadlock avoidance problem can be rigorously approached [4],…,[6].

The purpose of our paper is to underline the role of simulation based on `*P-timed PN models* in the efficiency analysis for the exploitation of the FMSs when different strategies can be implemented for the prevention of deadlock. The paper is organized as follows: Section 2 comments, in Petri net terms, the deadlock prevention strategies for FMSs within the context of time dependent performances and points out the characteristics a PN simulator must possess in order to allow a production efficiency study. Section 3 contains a brief overview of the Petri Net Toolbox for MATLAB designed and implemented at the Department of Automatic Control and Industrial Informatics of the "Gheorghe Asachi" Technical University of Iaşi. Several examples of such studies carried out in this toolbox are presented in Section 4. Finally, some conclusions are delivered in Section 5.

2. Petri Net Models of Flexible Manufacturing Systems

2.1. Untimed Models and Deadlock-Free Operation

The problem of deadlock, or "deadly embrace" as Edsger Wybe Dijkstra has called it [7], was first addressed by computer scientists in connection with the resource allocation problem in operating systems. As presented in [8], a deadlock state occurs only when all of the following four conditions are operative: ▪ *mutual exclusion*: a resource cannot be used by two or more processes simultaneously; ▪ *hold and wait*: there exists a process that is holding at least one resource and is waiting to acquire additional ones, currently held by other processes; ▪ *no preemption*: a resource in use is not released unless the process using it finishes; ▪ *circular wait*: there exists a sequence of n operations such that the i-th is waiting on the $(i+1)$-th to release resources and the n-th is waiting on the first.

There exist three strategies that can be used to deal with the problem of deadlock, namely *detection* (and recovery), *avoidance* and *prevention* [8]. In the context of FMSs, the third one is the most important. In order to exclude a priori the possibility of deadlock, then the controller must ensure that at any time at least one of the four necessary conditions cannot be satisfied. This is achieved by imposing restrictions on the way in which processes make requests for resources, so that the system is not permitted to reach deadlock states.

Within the PN formalism, a number of techniques were proposed for dealing with FMS deadlock, such as [5], [9], [10], [11]. The recent monograph [6] presents a synthesis of such methods based on an extensive list of references. The basic idea is of *qualitative* nature and consists in using untimed PN models in order to ensure the robustness with regard to unexpected changes that might affect the durations of the operations performed by the resources in the FMSs. If an untimed PN is live, then the FMS modeled by this PN will never be confronted with the deadlock problem, no matter how long each operation takes, provided that the sequencing of the operations along the entire production flow is not altered.

2.2. Timed Models and Production Efficiency

On the other hand, an extremely important criterion in exploiting an FMS consists in reducing the mean time spent by a part within the system, or, equivalently, in maximizing the throughput of the system. Therefore, such a performance analysis needs a timed PN model able to incorporate the *quantitative* information related to the duration of each operation [5], [12].

In many cases when deadlock appears in the untimed PN model, the addition of deterministic timing information results in a timed PN where deadlock does not occur because of a fortunate compensation of the time durations. These deterministic durations disable the firing sequences which lead to deadlock in the coverabillity tree of the untimed PN model. However, such a fortunate operation can be affected by perturbations of the time durations and, consequently, the occasional avoidance of deadlock might disappear. Hence, the correct exploitation of an FMS must combine the robustness in deadlock avoidance with the improvement of time dependent criteria.

2.3. Indispensable Role of Simulation for Refined Analysis and Design

In order to develop a relevant study of the quantitative behavior of an FMS, a stochastic timed PN model is requested so as to incorporate the significant details issued by the practical exploitation, when the durations of the operations often vary around a mean value. The analytical investigation based on such a model is far from a convenient approach and the usage of an appropriate simulation tool represents the only feasible solution. Furthermore, analytical tools can be helpful only for restricted classes of timed PNs, such as the max-plus algebra for event graphs [13], Markov chains for stochastic Petri nets [14].

A widespread technique for constructing the PN model of an FMS uses separate places for operation performance and resource availability (see for instance [4]), fact that requires the assignment of P-timing. Thus, the simulator must be able to operate with place-timed PN models so as one can allocate different probability distributions to each place in the net. Moreover, the simulator must provide statistical information to characterize the whole simulation period by means of standard performance indices such as mean values for arrival distance, throughput distance, queue length, etc.

It is worth mentioning that the capability of a simulator to operate only with stochastic transition-timed PNs represents a considerable impediment because the typical place-timed models cannot be directly used and their conversion into T-timed PNs brings the major disadvantage of enlarging the topology.

3. Brief Overview of the Petri Net Toolbox for MATLAB

The *Petri Net Toolbox* for MATLAB [15],…,[17] was designed and implemented at the Department of Automatic Control and Applied Informatics of the "Gheorghe Asachi" Technical University of Iaşi. It broadens the utilization domain of MATLAB toward the area of discrete-event systems, for which the offer of The MathWorks Inc. is limited to the State-Flow product, based on finite state machines, and to SimEvents which extends Simulink with tools for modeling and simulating discrete-event systems using queues and servers. The *PN Toolbox* was included, at the beginning of 2004, in the Connections Program of The MathWorks Inc [18].

In the *PN Toolbox* five types of classic PN models are accepted, namely: untimed, place-timed, transition-timed, stochastic and generalized stochastic. The timed nets can be deterministic or stochastic, and the stochastic case allows using appropriate functions to generate random sequences corresponding to probability distributions with positive support. The *PN Toolbox* has an easy to exploit *Graphical User Interface* (GUI) that gives the user the possibility to draw PNs in a natural fashion, to store, retrieve and resize such drawings. This GUI also permits the simulation, analysis and design of PN models. The integration of the *PN Toolbox* with MATLAB offers multiple advantages with regard to the simulation aspects we are interested in, among which:

(i) The *PN Toolbox* is able to operate with nets having infinite capacity places and regular or inhibitory arcs.
(ii) Priorities and/or probabilities may be assigned to concurrently enabled transitions.
(iii) For untimed PNs, the *coverability tree* [2] in text mode or graphical mode may be easily constructed and allows studying the behavioral properties of the PN model.
(iv) Special *topologies* of ordinary PNs may be identified, i.e. marked graph, state machine, free-choice net, extended free-choice net and asymmetric choice net. The *siphons* and *traps* of ordinary PNs may also be computed.

Thus, the *liveness* of PN models may be investigates via topology-based analysis.

(v) For each of the five types of PN models implemented in the ***PN Toolbox***, the progress of the simulation is ensured by a specific algorithm. An analyzer of time-dependent performances provides statistical information about transitions and places characterizing the whole simulation period.

4. A Case Study

Simulation experiments addressed in the *PN Toolbox* for MATLAB allow the user to choose the most efficient solution for deadlock avoidance based on the computation of throughput, as shown below. The FMS presented in Fig. 1 was selected as an illustrative example and consists of two different machines (a lathe (M1) and a drilling machine (M2)), a robot (R) and a buffer (D) with two slots between the two machines (adaptated from [4]). Every input part must be processed by M1 first and then by M2 in order to get the final product. Both machines are automatically loaded and are unloaded by the robot. The robot can breakdown when it is in the idle state. A variable number of pallets can be used to fix on the processed parts.

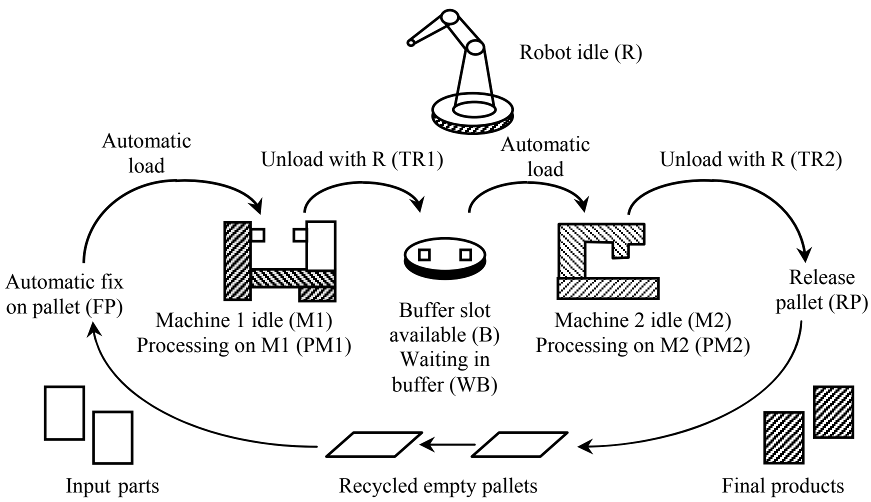

Fig. 1 − Schematic Representation of the FMS Used as Case-Study.

The PN model of this system drawn in the *Drawing Panel* of PN Toolbox is presented in Fig. 2. The places are labeled according to the abbreviations used in Fig. 1. The initial marking corresponds to the situation when 4 pallets are used to fix the parts and all resources are idle.

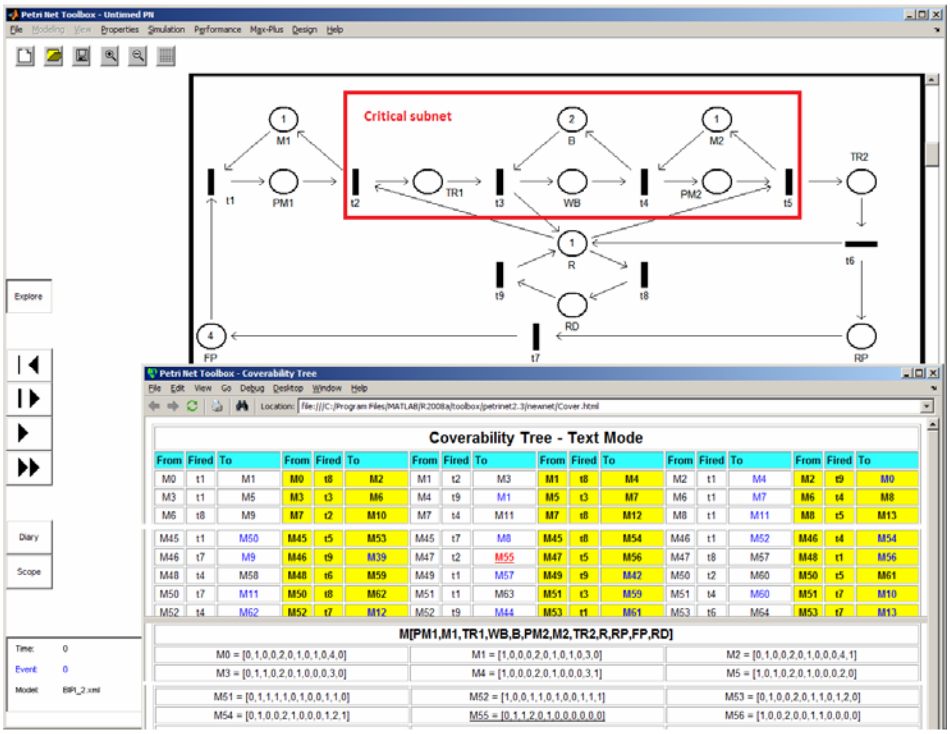

Fig. 2 – PN model of the FMS with 4 pallets used as case-study.

Several scenarios for analyzing the behavior of this FMS have been considered. The following two strategies for deadlock prevention have been envisaged in our simulation study:

(1^0) the limitation of the number of pallets in the system according to the token-capacity of the critical subnet in figure 2 [4], [10];

(2^0) the usage of a *kanban* [19] or "*lookahead*" *feedback* [20];

The analysis of the untimed PN model shows that in applying strategy (1^0), in order to ensure sequential mutual exclusion, a number of 3 pallets must be utilized. The coverability tree offered in Fig. 2 shows the presence of the deadlock marking (denoted M39) when using 4 pallets and allows its physical interpretation.

In order to get a deeper insight into the time-dependent properties of the FMS both stochastic and interval P-timed PN models have been further analyzed. The performances of the system may be obtained using a design experiment. In particular, the throughput of the system, *i.e.*, the number of final products per unit of time (obtained as the throughput of RP) is achieved by simulations when the repairing ratio is varying. All experiments described below have run for 30.000 time units (t.u.).

We first deal with the *stochastic* P-timed model for which the delays corresponding to the operations have exponential distributions with the following mean values:

- automatic fix on pallet: d(FP) ∈ *Exp*(7.5);
- unload from a machine with the robot: d(TR1), d(TR2) ∈ *Exp*(22.5);
- processing on M1: d(PM1) ∈ *Exp*(40);
- processing on M2: d(PM2) ∈ *Exp*(80);
- release pallet: d(RP) ∈ *Exp*(10);
- repairing of the robot: d(RD) ∈ *Exp*(x), where x ∈ [10,40].

Three different design experiments corresponding to different initial conditions have been considered. The number of pallets to fix on the parts is taken equal to 3, illustrating strategy 1 for deadlock prevention, and 4 or 6, respectively, illustrating strategy 2. Fig. 5 presents the PN model corresponding to the usage of a kanban for limiting the number of tokens (parts) in the critical subnet involved in the circular wait, explicitly delineated in Fig. 2. This figure also shows that results of topology and liveness analysis for this PN model, confirming that this is a live asymmetric choice net, therefore deadlock cannot occur.

The throughput evolution of place RP obtained by running a design experiment in PN Toolbox in the case when 3 pallets are used is presented in Fig. 3. From this graphic we can conclude that the best performance is obtained when the mean duration of place RD is equal to 11, leading to a throughput equal to 0.0084. This corresponds to an average time of 119.0474 t.u. for making one product.

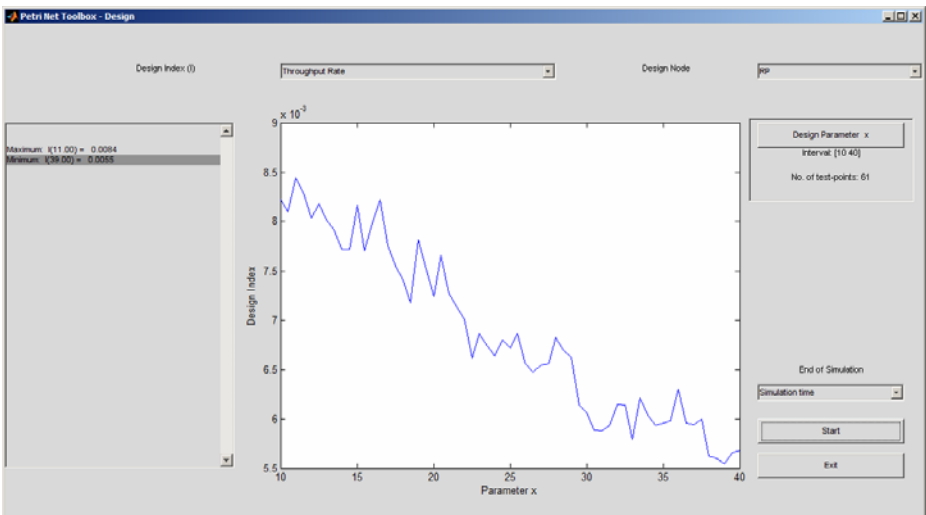

Fig. 3 − Results of the design experiment for the manufacturing system in Fig. 1 with exponential distribution for the timed places and 3 pallets.

Fig. 4 shows the evolution of the throughput for all three cases. It is easy to observe that the smaller throughput, *i.e.*, a slower system, is obtained in the case of using strategy (1^0). This is an intuitive result since only three pallets are used. On the other hand, in the case of 4 or 6 pallets and using strategy (2^0), the throughput is more or less the same. Therefore, four pallets and the "*kanban*" strategy seems to be the optimal policy in this case.

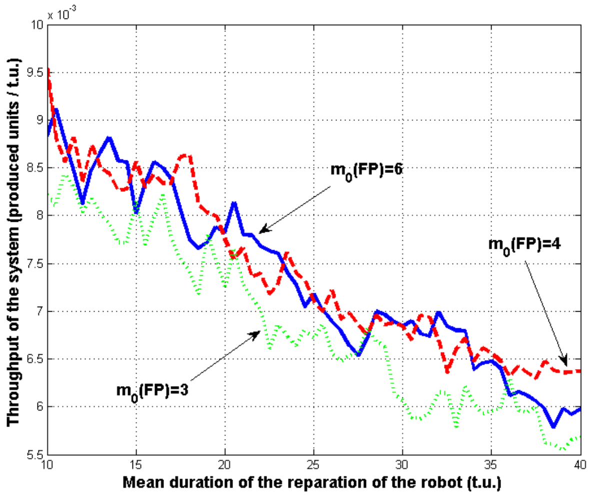

Fig. 4 − Throughput of the manufacturing system in Fig. 1 when the durations associated to the places are exponentially distributed and the mean delay of place RD vary from 10 to 40 and the number of pallets is 3, 4 and 6, respectively.

Assuming now that practical experience is able to provide a set of reasonable lower and upper bounds for all the operations, the uniform distribution was chosen for the delays associated to the corresponding places. The following numerical values were selected for the simulation experiments:

- automatic fix on pallet: d(FP) $\in$ *Unif*(6, 9);
- unload from a machine with the robot: d(TR1), d(TR2) $\in$ *Unif*(20, 25);
- processing on M1: d(PM1) $\in$ *Unif*(35, 45);
- processing on M2: d(PM2) $\in$ *Unif*(75, 85);
- release pallet: d(RP) $\in$ *Unif*(8, 12);
- repairing of the robot: d(RD) $\in$ *Unif*(5, x), $x \in [10,40]$.

where $y \in$ *Unif*(min, max) denotes a random variable uniformly distributed in the interval [min, max].

The throughput evolution of the three corresponding design experiments obtained using PN Toolbox is shown in Fig. 6. Practically, it is better to have 4 and 6 pallets than 3 even if the kanban strategy is used for deadlock avoidance. Remember that this strategy limits the maximum number of products in the critical subnet to 2.

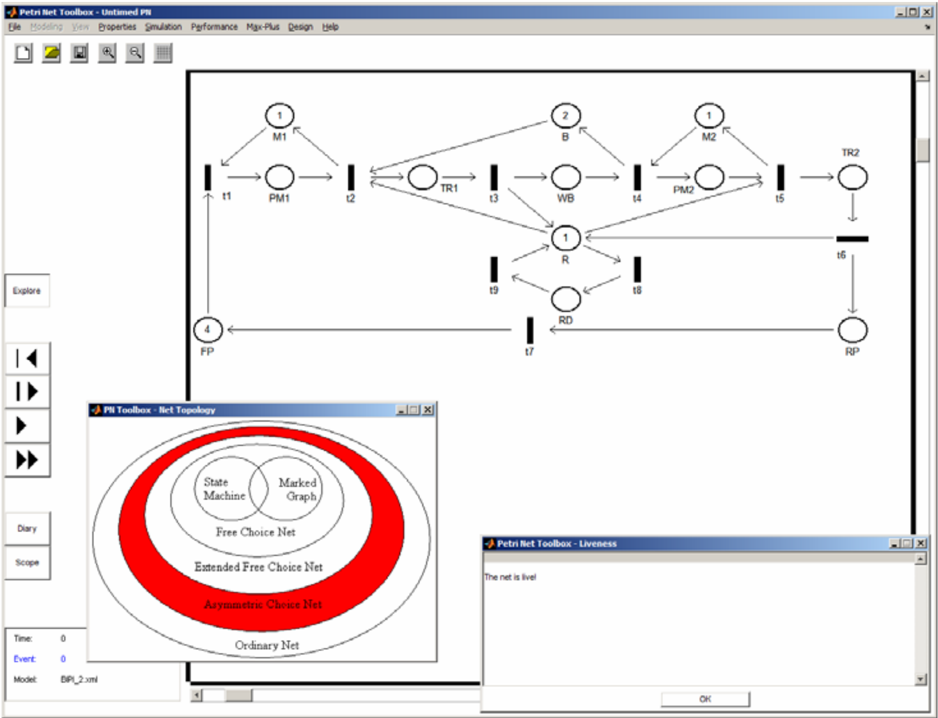

Fig. 5 – Screen capture of the PN Toolbox windows displaying the results of the topology and liveness tests for the PN model with kanban control of the FMS with 4 pallets.

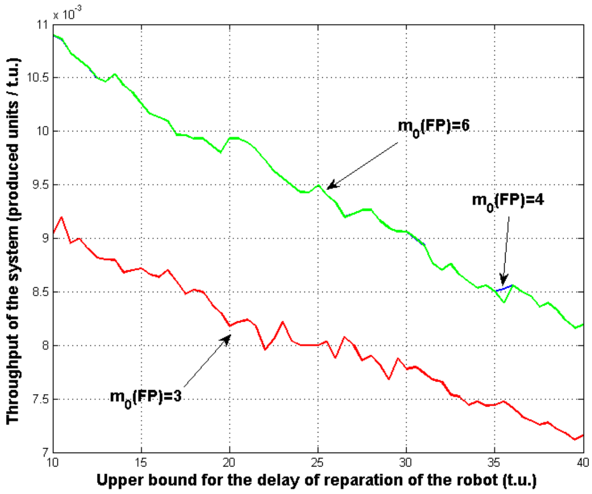

Fig. 6 – Throughput of the system when the delays are uniformly distributed and the initial number of pallets is 3, 4 and 6.

Since the results for 4 and 6 pallets are more or less the same we can conclude that 4 pallets and kanban strategy is the optimal control policy. Based also on the previous simulations when stochastic time was considered, the conclusion is that the kanban strategy with four pallets is the optimal policy ensuring deadlock avoidance and a "good" throughput under the current assumptions.

5. Conclusions

The paper focuses on the role of simulation-based study of efficient exploitation of FMSs in connection with the deadlock avoidance problem. In order to incorporate both qualitative and quantitative information associated with FMSs and perform an effective analysis, it is necessary to utilize timed models. The examples presented herein demonstrate that the selection of the most adequate policy in controlling the considered production flow cannot be achieved without relevant simulation tests. A deeper insight into the efficiency of an FMS utilization might be reached by assigning to the places in the PN model that correspond to the operations cost functions for the utilization of the resources, constructing the P-timed version of Stochastic Reward Petri Nets.

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ANALIZA ŞI PROIECTAREA SISTEMELOR FLEXIBILE DE FABRICAȚIE. TEHNICI CALITATIVE ŞI CANTITATIVE BAZATE PE UTILIZAREA REȚELELOR PETRI

(Rezumat)

Lucrarea de față prezintă rolul jucat de modelele de tip rețea Petri în analiza şi proiectarea sistemelor flexibile de fabricație. Tehnicile de analiză calitativă se bazează

pe utilizarea modelelor netemporizate pentru a determina diverse strategii de conducere a sistemelor respective. Aceste strategii trebuie să asigure corectitudinea succesiunii de operații pentru toate piesele prelucrate în sistem, odată cu asigurarea corectitudinii alocării şi eliberării resurselor necesare de fiecare operație în parte. Analiza cantitativă a utilizează modele temporizate care permit încorporarea informațiilor despre duratele operațiilor desfăşurate în sisteme. Studiul de caz prezentat în această lucrare ilustrează utilitatea unui simulator pentru rețele Petri temporizate în selectarea acelei strategii de control a sistemului care să permită maximizarea numărului de piese aflate în curs de prelucrare, în etape diferite.