Usage of Coloured Petri Nets for the Performance Evaluation of the Metallographic Samples Analysis Automated Systems

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Abstract. This paper presents the results that we attained about modeling and simulation of the metallographic samples preparation and analysis automated systems, made of two subsystems. The first subsystem polishes the samples and assesses the surface state by means of a microscope. In the second subsystem the samples are reagent attacked, washed, dried and analyzed by the electronic microscope. The evaluation of the system performance and the identification of possible bottlenecks was made by means of coloured Petri nets modeling and simulation. The CPN Tools software was used to make the model. Three coloured Petri nets models were developed. The first version assumes the analysis of the system operation by means of coloured Petri nets with simple colours, and such a simple colour was assigned to each entity of the subsystem: samples to be analyzed, robots, storage devices, microscopes etc. For a better observation of the analyzed sample path within the system, the second model version was designed, with complex colours assigned to the marks. The third version considers the time factor. The models with timed coloured Petri nets allow the system performance evaluation considering the number of analyzed samples in a given time interval. This paper presents the first and the third model, as the last one includes the second model.

1. Introduction

The modeling and simulation of the automated systems are efficient instruments for the evaluation of their performance and improvement of their operation. One of the most used of such instruments consists of Petri nets.

The timed coloured Petri nets allows the elaboration of models that accurately describe the real system, and their structure is simplified compared to the ordinary Petri nets models. Thus, [1] describes the timed coloured Petri nets model that has been recently made for a flexible fabrication cell with two CNC devices attended by a robot. The use of complex coloured Petri nets allows the elaboration of relatively simple models that consider multiple types of workpieces. The use of this factor allows the definition of the fabrication cycle.

The modeling and simulation of a flexible manufacturing cell (FMC) can be done by implementing hierarchical techniques based on Colored Timed Petri Nets. The paper [2] is focused on implementing decisions and strategies in a flexible manufacturing cell with colored and hierarchical techniques. In this context it discusses the decision making for machine, parts and allocated tools in transitions.
In the last years research in the field of automation of specific activities and operations of testing and (biology laboratory, chemical, material sciences). The development of drug industry and biology and medical research needs a huge amount of experimental studies on samples which in turn asks for automation of processes. As examples in the field of biology sciences, we can give Highres Biosolutions [3], Hombrechtikon System Engineering (HSE) [4], or in the field of material science we can give Picoquant [5] or SaxsLab (Xenocs) [6].

In the field of metallography there had been developed systems which contain a microscopes, storage devices and are assisted by a robot which handles samples, although without integrating the sample preparation equipment which it is still made with specialized machines outside the automated systems aided by human operators. The idea of an automatic metallography laboratory is sustained by the ever-rising need for an efficient quality control of industrial products. Such a laboratory can be seen as a development in the field of Computer Aided Testing which completes the CAD and CAM concepts. In [7] is presented an automated serial sectioning system with metallographic polisher, robotic arm, ultrasonic cleaner and Inverter Microscope.

The authors analyzed different aspects of this subject in previous work [8].

This paper presents models that use simple coloured Petri nets and complex coloured timed Petri nets of the automated system (flexible cell) for the preparation and analysis of metallographic samples that has been described in [9]. Also, paper [9] shows a detailed presentation of timed Petri nets model for this system. The coloured Petri nets models are structurally simpler and yield more information about the operation of the real system.

2. The Organizing of the Automated System for Preparation and Analysis of the Metallographic Samples

The automated system (flexible cell) for preparation and analysis of the metallographic samples, that was designed and realized at the University of Oradea, was presented structurally and functionally in paper [9]. The components of this system were integrated in a hierarchical structure (figure 1).

![Figure 1](image-url)

**Figure 1.** The organizing hierarchical structure of the automated system (flexible cell) for preparation and analysis of metallographic samples.

The informational integration of the cell components is made by means of informational networks, computers and command equipment (figure 2).
Figure 2. The informational interconnection of the components of the automated system (flexible cell) for preparation and analysis of metallographic samples.

Along the work posts and the robots, detailed presented in [9], the computer systems, the driving equipment and the acting elements of post M2 are shown in figure 2:

- Sc1, Sc2 – computer systems;
- Ec1, Ec2 – driving equipment for robots Ro1 and Ro2;
- μC – microcomputer;
- Dr1, Dr2 – driving circuits for stepper motors (MPP);
- M2m1, M2m2 – stepper motors for microscope table positioning;
- M2s1, M2s2 – position microlimiters for sample exchange (PSE).

The information flow between the cell elements is directed through the following communication channels:

- Re – local network LAN;
- USB11, USB21 – communication channels USB;
- COM11, COM12, COM21 – communication channels RS232;
- I/O – digital inputs and outputs for microcomputer μC.

Figure 3 shows the flow for all stages run by the metallographic samples throughout the automated system until their analysis is completed.

The metallographic samples are input by means of storage device St01. Polishing is carried out at the samples polishing posts Slf1, Slf2 by means of robot Ro1. The effective working of the sample is always followed by washing and drying at posts Sp1 and Us1 respectively. The assessment of the samples surfaces is carried out by microscope M1.

Once the metallographic sample is adequately worked, it is placed by robot Ro1 onto one of the storage devices St11, St12 and St13, and then the robot Ro2 takes them away. The reagent attack is carried out at post R1 or R2 and then the washing and drying operations are carried out at posts Sp2 and Us2 respectively. The final step of the metallographic sample consists of the metallographic analysis at post M2. The storage devices St21, St22 and St23 store the metallographic sample when post M2 is busy. If post M2 is available, the metallographic sample is transferred here, and the metallographic analysis is performed. After this analysis, the sample is evacuated by means of storage device St31.
3. Elaboration of Simple Coloured Petri Net Model

3.1. Elaboration of the Model

A simple coloured Petri net model was made in order to assess the performance of the automated system and to identify any possible bottlenecks. Thus, the colours that can be attached to several system entities are defined.

We define the set of the colours that will describe the fact that, at a given time, the buffer storage devices St11, St12 and St13 are able to store one sample (colset antiplace=with e):

\[ \text{antiplace}=\{e\} \tag{1} \]

Also, we define the set of colours that will be associated to the samples to be analyzed in the cell. Such colour will be named sample and will have value A for sample A and value B for sample B (colset sample=with A|B):

\[ \text{sample} = \{A, B\} \tag{2} \]

The colour robot has been defined for the two robots, with value r1 for robot Ro1 and value r2 for robot Ro2 (colset robot=with r1|r2):

\[ \text{robot} = \{r1, r2\} \tag{3} \]

The colour that is associated to the metallographic microscope is m (colset microscope=with m):

\[ \text{microscope} = \{m\} \tag{4} \]

Within the program CPN Tools a variable is assigned to every arch. Thus, variable r may have value r1 or r2:

\[ r \in \{r1, r2\} \tag{5} \]
Variable $i$ may have value $A$ or $B$:

\[ i \in \{A, B\} \]  

(6)

The coloured Petri net model features two kinds of nodes: positions and transitions. These are connected by means of oriented arches. The sequences performed by the industrial robots, coarse grinding, fine grinding, reagent attack, washing, microscope examination are modeled as transitions. The execution of a transition (the realization of a real sequence) is possible when certain conditions are met, which are modeled by means of positions. Some of the transitions and positions of the model are presented in table 1.

| Nr. crt. | Symbol | Type | Meaning | Characteristics |
|---------|--------|------|---------|-----------------|
| 1.      | P1     | Pos. | St01 stored one sample A or B | 1`A++1`B |
| 2.      | T1     | Tr.  | Ro1 grips one sample A or B   |      |
| 3.      | P2     | Pos. | Ro1 has one sample A or B in the grip |      |
| 4.      | T2     | Tr.  | Ro1 transfers sample A or B to Sf1 |      |
| 5.      | P3     | Pos. | Ro1 placed the sample A or B onto Sf1 |      |
| 6.      | T3     | Tr.  | Coarse grinding sequence (Slf1) |      |
| 7.      | P4     | Pos. | Ro1 has one sample A or B polished onto Sf1 |      |
| ...     | ...    | ...  | ...                              |      |
| 37.     | T18    | Tr.  | Ro2 transfers sample A or B to R1 and treats it |      |
| 38.     | P21    | Pos. | Ro2 has sample A or B treated by R1 |      |
| 39.     | T19    | Tr.  | Ro2 transfers sample A or B to R2 and treats it |      |
| 40.     | P22    | Pos. | Ro2 has sample A or B treated by R2 |      |
| 41.     | T20    | Tr.  | Ro2 transfers sample A or B to Sp2 and washes it |      |
| 42.     | P23    | Pos. | Ro2 has sample A or B washed |      |
| 43.     | T21    | Tr.  | Ro2 transfers sample A or B to Us2 and dries it |      |
| ...     | ...    | ...  | ...                              |      |
| 79.     | T37    | Tr.  | Ro2 evacuates sample A or B (St21) |      |
| 80.     | T38    | Tr.  | Ro2 evacuates sample A or B (St22) |      |
| 81.     | T39    | Tr.  | Ro2 evacuates sample A or B (St23) |      |
| 82.     | P44    | Pos. | Storage device St31- samples A |      |
| 83.     | P45    | Pos. | Ro1, Ro2 are available | 1`r1++1`r2 |

Compared to the timed Petri nets model [Blaga], this model is much simpler in terms of positions and transitions numbers.

3.2. Simulation

Figure 4 shows the simple coloured Petri nets model and the results of the simulation after 200 steps.
Figure 4. The simple coloured Petri nets model.

One can see that the model is viable and there are no bottlenecks. Also, the two types of samples are alternatively analyzed. The simulation showed that four A-type samples and four B-type samples were analyzes, as four colours A and four colours B are at position P44 (figure 4).

4. Realization of timed complex coloured Petri nets model

4.1. Building of the model

The positions and transitions of the timed complex coloured Petri nets are partially shown in table 2. Compared to the simple coloured Petri nets model, a smaller number of elements (positions and transitions) can be noticed. The number of positions and transitions decreased from 83 to 51.
Table 2. The positions and transitions of the timed complex coloured Petri net model.

| Nr. crt. | Symbol | Type | Meaning | Characteristics |
|----------|--------|------|---------|-----------------|
| 1.       | P1     | Pos. | St01 stored a sample A or B | 1’ A++1’ B |
| 2.       | T1     | Tr.  | Ro1 grips a sample A or B | 5 sec |
| 3.       | P2     | Pos. | Ro1 has a sample A or B in the gripping device | |
| 4.       | T2     | Tr.  | Ro1 transfers a sample A or B to Stf1 | 2 sec |
| 5.       | P3     | Pos. | Ro1 placed a sample A or B onto Stf1 | |
| 6.       | T3     | Tr.  | Coarse grinding sequence (Stf1) | 120 sec |
| …       | …      | …    | …       | …               |
| 23.      | T12    | Tr.  | Ro1 places a sample A or B to St11 | 5 sec |
| 24.      | P13    | Pos. | A sample A or B is in St12 | 1’1++1’2++1’3 |
| 25.      | P14    | Pos. | Available places left in St11 | |
| 26.      | P13    | Pos. | A sample A or B is in St12 | |
| 27.      | T13    | Tr.  | Ro2 grips a sample A or B from St12 | 5 sec |
| …       | …      | …    | …       | …               |
| 47.      | T22    | Tr.  | Ro2 grips sample A or B (St21) from M2 | 5 sec |
| 48.      | P26    | Pos. | Ro2 are sample A or B (St21) examined | |
| 49.      | T23    | Tr.  | Ro2 evacuates sample A or B (St21) | 5 sec |
| 50.      | P27    | Pos. | Storage St1- samples A | |
| 51.      | P28    | Pos. | Ro1, Ro2 is available | 1’r1++1’r2 |

In the case of timed complex coloured Petri nets model (figure 5) we defined the simple colours associated to samples, robots and microscope M2 as in the case of simple coloured model, according to relations (2), (3) and (4).

In this version, we defined the set of colours that will describe the fact that the buffer storage devices St11, St12 and St13 are able to store a single sample at a given time (\( \text{colset antiplace}=\text{int} \ 1..3 \)):

\[
\text{antiplace}=\{1,2,3\} \quad (7)
\]

In order to highlight the connection between the sample type and the buffer storage device which stores it before entering the analysis subsystem, the set of complex colours \( \text{storage} \) is defined (\( \text{colset storage}=\text{product sample} \ast \text{antiplace} \)). This is the cartesian product of the sets \( \text{sample} \) (relation (1)) and \( \text{antiplace} \) (relation (7)), with the following values:

\[
\text{storage}=\{(A, 1), (A, 2), (A, 3), (B, 1), (B, 2), (B, 3)\} \quad (8)
\]

The variables \( r \) and \( i \) are defined by relations (5) and (6). In the version with complex colours one more variable \( e \) is defined which can have the values 1, 2 sau 3:

\[
e \in \{1,2,3\} \quad (9)
\]

Also, there is a complex variable defined directly in the model \((e, i)\), which can have the following values:

\[
(e, i) \in \{(A, 1), (A, 2), (A, 3), (B, 1), (B, 2), (B, 3)\} \quad (10)
\]

This variable is associated to arches \(T13\rightarrow P12\) and \(P12\rightarrow T14\) (figure 6).

The introduction of time factor in the model has been made in two ways. Timings have been associated to the transitions that model sequences (operations) of the preparing and analysis processes for the metallographic samples. For example, a 120 seconds timing was associated to transition T3.

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Also, there is a complex variable defined directly in the model \((e, i)\), which can have the following values:

\[
(e, i) \in \{(A, 1), (A, 2), (A, 3), (B, 1), (B, 2), (B, 3)\} \quad (10)
\]

This variable is associated to arches \(T13\rightarrow P12\) and \(P12\rightarrow T14\) (figure 6).
which models the coarse grinding operation. This is enclosed in the model by expression $@+120$ (figure 5).

![Figure 5. The timed complex coloured Petri model.](image1)

Figure 5. The timed complex coloured Petri model.

![Figure 6. Definition of complex variable $(i,e)$.](image2)

Figure 6. Definition of complex variable $(i,e)$.

![Figure 7. Function that ensures the alternation of both sample types.](image3)

Figure 7. Function that ensures the alternation of both sample types.

Also, the time factor has been associated to the colours that symbolize samples: `colset sample=with A|B timed` (figure 8) and to complex colours `storage` (figure 8).

The alternation of both sample types is ensured by the decisional function that is associated to arch $T1→P1$ (figure 7):
\[ if \, i=A \, then \, 1 \, B \, else \, 1 \, A \]  

(11)

4.2. Simulation

An 8-hour interval (28800 sec) is considered for the simulation, and the duration of the simulation is set in the window Simulation (figure 5). 2236 steps have been executed during simulation (figure 8). Also, the program yields information about the analysis finalizing moment for each sample. For example, sample A was finalized at moment 438, and the last sample B at moment 28463 (figure 9).

Figure 8. Introduction of time factor in the model.

Figure 9. Counting of analyzed samples.

Figure 10. Simulation report.

Also, it can be seen that 97 samples have been analyzed during the 8 hours (figure 9). When the time factor is introduced in the model, the CPN Tools program allowed the generation of a report (figure 10) which shows the moments of each transition. That is, the moments of the execution of each sequence can be identified in the real system.

5. Conclusions

Modeling and simulation are efficient instruments for the performance assessment of automated systems. This paper described how the coloured Petri nets have been used for modeling and simulation: modeling of an automated system for preparation and analysis of metallographic samples.

The usage of coloured Petri nets for modeling and simulation of automated systems allows the replacement of the token-type marks with symbols (colours), which greatly simplifies the model. The colour-type mark can be seen interpreted as a parameter that can have various values, which in our case can be considered as several sample types. The model structure is simplified even more when complex colours are used, that is the number of positions and transitions significantly decreases.

In the case of the ordinary timed Petri nets, timings are associated to transitions (T timed Petri nets) or to positions (P timed Petri nets). In the case of coloured Petri nets, timings can be associated to colours, transitions and arches. In the model that was described in this paper, timings have been associated to colours and transitions, which allowed better fidelity for the description of the real system by means of the model. That is, the number of the analyzed samples in a given time interval can be shown. Also, it is possible to identify the finalizing moments of each sample analysis.

By means of the timed coloured Petri nets model, the sequences executed by the real system components can be monitored in the considered time interval.

The future research will pursue the way that coloured Petri nets models can be used to assess the random (stochastic) processes. These will give the models a higher accuracy degree in relation with the real system.
6. References
[1] Blaga F, Stanasel I, Pop A, Hule V and Buidos T 2014 A. U. O. Fasc. Man. Tech, En. 23 299
[2] Saren S K, Blaga F, Dzitac S and Vesselenyi T 2017 Procedia Computer Science Ahuja V Shi Y Khazanchi D Abidi N Tian Y Berg D and Tien M J New Delhi Elsevier B.V. 122 pp 253-260
[3] https://highresbio.com/laboratory-automation/range/ accessed on December 2019
[4] https://www.hseag.com/about-hombrechtikon-systems-engineering-ag/ accessed on January 2019
[5] https://www.picoquant.com/materialsscience accessed on January 2019
[6] http://saxslab.com/materials-science/automation/ accessed on December 2019
[7] Madison J, Spowart J E, Rowenhorst D. J., Fiedler J. and Pollock T. M. 2008 Characterization of three-dimensional dendritic structures in nickel-base single crystals for investigation of defect formation Proceedings of the Superalloys Conference Roger C. Reed and at.Champion Pennsylvania USA The Minerals, Metals & Materials Society pp 881-888
[8] Vesselényi T, Barabás T and Moga I 2004 Rob. & Man. Inter. J 9 37
[9] Blaga F S, Vesselenyi T, Ursu M P, Hule V and Stanasel I 2019 IOP Conference Series: Materials Science and Engineering Raval K R and at. Iasi Romania IOP Publishing 10

Acknowledgments
This paper was funded through the project “SmartDoct - High quality programs for doctoral students and postdoctoral researchers of the University of Oradea to increase the relevance of research and innovation in the context of regional economy”, ID / Project code: 123008, co-financed from the European Social Fund through the Human Capital Operational Program 2014-2020 and thanks to the Doctoral School of Engineering Sciences (University of Oradea) facilities at the scientific infrastructure.