Modeling with hierarchical colored Petri nets. Case study

F S Blaga[1], A Pop[1], T Vesselenyi[1], V Hule[1] and C I Indre[1]

[1]University of Oradea, Faculty of Management and Technological Engineering, str.Universității nr.1, Oradea 410087, Romania

E-mail: fblaga@uoradea.ro

Abstract. The paper presents the results of research on the use of hierarchical models with colored Petri nets in the evaluation of automated systems for the preparation and analysis of metallographic specimens. Modeling with hierarchical colored Petri nets was used to evaluate the performance of a preparation and analysis robotic system for metallographic samples. The automated system is composed of three subsystems: the subsystem for the preparation of metallographic samples, the subsystem for the attack with reagent of metallographic samples, the subsystem for the analysis of metallographic samples. Two models were made: a model with colored Petri nets with simple colors and a model with timed colored Petri nets with complex colors. Each model was developed on two hierarchical levels. Level 1 contains the model of the entire flexible system for the preparation and analysis of metallographic samples. Level 2 consists of three sub-models: the sub-model of the system for the preparation of metallographic samples, the sub-model of the system for the reagent attack of metallographic samples, the sub-model of the system for the analysis of metallographic samples. Models with timed colored Petri nets allow the evaluation of system performance in terms of the number of samples analyzed in a time interval. The performance of the modeled system was evaluated by simulation, considering a time interval of eight hours.

1. Introduction

In the field of metallography there had been developed systems which contain a microscope, 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 [1] 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 [2].

Modeling and simulation of automated systems are effective tools for evaluating their performance and improving their operation. Among the modeling and simulation tools, one of the most used are Petri nets.

Timed colored Petri nets offer the possibility of making models that describe very accurately the real system and whose structure is simplified compared to models with ordinary Petri nets. Thus, in [3] is present the model with timed colored Petri nets made for a flexible manufacturing cell composed of two CNC machines served by a robot. The use of Petri Nets with complex colors allows the realization of relatively simple models that take into account the fact that in the cells several types of parts are processed. The introduction of the time factor allows the determination of the manufacturing cycle.

The use of models with hierarchical colored Petri nets, allows a more rigorous analysis of the way in which each subsystem within the analyzed system works [4]

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 [5] 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 [6], Hombrechtikon System Engineering (HSE) [7], or in the field of material science we can give Picoquant [8] or SaxsLab (Xenocs) [9].

In this paper are developed the hierarchical models with colored Petri nets with simple colors and with complex timed colors of the automated system of preparation and analysis of metallographic samples described in [10]. In the paper [10] was presented in detail the model with T-timed Petri nets of the system. The hierarchy of the models highlights the details of the functioning of the subsystems within the analyzed system.

2. Organizing the automated system for preparation and analysis of metallographic samples

The automated system for preparation and analysis of metallographic samples was designed taking into account the existing technical-material resources in the laboratories of Mechatronics and Materials Science of the University of Oradea. The layout of the designed cell is shown in figure 1. Three subsystems can be distinguished:

- S1 subsystem for the preparation of metallographic samples;
- S2 subsystem for reagent attack of metallographic samples;
- S3 subsystem for metallographic analysis.

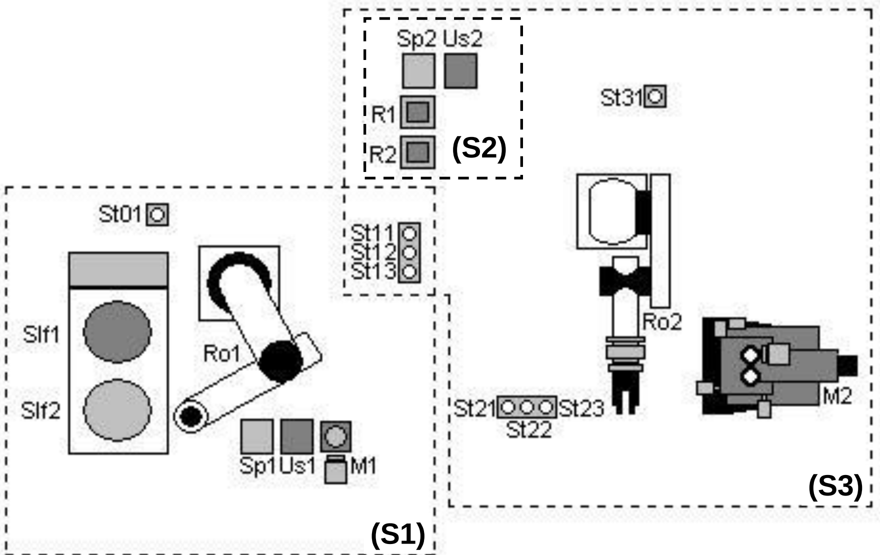

Figure 1. Automated system layout (flexible cell) preparation and analysis of metallographic samples.

Figure 1 can distinguish the following components of the automated system:

- polishing stations for samples: Slf1, Slf2;
- storage units:

    - input storage system: St01;
    - buffer storage system between subsystem S1 and subsystem S2: St11, St12, St13;
    - sample storage devices that are prepared for analysis under the M1 microscope: St21, St22, St23;
    - system exhaust storage: St31.
- industrial robots: Ro1, Ro2;
- washing stations for metallographic samples: Sp1, Sp2;
- attack stations with reagents: R1, R2;
- station (microscope) to determine the state of the M1 surface;
- M2 post (microscope) for determining the metallographic structure M2.

In terms of service by robots, those in two subsystems are served as follows:

- the subsystem (S1) which has in its composition the stations: Slf1, Slf2, Sp1, Us1, M1, St01, these being served by the robot Ro1;
- the subsystem (S2) that includes the stations: R1, R2, Sp2, Us2, these being served by the robot Ro2;
- the subsystem (S3) which includes the stations: R1, R2, Sp2, Us2, M2, St21, St22, St23, St31, these being served by the Ro2 robot.

3. Defining hierarchical levels

Two hierarchical levels of the model with colored Petri nets are defined:

- Level 1: is the model of the entire flexible system for preparation and analysis of metallographic samples;
- Level 2 contains three sub-models:
    - the sub-model of the system for the preparation of metallographic samples;
    - the sub-model of the system for reagent attack of metallographic samples;
    - the sub-model of the system for the analysis of metallographic samples.

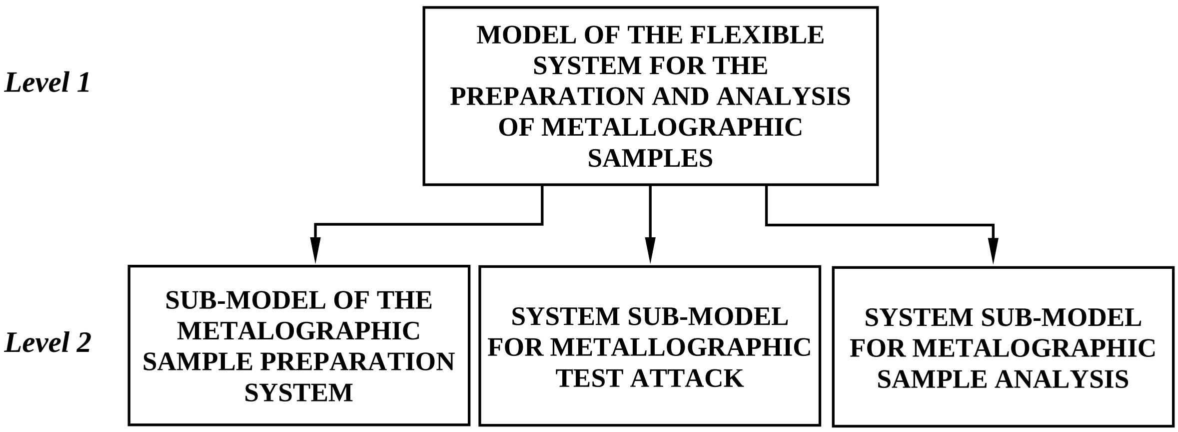

Figure 2. Hierarchical levels of the model with colored Petri nets.

This hierarchical structure corresponds to both the model with colored Petri nets with simple colors and the model with complex colors.

4. The hierarchical model with colored Petri nets with simple colors

4.1. Building the model

A first step in building the model is to define the colors that are associated with the different entities that can be identified in the system.

It is defined the set of colors that will describe the fact that the buffer storage St11, St12, St13 can store, at a given time, a single sample (*colset antiplace=with e)*:

$$antiplace=\{e\} \tag{1}$$

It is also defined the set of colors that will be associated with the samples to be analyzed in the cell. This color will be called sample and will have the following values: A for sample A and B for sample B (*colset sample=with A|B*):

$$sample=\{A,B\} \tag{2}$$

For the two robots, the robot color was defined, with two values: r1 for the Ro1 robot and r2 for the Ro2 robot (*colset robot=with r1|r2*):

$$robot=\{r1, r2\} \tag{3}$$

The color associated with the microscope with which the analysis of metallographic samples is made, is m (*colset microscope=with m*):

$$microscope=\{m\} \tag{4}$$

In the case of the CPN Tools program, each arc is assigned a variable. Thus, the variable r can have the values r1 or r2:

$$r\ \{r1, r2\} \tag{5}$$

The variable *i* can have the values A or B:

$$i\ \{A, B\} \tag{6}$$

The model with colored Petri nets contains two types of nodes: positions and transitions. They are connected by oriented arches. The sequences executed by the industrial robots, the roughing sanding, the finishing sanding, the reagent attack, the washing, the examination under the microscope are modeled by transitions. Execution of a transition (realization of a real sequence) is possible if some conditions are met. These conditions are modeled through positions. Some of the transitions and positions of the model are presented in table 1.

Table 1. Positions and transitions of the model with colored Petri nets with simple colors

Nr. crt.	Symbol	Type	Signification	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	
…	…	…	…	…
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 la R2 and treats it	
…	…	…	...	…
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 model made with timed Petri nets [10], it is much simpler in terms of the number of positions and transitions.

After the construction of the model, the main model will be defined with colored Petri nets with simple colors and sub-models. Figure 3 shows the main model (*Level 1*) called *System*. Level 2 sub-models are highlighted: Sample *Preparation, Sample Attack and Sample Analysis*. The model and sub-models are displayed on independent pages (in windows), as follows:

- the main model is displayed on the *System* page;
- the sub-model of the system for the preparation of metallographic samples is displayed on the *Preparation* page;
- the sub-model of the system for reagent attack of metallographic samples is displayed on the *Attack* page;
- the sub-model system for the analysis of metallographic samples is displayed on the *Analysis* page.

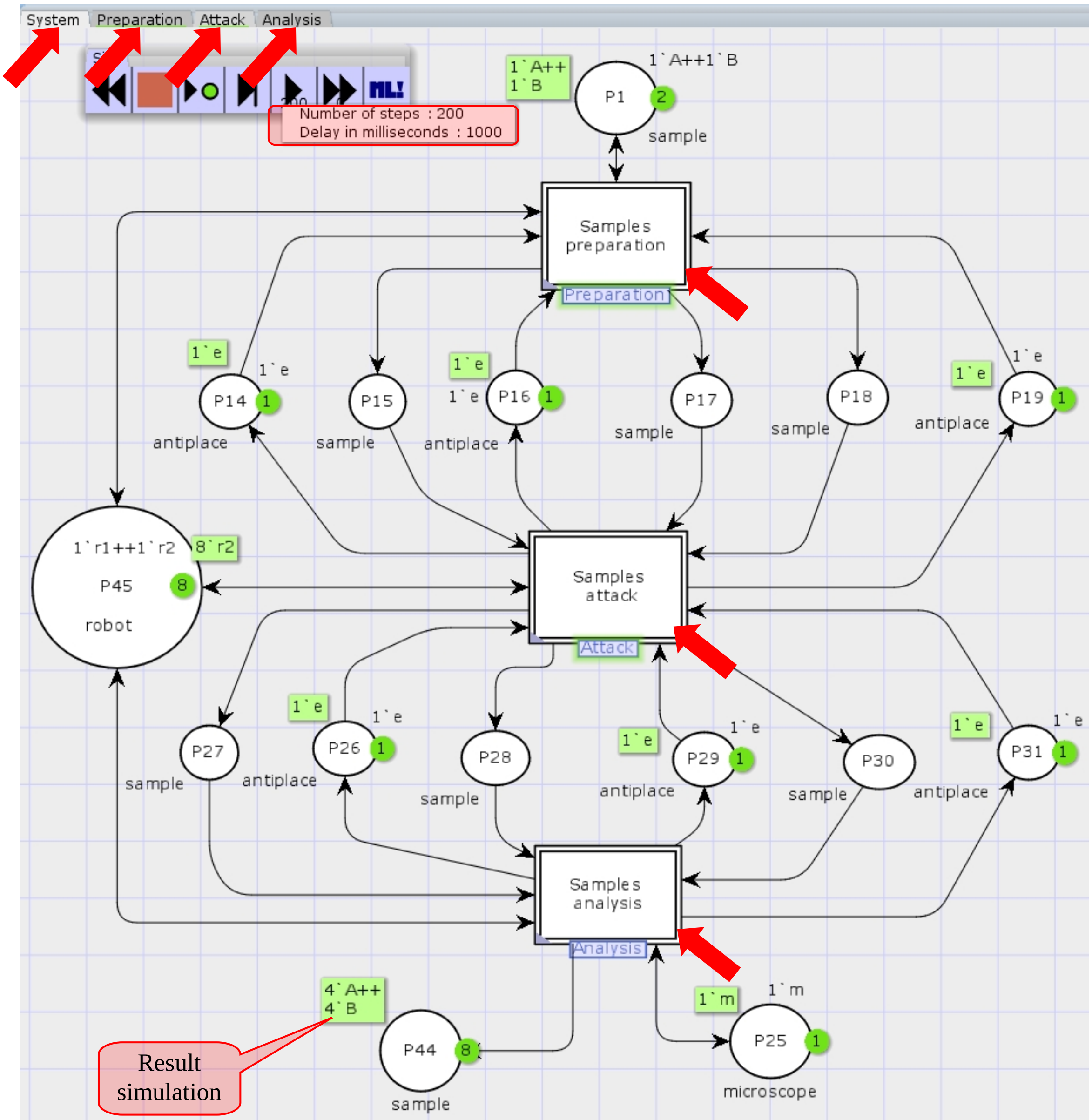

Figure 3. The main model with colored Petri nets with simple colors.

Figure 4 shows the sub-model of the system for preparing metallographic samples. The positions through which the sub-model connects to the main model are highlighted. These positions can be of three types: input positions (P14, P16, P19), output positions (P15, P17, P18) and input / output positions (P1, P45).

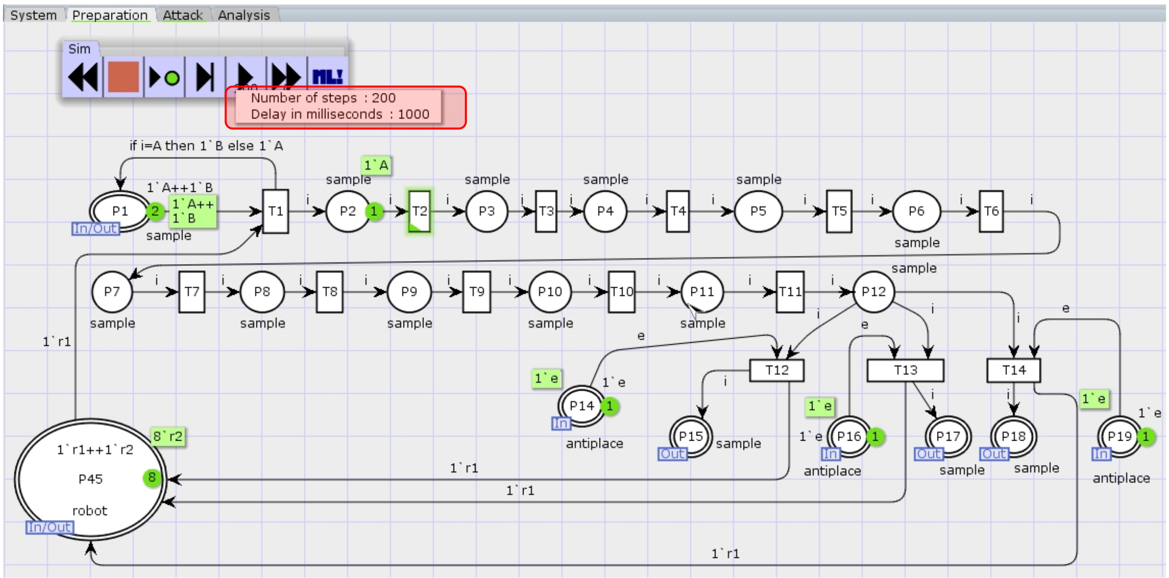

Figure 4. Sub-model of the system for the preparation of metallographic samples.

Figure 5 shows the sub-model of the system for reagent attack of metallographic samples. In this sub-model, the input positions (P15, P17, P18, P26, P29, P31), the output positions (P14, P16, P19, P27, P29, P30) and the input / output position (P45) also appear.

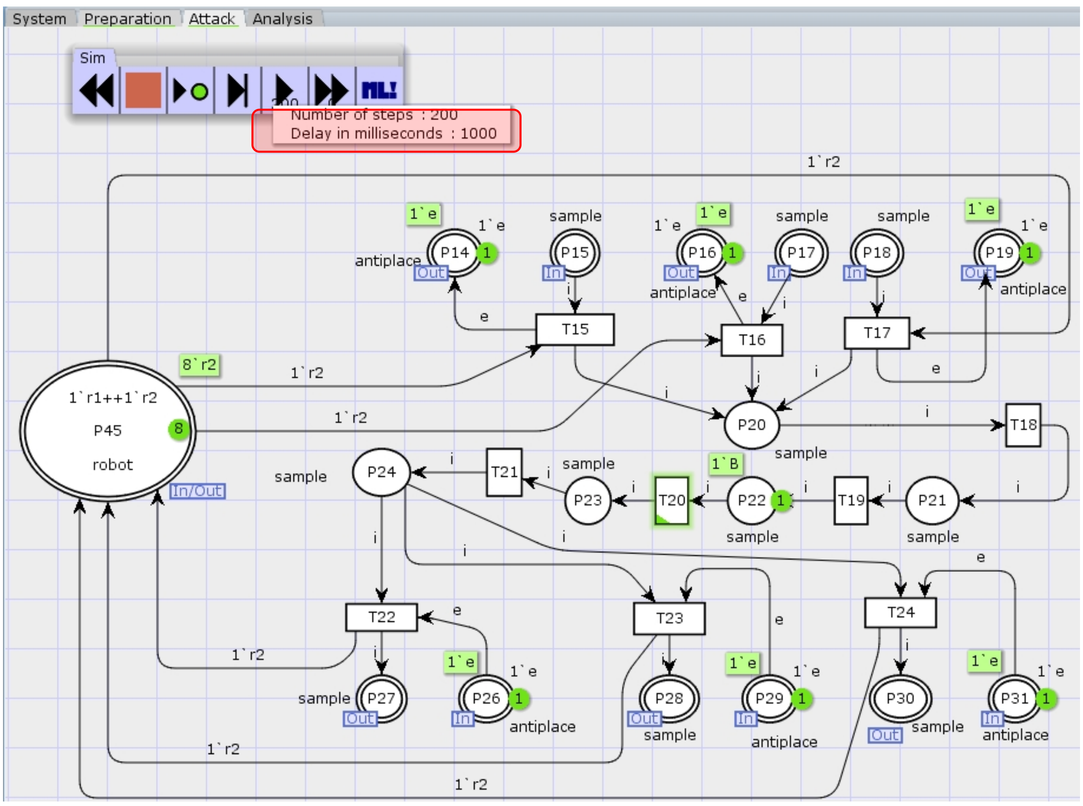

Figure 5. Sub-model of the system for the attack with reagents of metallographic samples.

Figure 6 shows the sub-model of the system for the analysis of metallographic samples. In this sub-model also appear the input positions (P27, P28, P30), the output positions (P26, P29, P31, P44) and the input / output positions (P25, P45).

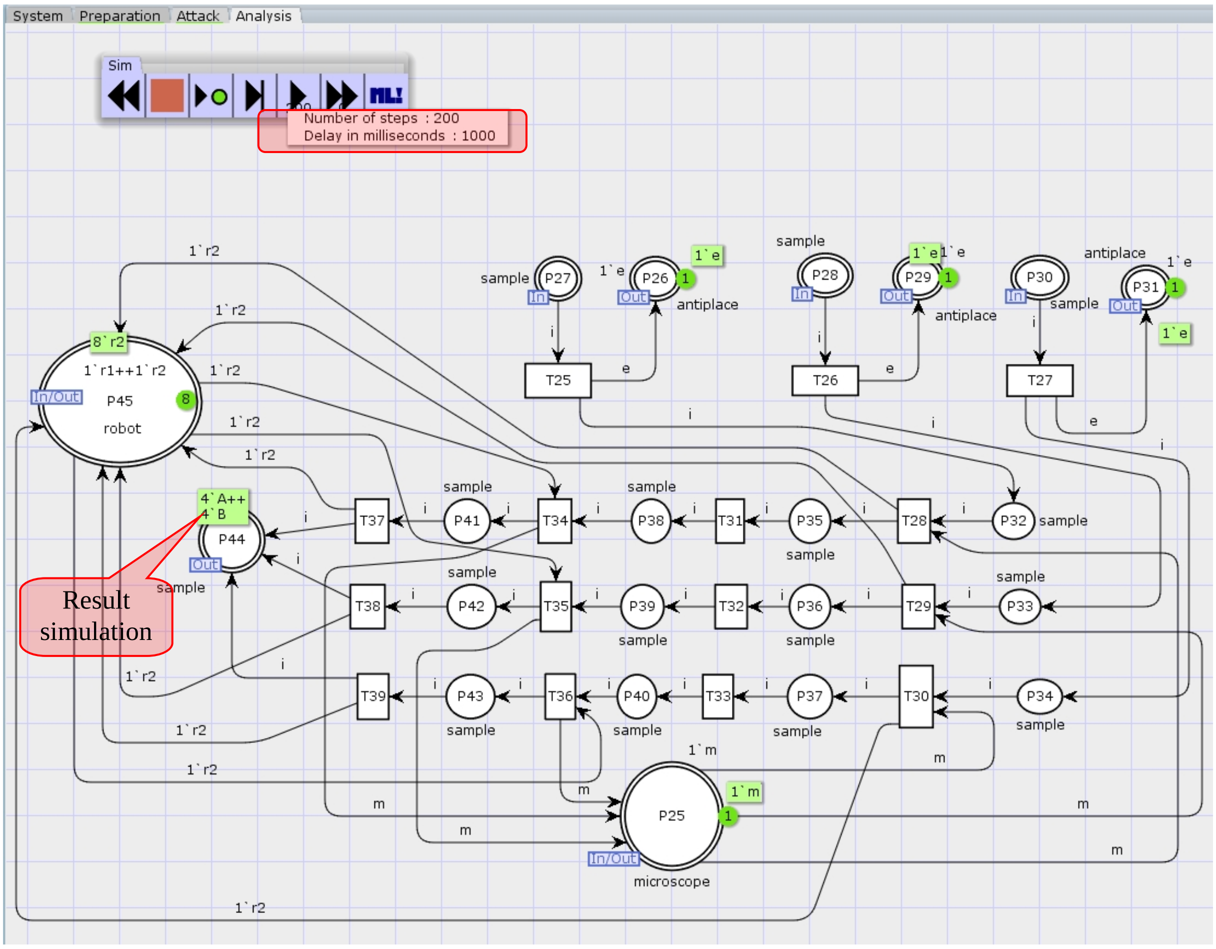

Figure 6. Sub-model of the system for the analysis of metallographic samples.

4.2. Simulation

The system simulation was performed over 200 steps (sequences) (figure 3, figure 4, figure 5 and figure 6). The result of the simulation, the number and type of samples analyzed, is presented in position P44 (figure 3 and figure 6). The simulation showed that four type A samples and four type B samples were analyzed. The two types of samples are analyzed alternately.

During the simulation, the way in which all the components of the model behave are highlighted: the main model and the sub-models. It is found that the model is viable, there are no blockages.

5. Realization of the hierarchical model with timed colored Petri nets with complex colors

5.1. Model building

The hierarchical model with timed colored Petri nets with complex colors has the structure presented in section 3. The main model is presented in figure 7.

The positions and transitions of the hierarchical model with timed colored Petri nets with complex colors are partially presented in table 2. A significant reduction in the number of elements (positions and transitions) can be seen compared to the model with simple color colored Petri nets. More precisely, the number of positions and transitions was reduced from 83 to 50.

Table 2. Positions and transitions of the model with timed colored Petri nets with complex colors

Nr. crt.	Symbol	Type	Signification	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 Sf1	
5.	P3	Pos	Ro1 placed a sample A or B to Sf1	
6.	T3	Tr.	Roughing grinding sequence (Slf1)	
7.	P4	Pos.	Ro1 has the sample A or B ground on Slf1	
8.	T4	Tr.	Ro1 transfers sample A or B to Sf2	2 sec
…	…	…	…	…
23.	T12	Tr.	Ro1 places a sample A or B to St11	
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.	T13	Tr.	Ro2 grips a sample A or B from St12	5 sec
27.	P15	Pos	Confirmation- Ro2 has a sample A	
28.	T14	Tr.	Ro 2 transfers sample A or B to reagent 1 and treats it	12 sec
…	…	…	...	…
44.	T21	Tr.	Sample A or B (St21) is examined at M2	60 sec
45.	P25	Pos	Sample A or B (St21) was examined at M2	
46.	T22	Tr.	Ro2 grips sample A or B (St21) from M2	5 sec
47.	P26	Pos	Ro2 are sample A or B (St21) examined	
48.	T23	Tr.	Ro2 evacuates sample A or B (St21)	5 sec
49.	P27	Pos	Storage St1- samples A	
50.	P28	Pos	Ro1, Ro2 is available	1\`r1++1\`r2

In the case of the model with timed colored Petri nets with complex colors (figure 7), the simple colors associated with the samples, robots and the M2 microscope were defined as in the case of the model with simple colors, according to relations (2), (3) and (4).

This variant defines the set of colors that will describe the fact that the buffer storage St11, St12, St13 can store, at a given time, a single sample (*antiplace package = int 1..3*) :

$$antiplace=\{1,2,3\} \qquad (7)$$

To highlight the connection between the sample type and the buffer storage on which it is stored before entering the analysis subsystem, the set of complex storage colors (*colset storage = product sample * antiplace)* is defined. This is the Cartesian product of the sample sets (relation (1)) and antiplates (relation (7)), having the following values:

$$storage=\{(A, 1), (A, 2), (A, 3), (B, 1),(B, 2), (B, 3)\} \qquad (8)$$

The variables r and i are defined, also in this case, with relations (5) and (6). In the variant with complex colors, another variable is defined, e, which can have three values 1, 2 or 3. Thus,

$$e \ \{1,2,3\} \qquad (9)$$

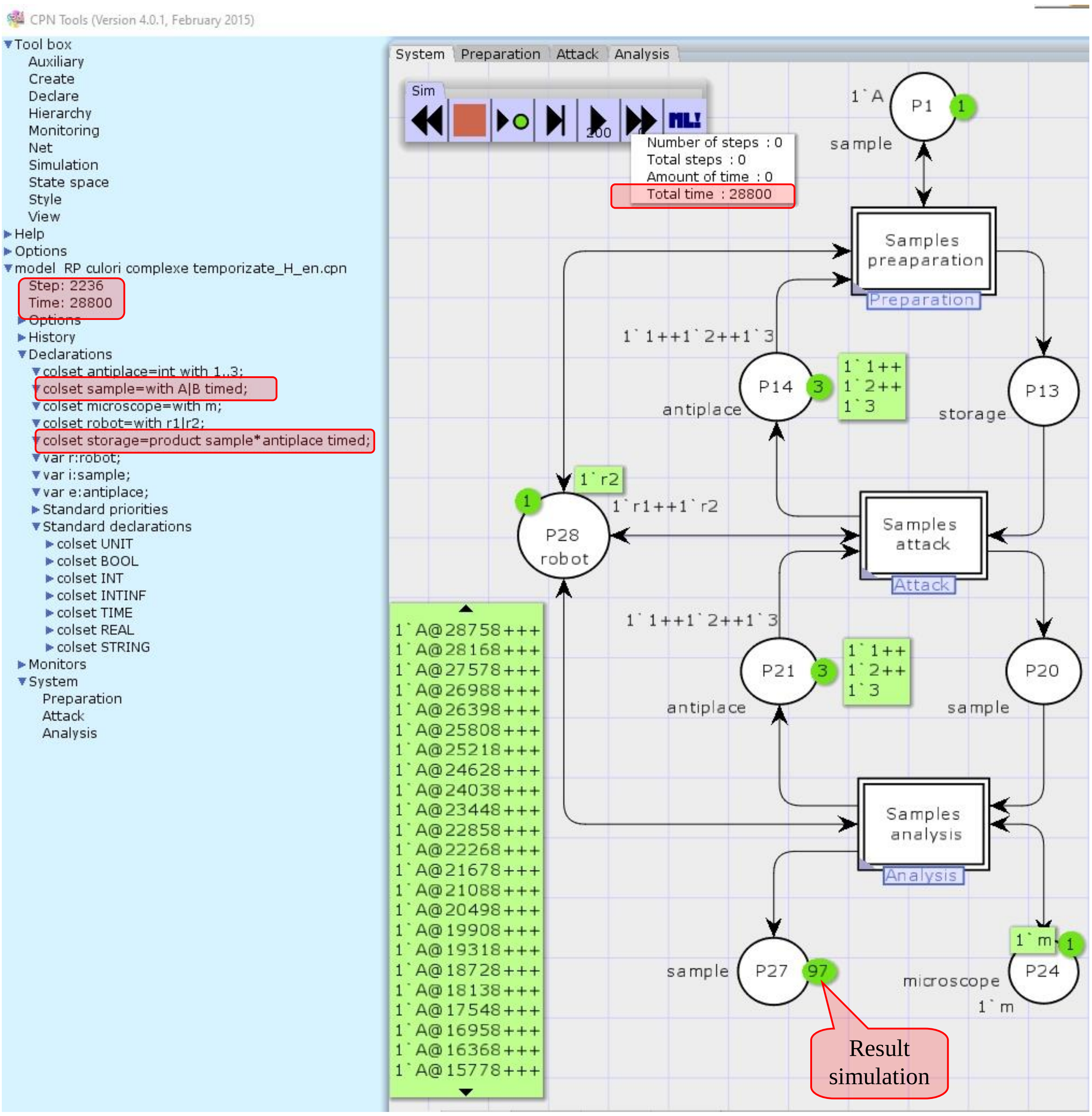

Figure 7. The main model with timed colored Petri nets with complex colors.

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

$$(e, i) = \{(A, 1), (A, 2), (A, 3), (B, 1), (B, 2), (B, 3)\} \qquad (10)$$

The variable is associated with the arcs T12 → P13 (figure 8) and P13 → T13 (figure 9).

The introduction of the time factor in the model was done in two ways. Thus, the time factor was associated with the colors that symbolize the samples: *colset sample=with A|B timed* (figure 7) and complex *storage* colors (figure 7). Also, they were associated with timings of the transitions that model sequences (operations) of the processes of preparation and analysis of metallographic samples. For example, the T5 transition that models the finishing grinding operation (sequence) was associated with the 80 sec delay. This is materialized in the model by the expression @ + *80* (figure 8).

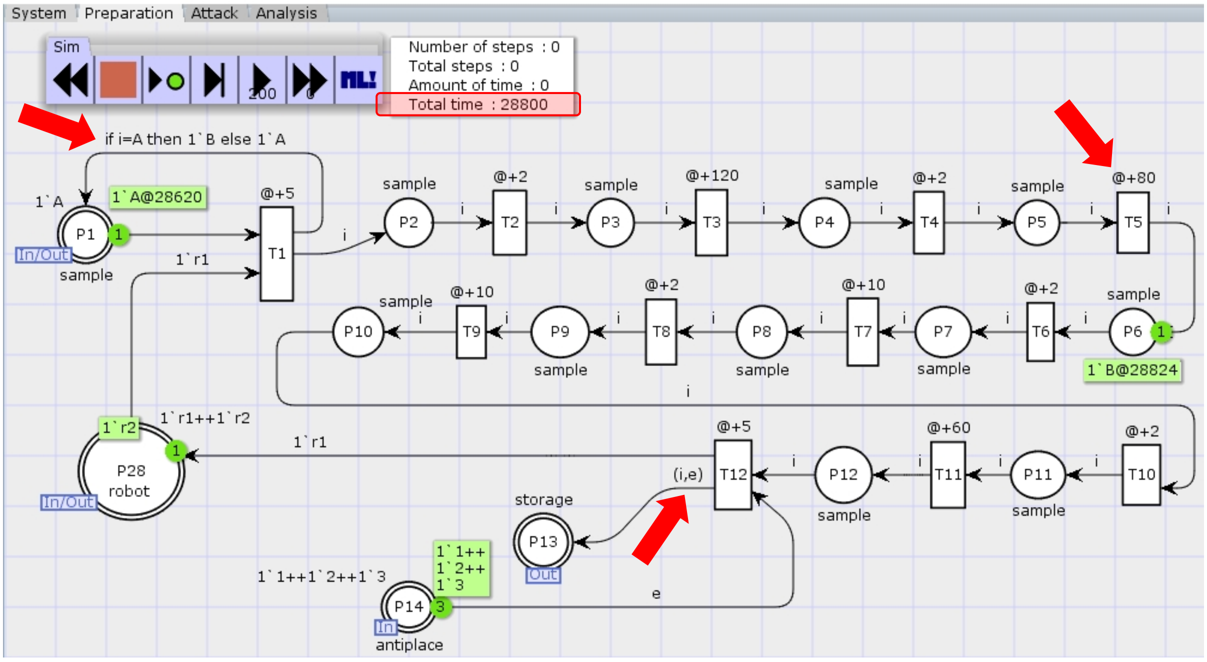

Figure 8. Sub-model of the system for the preparation of metallographic samples - complex colors.

The alternation of the two types of samples is ensured by the decisional function associated with the arc T1 → P1 (figure 8):

$$if =A\ then\ 1`B\ else\ 1`A \qquad (11)$$

In the case of the hierarchical model with colored Petri nets timed with complex colors, as in the case of the model with simple colors, the interconnection between the main model and the sub-models is made through input positions, output positions and input / output positions.

Figure 8 shows the sub-model of the system for preparing metallographic samples. Figure 9 shows the details of the model of the reagent attack system of the metallographic samples.

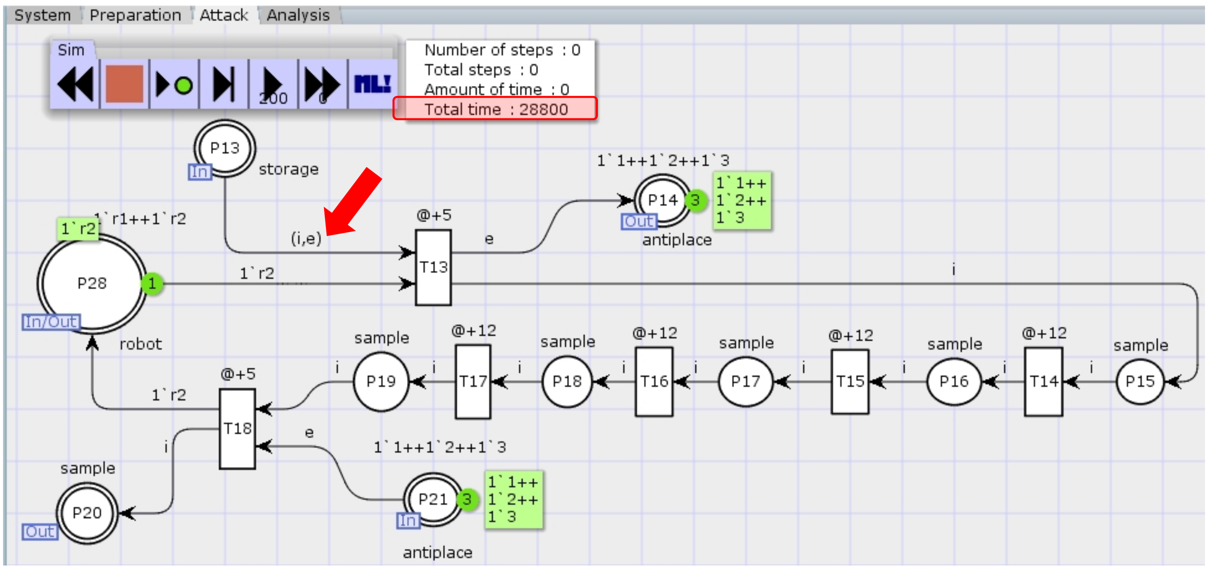

Figure 9. Sub-model of the system for the attack with reagents of metallographic samples - complex colors

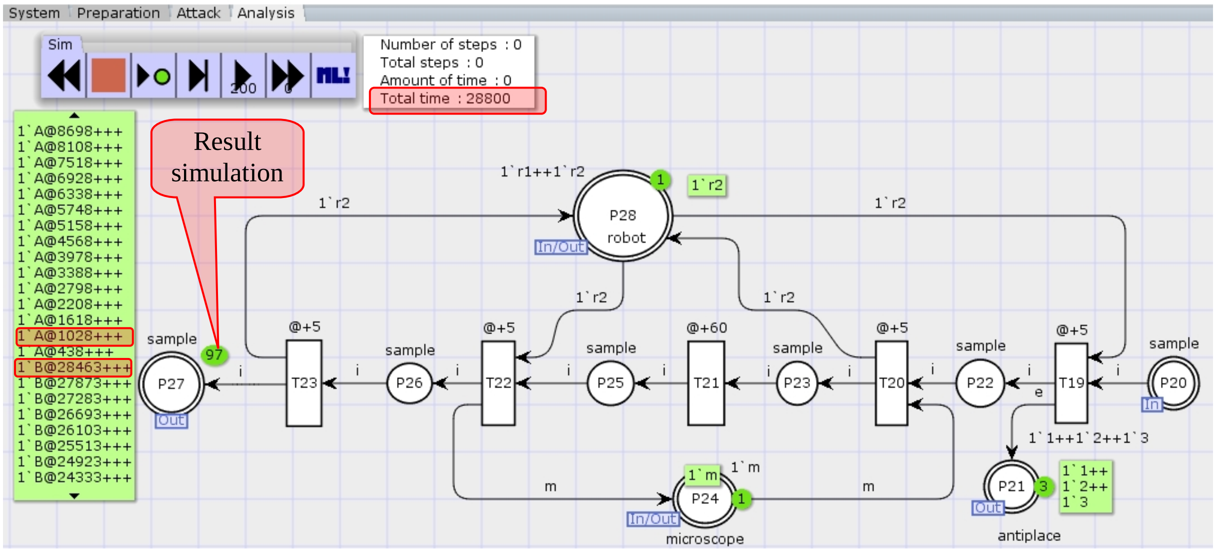

Figure 10. Sub-model of the system for the analysis of metallographic samples - complex colors

Figure 10 shows the sub-model for the analysis of metallographic samples.

5.2. Simulation

For simulation, a time interval of 8 hours (28800 sec) is considered. The simulation duration is set in the *Simulation* window (figure 7, figure 8, figure 9 and figure 10). During the simulation, 2236 steps were performed (figure 7). The program also provides information on when the analysis of each sample is completed. For example, the last type B test was completed at time 28463, and the second type A test at the time (figure 10).

It can also be noted that during the 8 hours a number of 97 samples were analyzed (figures 7 and figures 10).

When introducing the time factor into the model, the CPN Tools software allowed the generation of a report (figure 10) that highlights the times at which each transition is executed. In other words, one can identify the moments at which each sequence (operation) is executed in the real system.

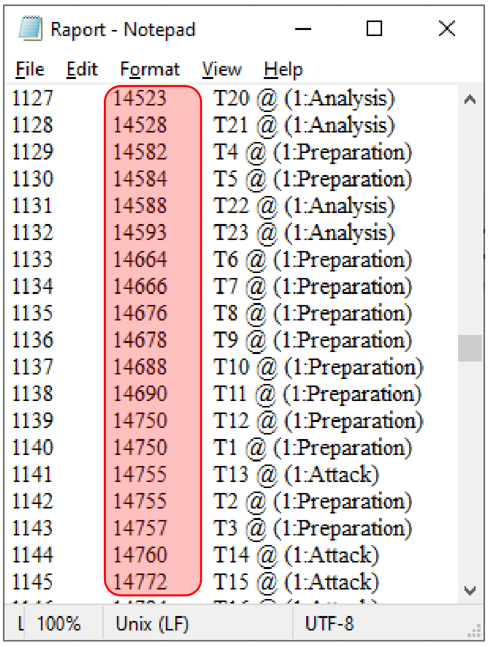

Figure 11. Simulation report. Execution moments of transitions.

6. Conclusions

Modeling and simulation with colored Petri nets are effective tools for evaluating the performance of automated systems.

The paper shows how colored Petri nets were used for modeling and simulation: modeling an automated system for preparing and analyzing metallographic samples.

The token can be interpreted as a parameter that can take different values. In the analyzed case, two types of samples were considered. The structure of the model is simplified (the number of positions and transitions decreases significantly) and more when using complex colors.

In the case of ordinary timed Petri nets, timings are associated with transitions (T-timed Petri nets) or positions (timed P-Petri nets). In the model described in the paper, the timings were associated with colors and transitions. The number of samples analyzed over an eight-hour time period was highlighted by simulation. The introduction of timings allows the identification of the moments when the analysis of each sample is completed.

By using the model with timed colored Petri nets, the sequences executed by the components of the real system over the considered time interval can be monitored.

The hierarchical organization of the models with colored Petri nets allowed the highlighting of the way in which each subsystem works within the automated system for the preparation and analysis of metallographic samples.

Future research will look at how models with fuzzy colored Petri nets. These will give the models a higher degree of accuracy compared to the real system.

7. References

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