

The efficiency of modeling and simulation of manufacturing systems using Petri nets

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Abstract. The paper is a partial synthesis of the work that a team within the Faculty of Managerial and Technological Engineering has in the field of modeling and simulation of systems with Petri nets. The paper deals with three issues. The first part is Modeling and simulation of manufacturing systems with timed Petri nets. The first part presents the way in which the performances of some manufacturing systems are evaluated using timed Petri nets. The first example is a manufacturing system specific to the textile industry. The system has three production lines. In this case, the modeling with timed Petri nets allows the analysis of the operation of the flow lines and highlights the bottleneck. Another modeled manufacturing system is specific to a series production, more precisely it refers to the manufacture of gas cookers within a company from Oradea. The model with Petri nets also describes the supply sequences of the stocks of parts and subassemblies. The next modeled system is an automated manufacturing system for the packaging of detergents. The complexity of the Detergent Packing System and the high level of automation, require the use of efficient modeling and simulation methods to verify the validity of the solutions adopted. In this chapter is present the model of a robotic welding cell. The second part of the paper, the transition from timed Petri nets to hierarchical colored Petri nets, shows how Petri nets were developed for a robotic cell for metallographic analysis. The third part is dedicated to modeling with colored Petri nets timed with complex colors of the flexible manufacturing cell A007 within the Department of Industrial Engineering.

1. Introduction

The concept of Petri nets was introduced by Carl Adam Petri in his work *Kommunikation mit Automaten* (dissertation) [1]. Further the method of modeling and simulation of Petri nets was developed and found more and more fields of application. [2], [3], [4], [5] and [6].

At the University of Oradea, within the department of industrial engineering there are significant concerns in the field of using Petri nets in modeling and simulation of systems. In particular, research has focused on modeling and simulating manufacturing systems.

The paper [7] proposes the use of modeling and simulation with timed Petri nets in evaluating the performance of manufacturing lines in the textile industry. The paper [8] presents the results of research in the field of manufacturing process management through modeling and simulation. The research object is the manufacturing process that is specific to the mass production, more specifically refers to the gas cooker manufacturing within a company in Oradea.

An automated manufacturing system is present in [9] for the packaging of detergents can be modeled using Petri nets. The complexity of the Detergent Packing System and the high level of

automation, require the use of efficient modeling and simulation methods to verify the validity of the solutions adopted. For this purpose, a modern modeling and simulation method based on Petri nets is used. The models associated with the system are developed into a hierarchical structure: the model of some modules in a line; the model of a line; system model as a whole.

The paper [10] presents the model with timed Petri nets of a robotized manufacturing cell specific to the automotive industry.

There is a concern to model the same system using several types of Petri nets. Thus, the robotic cell destined for the preparation and analysis of metallographic samples was modeled with: timed Petri nets [11], colored Petri nets [12] and hierarchical colored Petri nets [13]. Also in this context are the works [14] and [15]. They propose two models with colored Petri nets with complex colors of the flexible manufacturing cell A007 from the University of Oradea.

The paper [16] proposes an approach of modeling and simulation of a manufacturing process based on timed colored Petri nets, by developing an application based on XML (eXtensible Markup Language) technology.

There is a concern to develop models with Petri nets in which to find the techniques specific to fuzzy sets [17]. Also, models of hierarchical colored Petri nets are developed for the analysis of the performances of flexible manufacturing systems [18], [19], [20], [21]. An analysis of the modules in which it can be used state space is presented in [22].

2. Modeling and simulation of manufacturing systems with timed Petri nets

2.1. Evaluation of the textile industry fabrication lines performances using Petri networks models

The paper [7] presents an approach to the matters of the flux lines which are specific to the industry of textile clothes, from the point of view of their balance. Frequently, it happens that the time periods of the operations are much different, and this leads to jams and extended waiting times, with negative influence on the efficiency. This paper proposes the use of a modeling and simulation method based on timed Petri networks, which will allow the analysis of the flux lines operation, the highlighting of the bottlenecks and to yield information to the personnel that take managerial decisions. Three lines, which manufacture the following products: jacket, skirt and trousers, are analyzed. For each case, the modeling and simulation procedure yields solutions for jam solving.

The specific products of the company SC TRICOUL SRL belong to the category of (ready-made) clothes for children, women and men.

Figure 1 shows specific products of this company of type “jacket”, “skirt” and “trousers”.

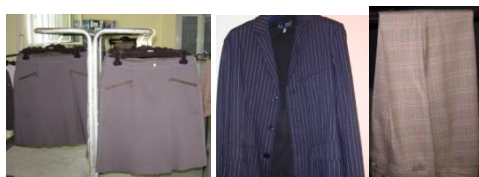


Figure 1. Products of company SC TRICOUL SRL [7]

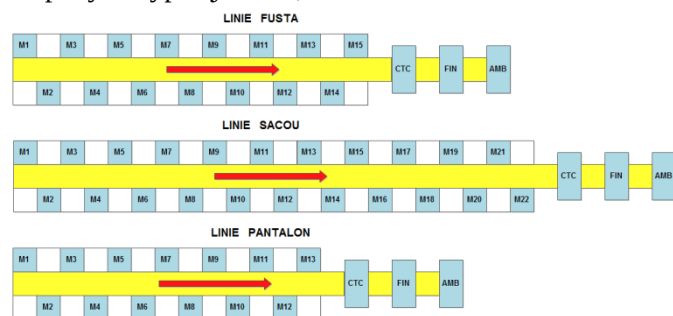


Figure 2. The fabrication lines in the company [7]

Figure 3 shows the Petri networks model for the skirt fabrication lines. Each operation is modelled by a transition. The temporisation of a transition corresponds to the duration of the modelled operation.

Figure 4 shows the Petri networks model for the jacket fabrication and figure 5 shows the model for trousers fabrication lines

In order to evaluate the production on the three fabrication lines, the time period is set to 8 hours (one shift), that is 28800 seconds.

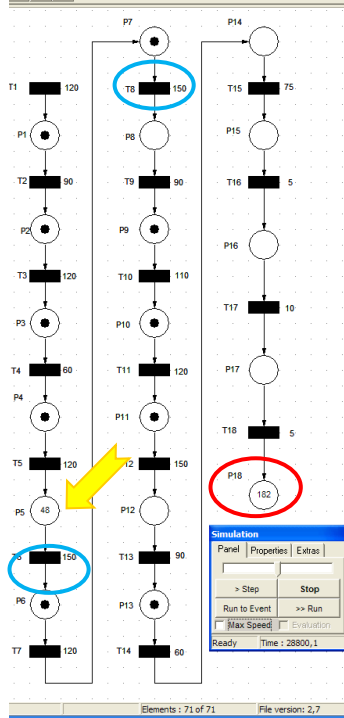


Figure 3. Petri networks model for the skirts fabrication lines [7]

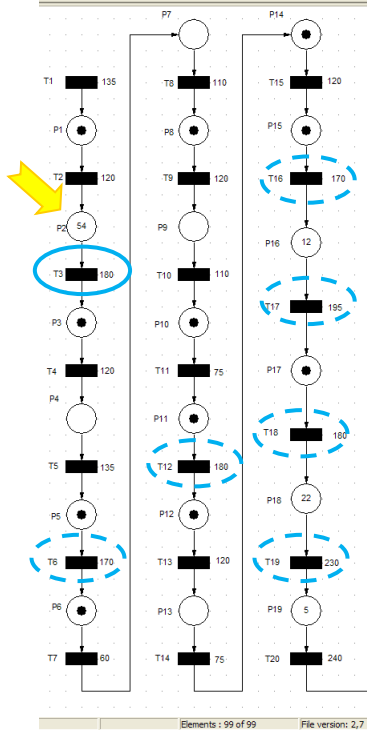


Figure 4. Petri networks model for jacket fabrication line [7]

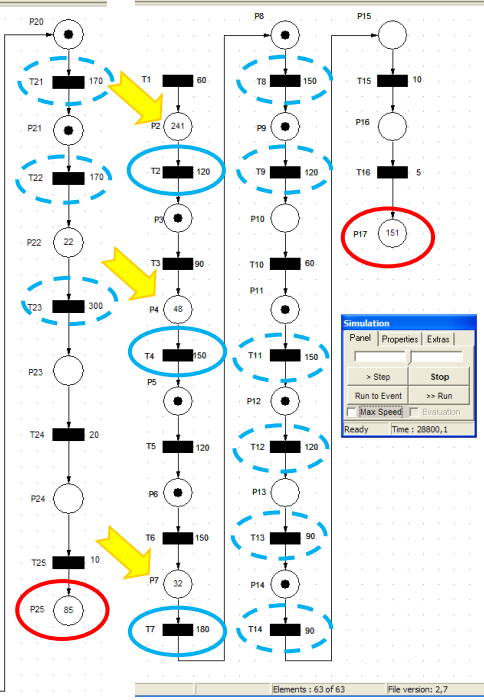


Figure 5. Petri networks model for trousers fabrication lines [7]

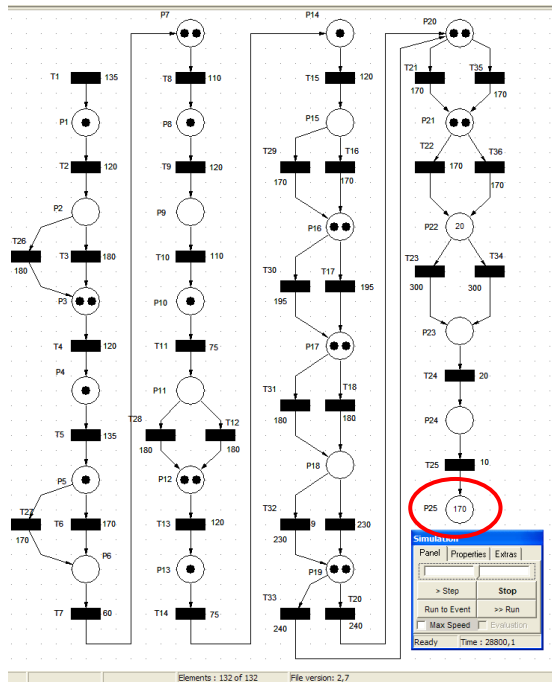


Figure 6. Petri networks model for jacket fabrication line after the multiplication of the work places [7]

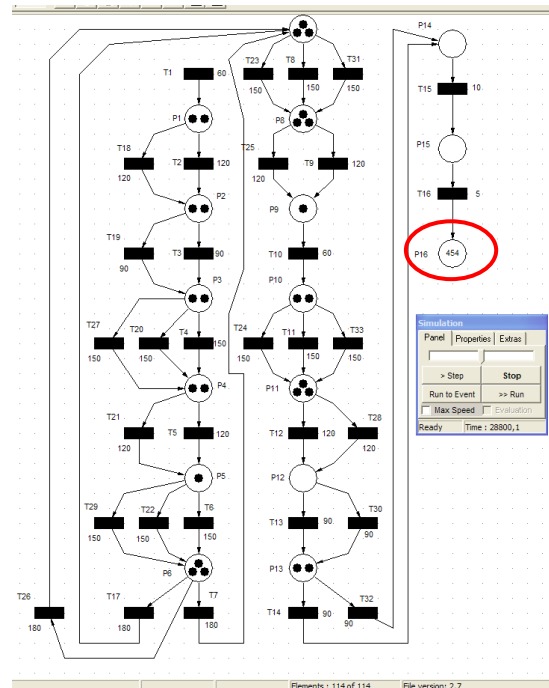


Figure 7. Petri networks model for trousers fabrication lines after the multiplication of the work places [7]

2.2. Description of product and assembly line [8]

The *Metalica 1685 F4-SI* gas cooker is a household appliance intended for the preparation of food. Through construction and execution, it is a superior finish product with easy use and maintenance, with economic functioning.

The gas cooker is equipped with 4 burners on the hob and a burner in the oven, gray glass cover of the hob. The oven is equipped with a thermocouple fuse. The gas cooker has 60 types of parts and subassemblies.

There are 26 operations on the assembly line. Each operation, in turn, has several phases. Moving the work object from one workstation to another, is made by a conveyor belt with imposed speed and therefore the speed of the transport means requires a certain rhythm of work. Figure 8 shows the panoramic view of the assembly line.

The model was built in four versions using Visual Object Net ++ software. For each version, the line operation was simulated during a work shift (8 hours). The results of the simulation have been analyzed and can be used as information in the decision-making process specific to production management.



Figure 8. Panoramic view of the assembly line [8]

We will present the fourth version, the most complex. The assembly operations performed on the manufacturing line involve the existence of storage spaces for the parts, subassemblies and materials that are part of the finished product component. Some components have a larger gauge and cannot be stored in the quantities needed for a shift. It is therefore necessary to supply the stocks during the manufacturing process. The supply procedure was modeled using generalized Petri nets. The arc capacities define the amount of supply components. In the detail of figure 9 there is an example of modeling the supplying for operation 6 – *mounted sidewalls* (transition 6). Position P19 models the stock of sidewalls.

This has the initial value of 80. For each of the finished product required two pieces of side wall component. This is modeled by the fact that the P19 → T6 arc has a load of 2. After each execution of the T6 transition from position P19, two tokens are withdrawn and two tokens are also deposited in the P19 'position. When the position P19' is equal to 80, the transition T6' is executed, which results in the deposition of 80 jets in position P19. In the real system this means supplying the stock of sidewalls.

In the case of version 4, after the 8-hour simulation of the line, the estimated output production is 238 gas cookers.

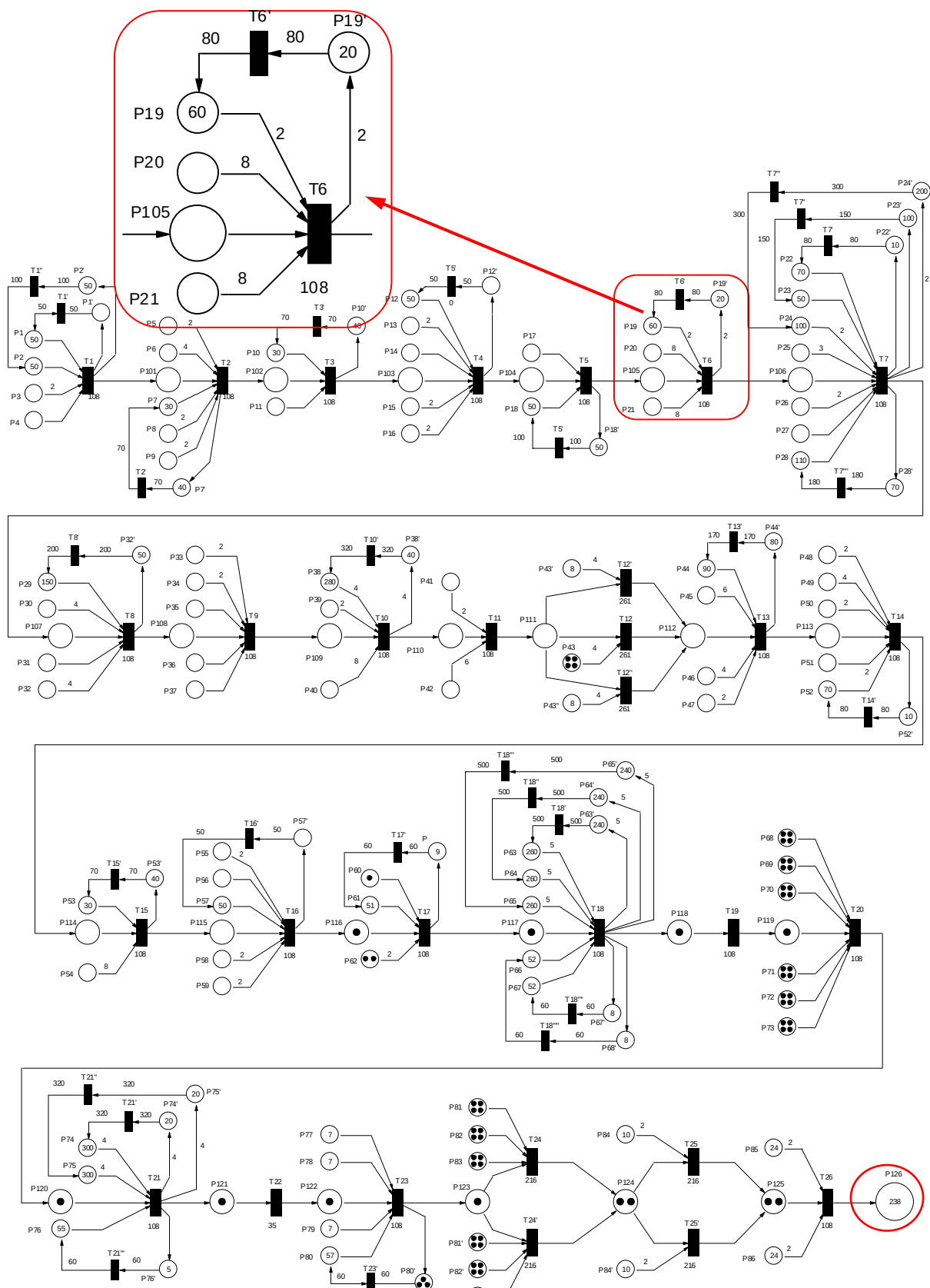


Figure 9. Petri nets model. Version 4.[8]

2.3. Modeling and simulation of a flexible packaging system for detergents [9]

2.3.1 Description of the manufacturing system

The automatic detergent packaging system consists of six manufacturing lines. Figure 10 shows a schematic diagram of a manufacturing line structure. For each line, the following subsystems can be highlighted: I – the bag filling subsystem; II- the subsystem for grouping bags in boxes; III – the box grouping in a row subsystem; IV – palletizing subsystem; V – full pallet evacuation subsystem; VI – supply subsystem with empty euro pallets

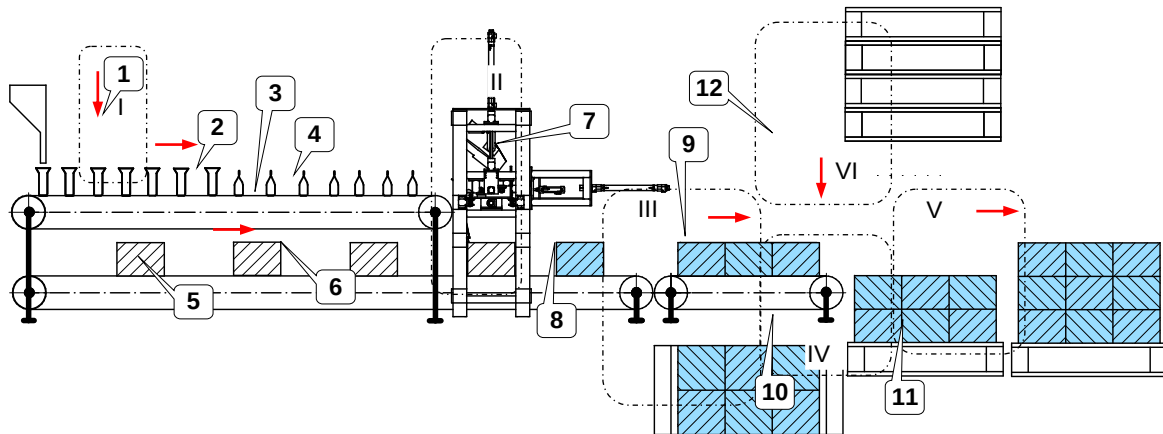


Fig. 10. Layout of a packing line and its subsystems. [9]

Figure 10 also describes the operation of the detergent packaging line. The detergent is dosed from the hopper 1 into the open bags 2. They are transferred through the transfer system 3 (conveyor belt). During the transfer, the closing of the bags is also carried out (4-closed bag). Under the bag conveyor belt there is a transfer system of roller conveyor type (6) for transferring boxes (6). Through the case packer equipment 7, the filled bags are grouped in boxes. The filled boxes (8) are grouped in rows (9). When a row is complete, it is transferred to pallet 10. The pallet is evacuated from the system. After evacuation of the full pallet, an empty pallet is inserted in the pallet supply subsystem (12).

Figure 11 shows the case packer system made at [9]. Also, a part of a packing line is shown in figure 12 [9].



Figure 11. Case packer system [9]



Figure 12. Packaging line [9]

2.3.2. Modeling and simulation of the automatic detergent packaging system

The models associated with the system are developed in a hierarchical structure: the model of the system as a whole, the model of a line, the model of some modules in the composition of a line.

In these conditions, the operation mode is checked step by step and the necessary corrections can be made until the optimal solution is found.

The model with Petri nets consists, in fact, of six submodels (figure 12), these correspond to the modules in the line structure: I- the submodel of filling the bags; II- the submodel for grouping bags into boxes; III- the submodel for grouping boxes in a row; IV - the palletizing submodel; V - the submodel for the evacuation of full euro pallets; VI - the sub-model of supply with empty euro pallets.

Two model versions were built with Petri nets:

Version I. Each line packs detergents in bags of different sizes:

- Line I: 1 kg/bag; 45 bags/min; 12 bags/box;
- Line 2: 2 kg/bag; 45 bags/min; 6 bags/box;
- Line 3: 2.2 kg/bag; 45 bags/min; 6 bags/box;
- Line 4: 3 kg/bag; 40 bags/min; 4 bags/box;
- Line 5: 3.3 kg/bag; 40 bags/min; 4 bags/box;
- Line 6: 4 kg/bag; 30 bags/min; 3 bags/box.

Version II. Detergents are packed on all lines in this way: 3.3 kg/bag; 40 bags/min; 4 bags/box.

Figure 13 shows the version I- on each line detergents are packed in bags of different sizes. The model is a Hybrid Petri Nets: it has a continuous component and a discrete component.

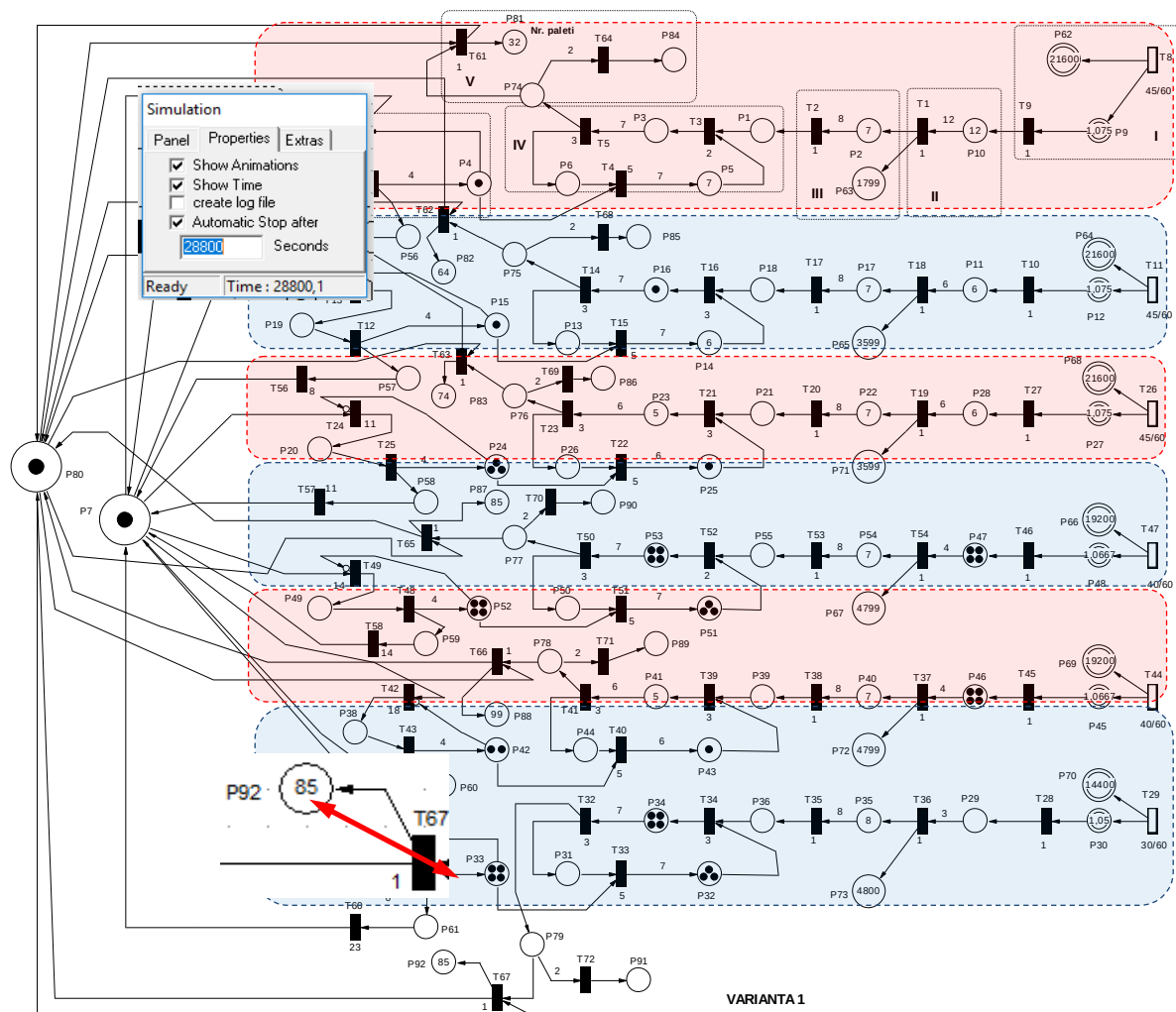


Figure 13 Detergents packing system modeled with Petri nets [9]

The model is designed so that potential conflicts are avoided. By simulation, it is possible to determine the number of euro pallets that can be made during an 8-hour work shift (figure 13). The simulation result of the system operation during the 8 hours is presented in table 1.

Table 1. Summary of information regarding the automatic detergent packaging system. Estimated productivity. Simulation results. [9]

LINE	SIZE [kg/bag]	Frequency of bags [bags/min]	Nbr. of bags box [bags/box]	The frequency of the boxes [boxes/min]	Nbr. of boxes in a row [boxes/row]	Nbr. of rows on europallets [rows/europallets]	Simulation results 8 hours	
							boxess	europallets
1	1	45	12	3.75	8	7	1799	32
2	2	45	6	7.5	8	7	3599	64
3	2.2	45	6	7.5	8	6	4799	74
4	3	40	4	10	8	7	4799	85
5	3.3	40	4	10	8	6	4799	99
6	4	30	3	10	8	7	4800	85

2.4.Evaluation of the performance of robotic welding cells by modeling with timed Petri nets [10]

Welding is a very common technological process used in the automotive industry, especially in assembling car bodies. Modern assembly lines are characterized by the fact that they have complex devices in their component and in most cases are robotic.

The welding cell is intended for assembling the structure Central lower floor subassembly. This subassembly has three components: sheet 1, welded subassembly and sheet 2 (Figure 14)

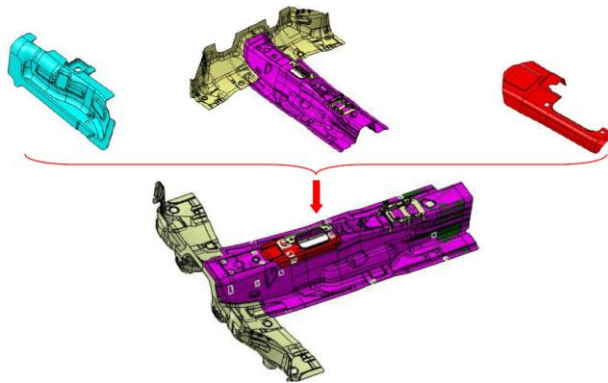


Figure 14. Central lower floor subassembly components [10]

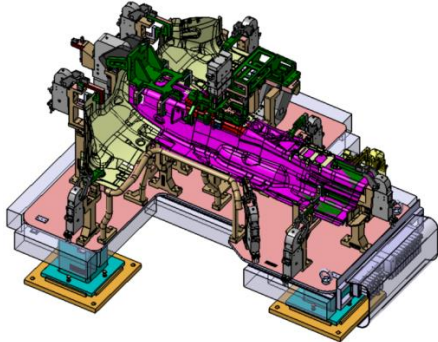


Figure 15. The components to be welded are positioned and fixed [10]

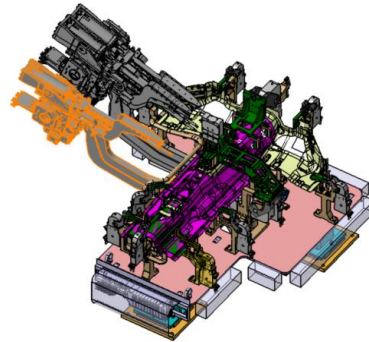


Figure 16. Type C gun welding [10]

The automated welding cell is of human-robot type and works sequentially, ie first, the operator loads the sheet elements to be welded after which the robot performs the welding operation. The body elements to be assembled are oriented by means of the pins and fixed with the help of pneumatic clamps in the geometric welding station. Figure 15 shows the components to be welded positioned and fixed in the welding station. Welding is performed with the help of welding pliers. All welding points defined on the road elements can be accessed by the welding pliers, so there will be no need for respot points. Welding a point takes 4 sec. Welding is done successively, only one welding point at each step until all welding points are executed. The robot starts spot welding with type X guns, and then with type C guns (figure 16). Figure 17 shows the station and the numbering of the component units. A complete cell operating cycle is composed of a sequence of sequences.

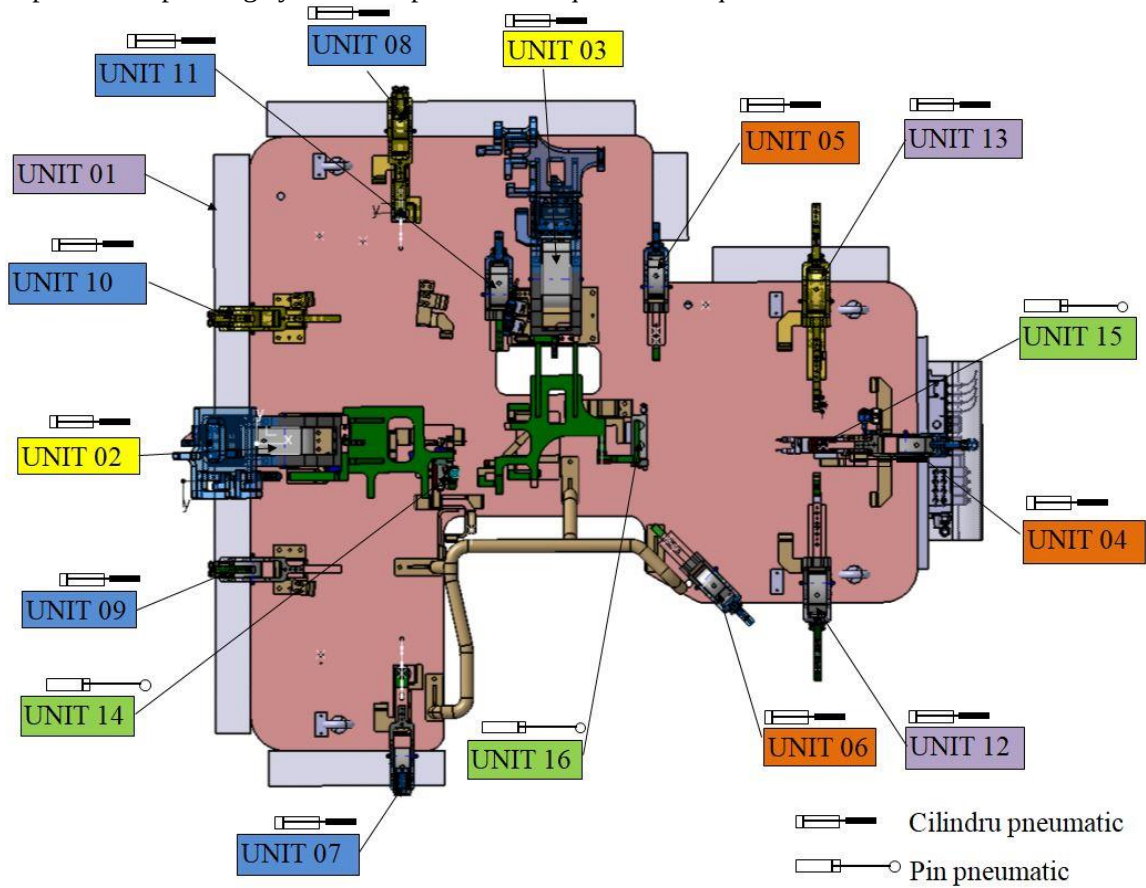


Figure 17. The units within the station [10]

To evaluate the performance of the welding cell and to identify possible blockages, a model with Petri nets was developed. Three models with Petri nets were made. Table 2 shows the sequences performed by the cell components. These correspond to the transitions from the model with Petri nets. The states of the cell components are modeled by positions (places).

Table 2. Petri net positions and transitions [10]

No.	Symbol	Type	Description	Characteristics		
				Version 1	Version 2	Version 3
1	P1	Position	The operator is free	$m_0(P1)=1$	$m_0(P1)=1$	$m_0(P1)=1$
2	P2	Position	Stock of type 1 sheets	$m_0(P2)=150$	$m_0(P2)=160$	$m_0(P2)=20$
3	T1	Transition	Loading the sheet 1	$d_1=10,5$ sec	$d_1=10,5$ sec	$d_1=10,5$ sec

No.	Symbol	Type	Description	Characteristics		
				Version 1	Version 2	Version 3
4	P3	Position	Table 1 is on the station	$m_0(P4)=0$	$m_0(P4)=0$	$m_0(P4)=0$
...	...	...	...	...	...	...
19	P11	Position	The robot is in position	$m_0(P11)=0$	$m_0(P11)=0$	$m_0(P11)=0$
20	T7	Transition	Welding the 12 (8) points with X-type welding pliers	$d_7=48$ sec	$d_7=32$ sec	$d_7=32$ sec
21	P12	Position	All 8 points are welded	$m_0(P12)=0$	$m_0(P12)=0$	$m_0(P12)=0$
22	T8	Transition	The robot rotates 180 °	$d_8=2,7$ sec	$d_8=2,7$ sec	$d_8=2,7$ sec
23	P13	Position	The robot is in position	$m_0(P13)=0$	$m_0(P13)=0$	$m_0(P13)=0$
24	T9	Transition	Replacing the welding pliers X with the tee type C	$d_9=15$ sec	$d_9=15$ sec	$d_9=15$ sec
25	P14	Position	Type C welding pliers are on the robot	$m_0(P14)=0$	$m_0(P14)=0$	$m_0(P14)=0$
26	T10	Transition	The robot rotates 180 °	$d_{10}=2,7$ sec	$d_{10}=2,7$ sec	$d_{10}=2,7$ sec
27	P15	Position	The robot is in position	$m_0(P15)=0$	$m_0(P15)=0$	$m_0(P15)=0$
28	T11	Transition	Welding the 10 (6) points with type C welding pliers	$d_{11}=40$ sec	$d_{11}=24$ sec	$d_{11}=24$ sec
...	...	...	...	...	...	...
52	P30	Position	Consumption counter table 2	-	-	$m_0(P30)=0$
53	T22	Transition	Supply of sheet metal stock 2	-	-	-
54	P31	Position	Sheet stock reload number 2	-	-	$m_0(P31)=0$
55	P32	Position	Confirmation of completion of sheet metal assembly	-	-	$m_0(P32)=0$
56	T23	Transition	The waiting time of the station until the operator is free	-	-	-

The models were gradually developed. Thus, in the first variant the number of welding points was 22, having a cell cycle duration of 215 sec, and after simulating the operation of the station for 8 hours, it was found that 133 pieces were welded to the lower central floor subassemblies. In the second version the number of welding points was reduced from 22 to 14, and the cycle time decreased to 183 sec, is by 32 sec. After simulating the operation of the 8h station, it was found that 157 pieces of Central lower floor subassemblies were welded.

Version 3 (figure 18) included in the model with timed Petri nets and stock refueling sequences with components that are welded. Thus, it is considered that the storage space of the sheets, respectively of the subassemblies, which are welded, is not enough to store the necessary for 8 hours. Consequently, the stocks, modeled with positions P2 (Table 1), P4 (welded semi-finished product) and P6 (Table 2), will be replenished periodically during the 8 hours. Items P26, P28 and P30 count the number of Tables 1, Welded Subassemblies, Tables 2 consumed from stock. When the number of tokens in these positions (the number of components used) is equal to the capacity of the stocks, their

replenishment is done. Stock replenishment is modeled, through transitions T20, T21 and T22. The model becoming a generalized timed Petri nets.

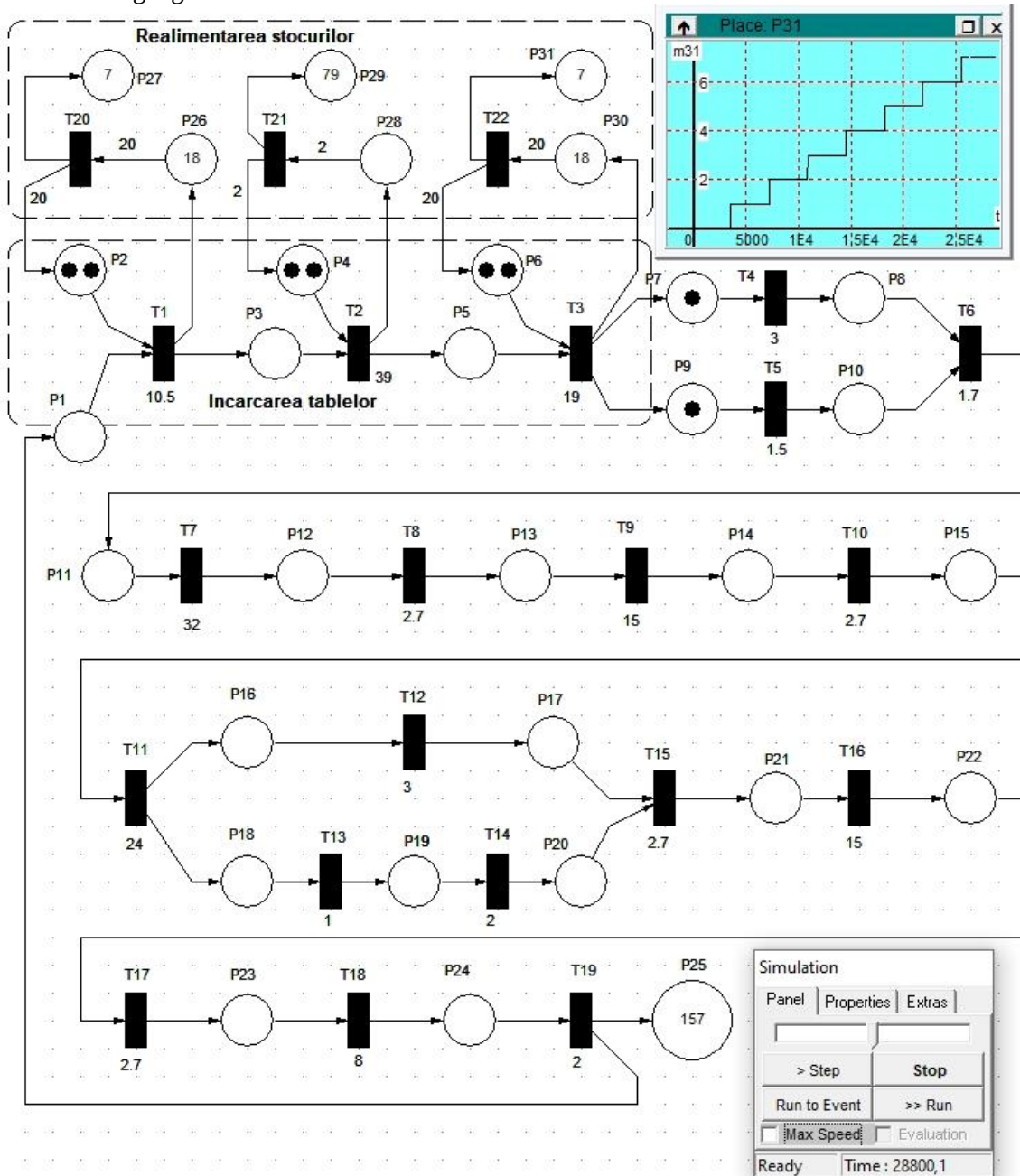


Figure 18. Model with timed Petri nets. Variant 3 [10]

3. The transition from timed Petri nets to hierarchical colored Petri nets

3.1. Description of the automated system for preparation and analysis of metallographic samples

The automated system (flexible cell) for the preparation and analysis of metallographic samples has been designed taking into account the technical and material resources of the Mechatronics and Science of Materials laboratories (University of Oradea) [11]. The layout of the designed cell is shown in figure 19. Two subsystems can be seen:

- subsystem S1, which prepares the metallographic samples;
- subsystem S2, which performs the metallographic analysis.

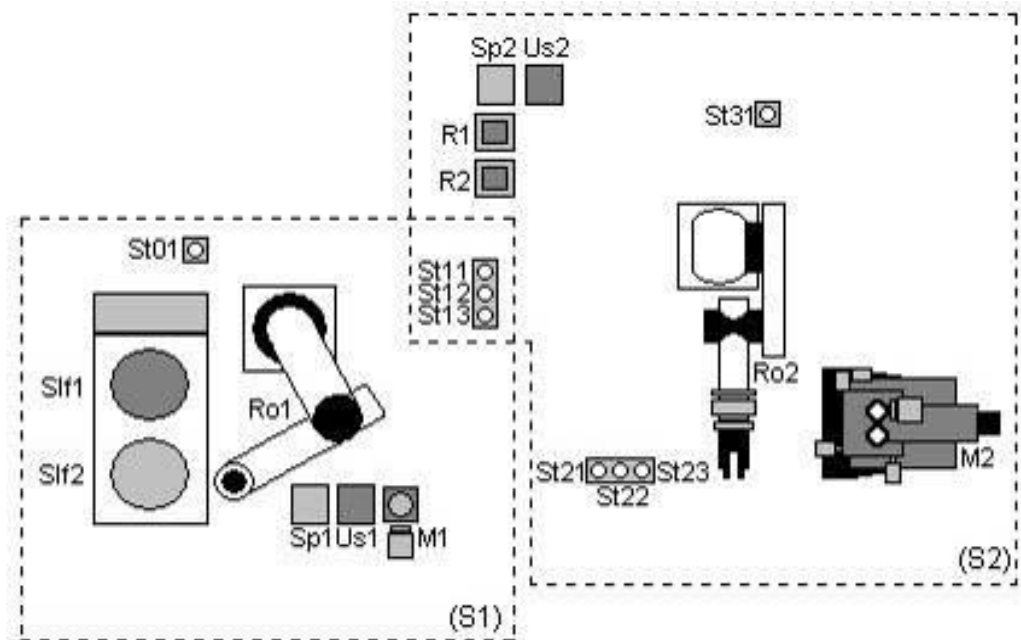


Figure 19. The layout of the automated system (flexible cell) for the preparation and analysis of metallographic samples. [11]

The following components of the automated system can be seen in figure 19:

- samples polishing posts: *Slf1*, *Slf2*;
- storage devices:
 - input storage device: *St01*;
 - buffer storage devices between subsystem S1 and subsystem S2: *St11*, *St12*, *St13*;
 - storage devices for the samples that have been prepared for analysis with microscope *M1*: *St21*, *St22*, *St23*;
 - output storage device: *St31*.
- industrial robots: *Ro1*, *Ro2*;
- samples washing posts: *Sp1*, *Sp2*;
- samples drying posts: *Us1*, *Us2*;
- reagent attack posts: *R1*, *R2*;
- surface assessment post (microscope): *M1*;
- metallographic structure assessment post (microscope): *M2*.

The two subsystems are served by robots in the following manner:

- posts *Slf1*, *Slf2*, *Sp1*, *Us1*, *M1*, *St01* of subsystem S1 are served by robot *Ro1*;
- posts *R1*, *R2*, *Sp2*, *Us2*, *M2*, *St21*, *St22*, *St23*, *St31* of subsystem S2 are served by robot *Ro2*.

3.2 The realization of the generalized timed Petri nets model [11]

A generalized timed Petri nets model was made in order to assess the performances of the automated system and to identify the probable bottlenecks. The model takes into account the analysis of two types of metallographic samples, A and B. The sequences performed by the robots are modelled by transitions, to which timings were attached, equal to the time intervals needed by the robots to perform these transitions. Other activities were modelled, such as coarse grinding, polishing, reagent attack, washing, microscope examination. The execution of one transition, equivalent to the execution of a

real sequence, is possible if certain conditions are fulfilled. These conditions are modelled in the Petri net by means of positions. Some of the transitions and positions of the model are shown in table 3.

Table 3. Positions and transitions of Petri nets model. [11]

Nr.	Symbol	Type	Meaning	Characteristics
1.	P1	Pos.	<i>Ro1</i> is free	$m_0(P1)= 1$
2.	P2	Pos.	<i>St01</i> holds sample A	$m_0(P2)= 1$
3.	T1	Tr.	<i>Ro1</i> grips sample A	$d_1= 5$ sec.
4.	P3	Pos.	<i>Ro1</i> holds sample A in its grip	$m_0(P3)= 0$
5.	T2	Tr.	<i>Ro1</i> transfers sample A to <i>Slf1</i>	$d_2= 2$ sec.
6.	P4	Pos.	<i>Ro1</i> placed sample A to <i>Slf1</i>	$m_0(P4)= 0$
7.	T3	Tr.	Coarse grinding sequence (<i>Slf1</i>)	$d_3= 120$ sec.
8.	P5	Pos.	<i>Ro1</i> takes sample A polished on <i>Slf1</i>	$m_0(P5)= 0$
9.	T4	Tr.	<i>Ro1</i> transfers sample A to <i>Slf2</i>	$d_4= 2$ sec.
10.	P6	Pos.	<i>Ro1</i> placed sample A to <i>Slf2</i>	$m_0(P6)= 0$
...	...	...	...	...
75.	P40	Pos.	Confirmation – <i>Ro2</i> has sample B from <i>St12</i>	$m_0(P40)= 0$
76.	P41	Pos.	Confirmation – <i>Ro2</i> has sample B from <i>St13</i>	$m_0(P41)= 0$
77.	T36	Tr.	<i>Ro2</i> has one sample B (logical transition)	$d_{36}= 0$ sec.
78.	P42	Pos.	Confirmation – <i>Ro2</i> has one sample B	$m_0(P42)= 0$
79.	T37	Tr.	<i>Ro2</i> transfers sample A to <i>R1</i> and processes it	$d_{37}= 12$ sec
80.	P43	Pos.	<i>Ro2</i> has sample A processed by <i>R1</i>	$m_0(P43)= 0$
81.	T38	Tr.	<i>Ro2</i> transfers sample A to <i>R2</i> and processes it	$d_{38}= 12$ sec
82.	P44	Pos.	<i>Ro2</i> has sample A processed by <i>R2</i>	$m_0(P44)= 0$
83.	T39	Tr.	<i>Ro2</i> transfers sample A to <i>Sp2</i> and washes it	$d_{39}= 12$ sec
84.	P45	Pos.	<i>Ro2</i> has sample A washed	$m_0(P45)= 0$
85.	T40	Tr.	<i>Ro2</i> transfers sample A to <i>Us2</i> and dries it	$d_{40}= 12$ sec
...	...	...	...	...
153.	P79	Pos.	Sample B (<i>St23</i>) was examined at <i>M2</i>	$m_0(P79)= 0$
154.	T75	Tr.	<i>Ro2</i> grips sample B (<i>St21</i>) from <i>M2</i>	$d_{80}= 5$ sec
155.	T76	Tr.	<i>Ro2</i> grips sample B (<i>St22</i>) from <i>M2</i>	$d_{81}= 5$ sec
156.	T77	Tr.	<i>Ro2</i> grips sample B (<i>St23</i>) from <i>M2</i>	$d_{82}= 5$ sec
157.	P80	Pos.	<i>Ro2</i> has sample B (<i>St21</i>) examined	$m_0(P80)= 0$
158.	P81	Pos.	<i>Ro2</i> has sample B (<i>St22</i>) examined	$m_0(P81)= 0$
159.	P82	Pos.	<i>Ro2</i> has sample B (<i>St23</i>) examined	$m_0(P82)= 0$
160.	T78	Tr.	<i>Ro2</i> evacuates sample B (<i>St21</i>)	$d_{83}= 5$ sec
161.	T79	Tr.	<i>Ro2</i> evacuates sample B (<i>St22</i>)	$d_{84}= 5$ sec
162.	T80	Tr.	<i>Ro2</i> evacuates sample B (<i>St23</i>)	$d_{85}= 5$ sec
163.	P83	Pos.	Storage device <i>St31</i> – samples B	$m_0(P83)= 0$

In fact, the Petri nets model consists of two sub-models (figure 20): sub-model for samples A (colored blue) and sub-model for samples B (colored yellow). The resources of the system consist of

robots, storage devices, polishing devices and reagent attack sections, which must be shared between the two sample types.

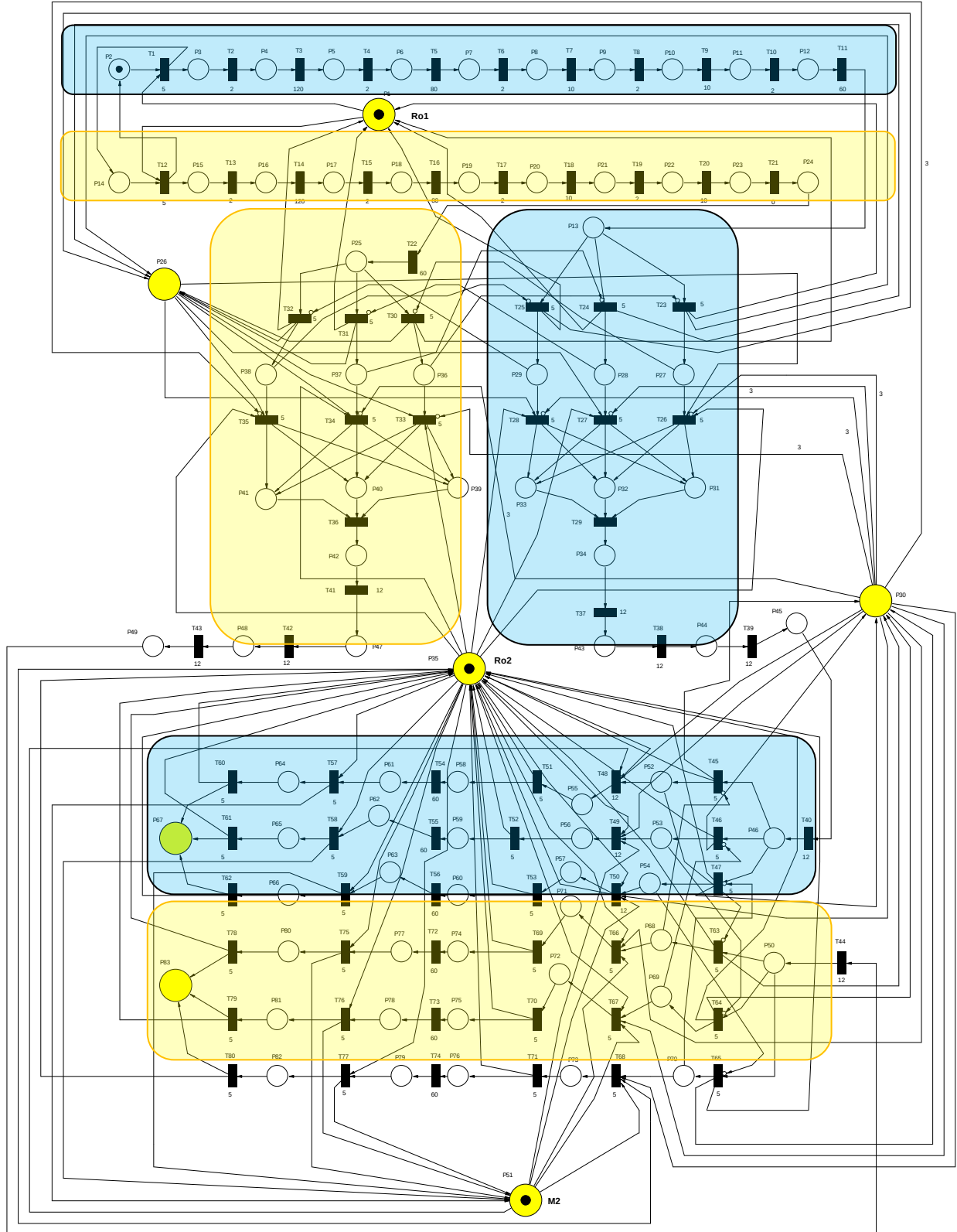


Figure 20. The timed generalized capacity Petri nets model of the automated system. [11]

In the first version of the automated system simulation it has been assumed that the two types of samples enter the system alternatively as soon as the initial storage device is free. A time interval of 8 hours (28800 seconds) is considered for simulation. The simulation shows that 47 samples A and 47 samples B have been processed and analysed.

In the next model version, we will assume that the samples are input at certain time intervals. Thus, samples A are input at 20 minutes (1200 seconds) each, and samples B are input at 15 minutes (900 seconds) each. The following modifications have been performed in order to simulate this:

- for sample A, the discrete transition T_A has been added, with 1200 second timing and position *Sample A* (figure 21);
- for sample B, the discrete transition T_B has been added, with 900 second timing and position *Sample B* (figure 22);

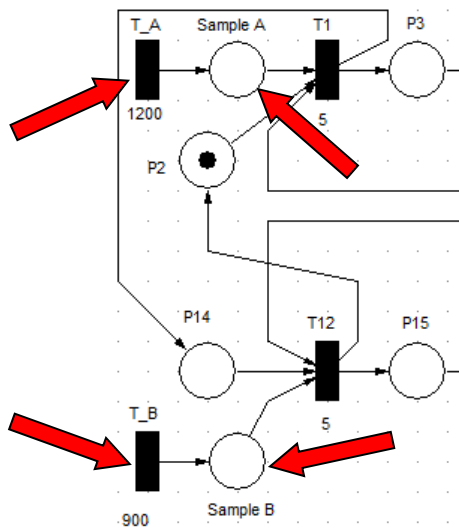


Figure 21. Modelling of the inputs of the system – version 2. [11]

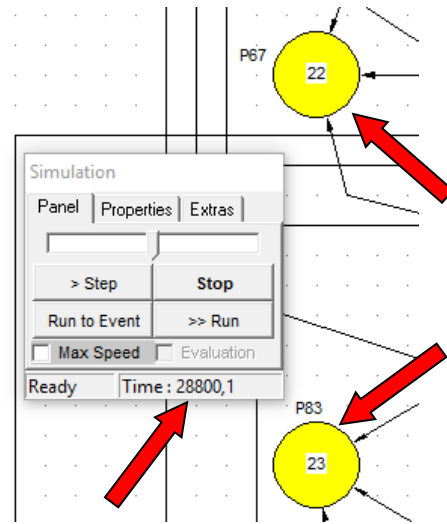


Figure 22. Simulation results – version 2. [11]

The simulation shows that 22 samples A and 23 samples B have been processed and analysed. Both versions have been designed in such manner that the two types of samples are processed and analysed alternatively.

3.3. Elaboration of Simple Colored Petri Net Model [12]

A simple colored 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*):

$$antiplace=\{e\} \quad (1)$$

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*):

$$sample=\{A,B\} \quad (2)$$

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*):

$$robot=\{r1, r2\} \quad (3)$$

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

$$microscope=\{m\} \quad (4)$$

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

$$r \{r1, r2\} \quad (5)$$

Variable i may have value A or B :

$$i \{A, B\} \quad (6)$$

Some of the transitions and positions of the model are presented in table 4.

Table 4. Positions and transitions of the simple colored Petri net model. [12]

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 Slf1	
8.	T4	Tr.	Ro1 transfers samples A or B to Sf2	
9.	P5	Pos.	Ro1 positioned sample A or B to Sf2	
...	...	...	...	...
35.	T17	Tr.	Ro2 take sample A or B to St13	
36.	P20	Pos.	Confirmation- Ro2 has a sample A	
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	
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	
44.	P24	Pos.	Ro2 has a dry sample A or B	
45.	P25	Pos.	The M2 microscope is free	1`m
...	...	...	...	...
75.	T36	Tr.	Ro2 take the sample A or B (St21) to M2	
76.	P41	Pos.	Ro2 has one sample A sau B (St21) examined	
77.	P42	Pos.	Ro2 has one sample A sau B (St22) examined	
78.	P43	Pos.	Ro2 has one sample A sau B (St23) examined	
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

Figure 23 shows the simple colored Petri nets model and the results of the simulation after 200 steps.

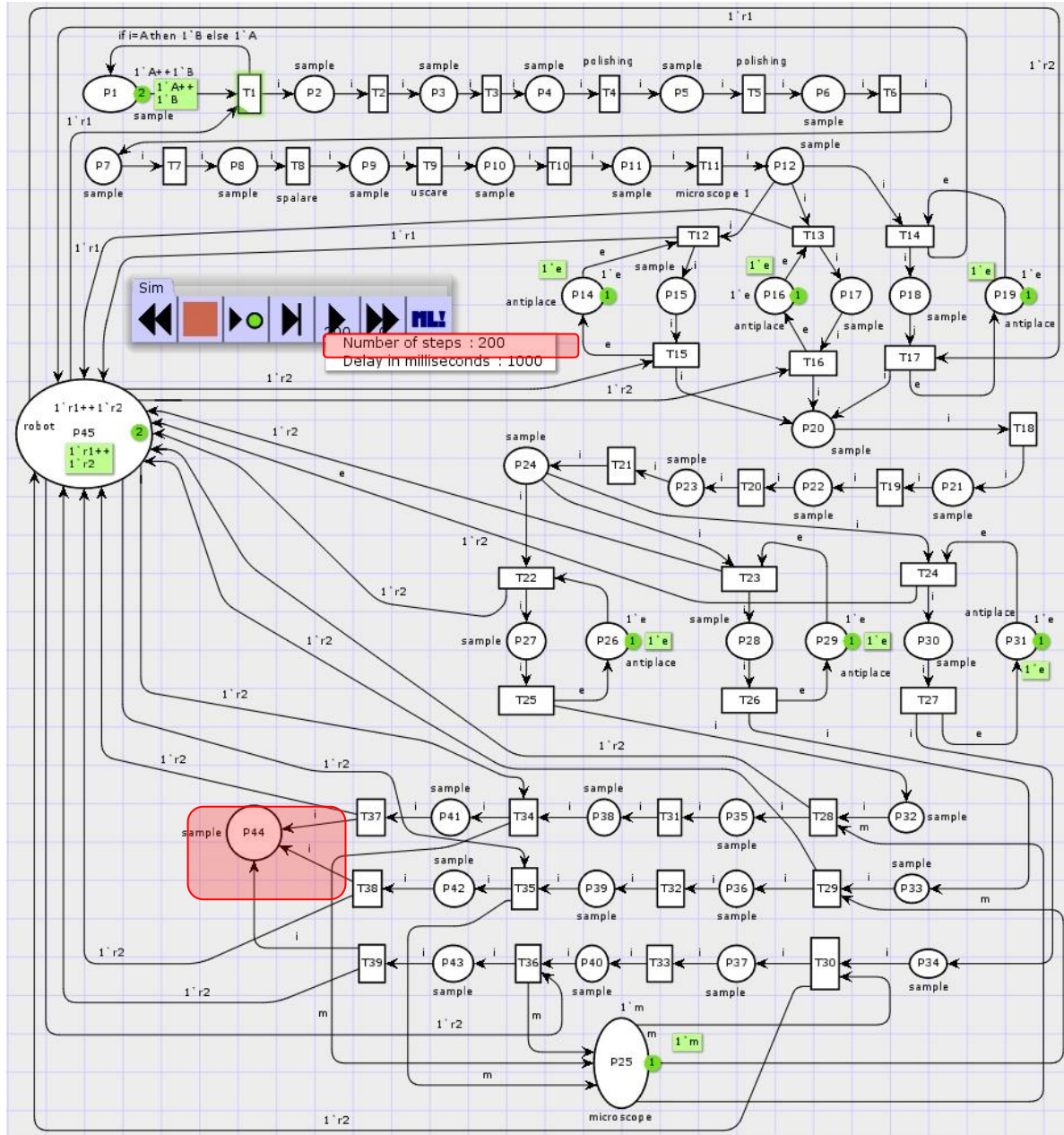


Figure 23. The simple colored Petri nets model. [12]

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 analyzed, as four colours A and four colours B are at position P44 (figure 23).

3.4. Realization of timed complex colored Petri nets model

The positions and transitions of the timed complex colored Petri nets are partially shown in table 5. Compared to the simple colored 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 5. The positions and transitions of the timed complex colored Petri net model. [12]

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 the sample A sau B in the gripper	
4.	T2	Tr.	Ro1 transfers sample A or B to Sf1	
...	...	...	...	...
21.	P11	Pos.	Ro1 positioned with specimen A or B at M1	
22.	T11	Tr.	Structural analysis of specimen A or B on M1	
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.	Sample A or B is in St12	
...	...	...	...	...
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 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 (*colset antiplace=int 1..3*):

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

In order to highlight that at a link between the sample type and the buffer storage on which it is stored before entering the analysis subsystem, the set of complex colors is defined *storage* (*colset storage = product sample*antiplace*). This is the cartesian product of the colors *sample* (relation (1)) and *antiplace* (relation (7)), having the following values:

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

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:

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

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

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

This variable is associated to arches T13→P12 and P12→T14 (figure 24).

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 which models the coarse grinding operation. This is enclosed in the model by expression @+120 (figure 24).

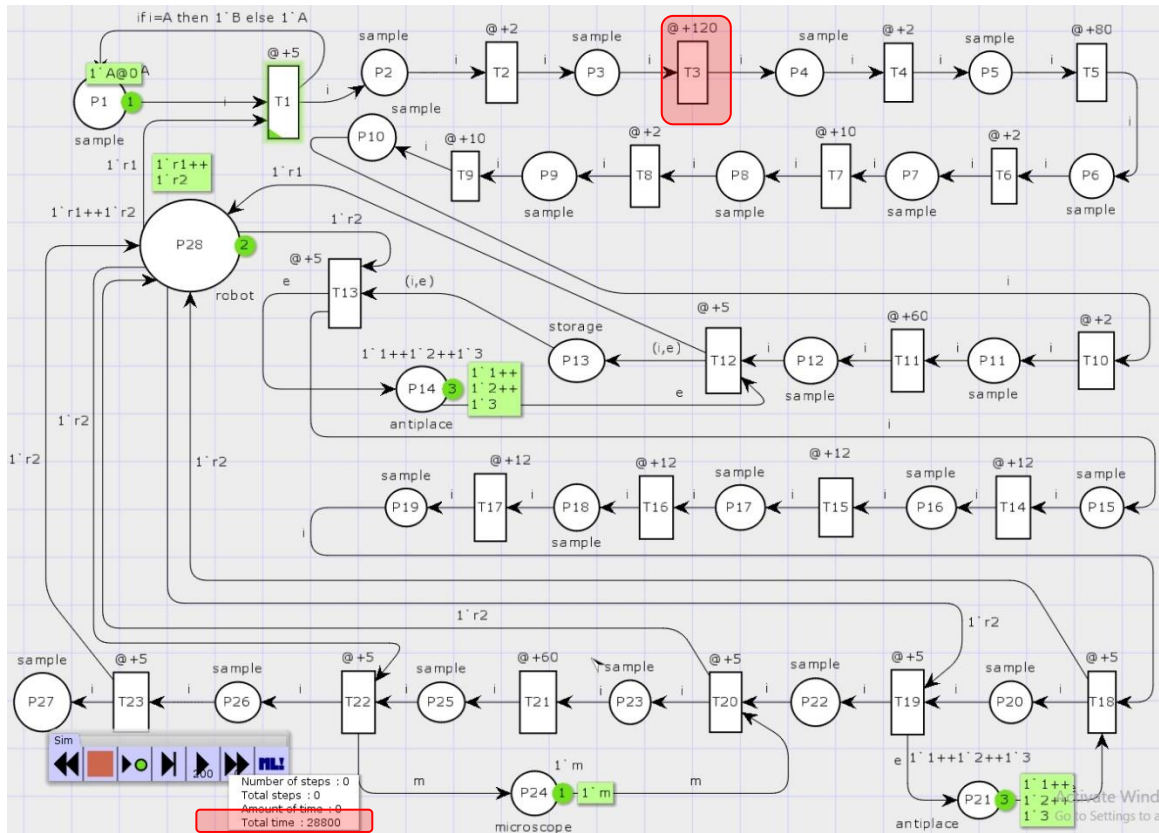


Figure 24. The timed complex colored Petri model. [12]

3.5. Defining hierarchical levels [13]

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.

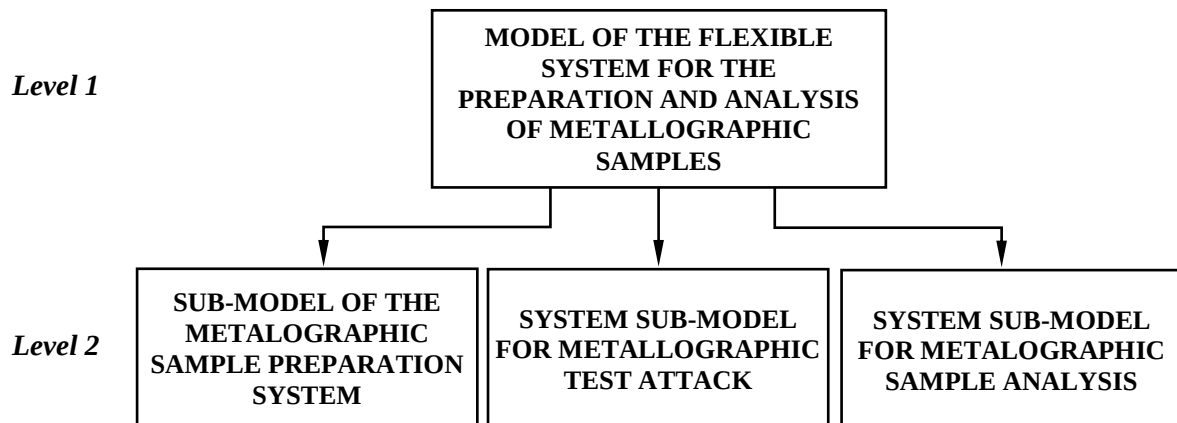


Figure 25. Hierarchical levels of the model with colored Petri nets. [13]

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

Figure 26 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.

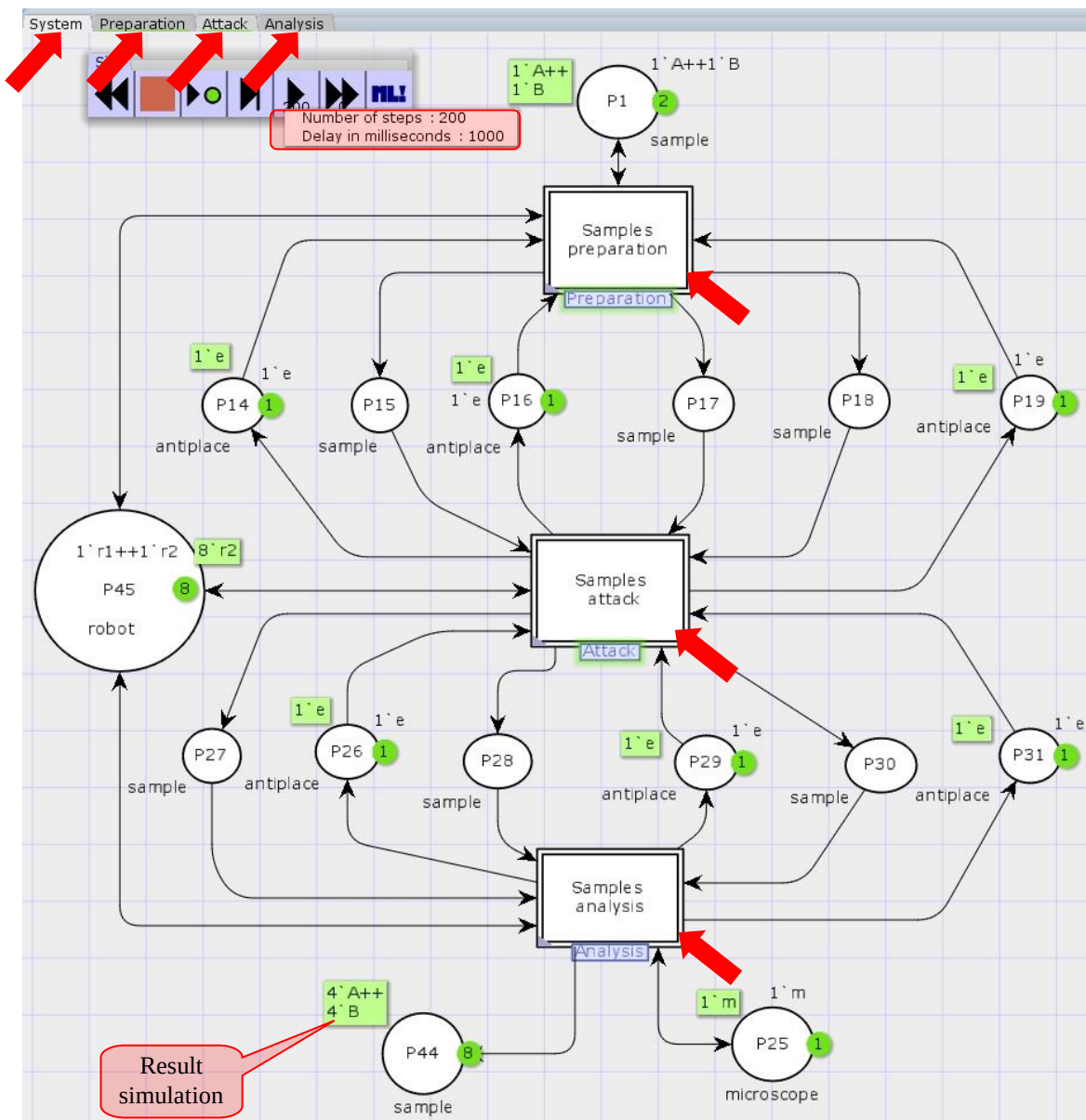


Figure 26. The main model with colored Petri nets with simple colors. [13]

Figure 27 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).

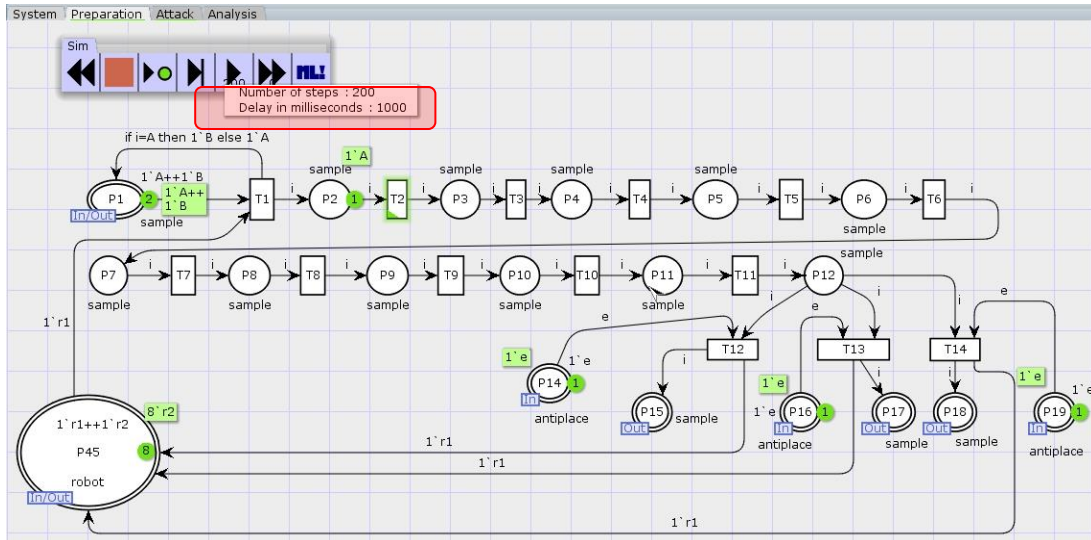


Figure 27. Sub-model of the system for the preparation of metallographic samples. [13]

Figure 28 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.

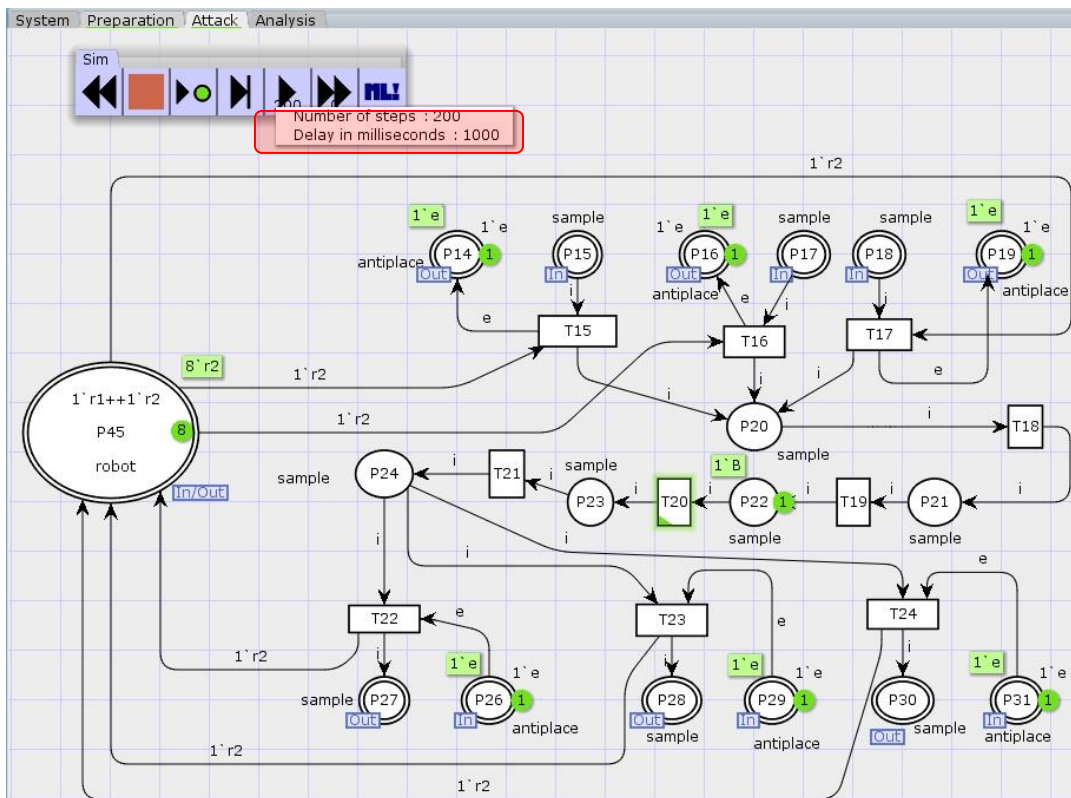


Figure 28. Sub-model of the system for the attack with reagents of metallographic samples. [13]

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 29.

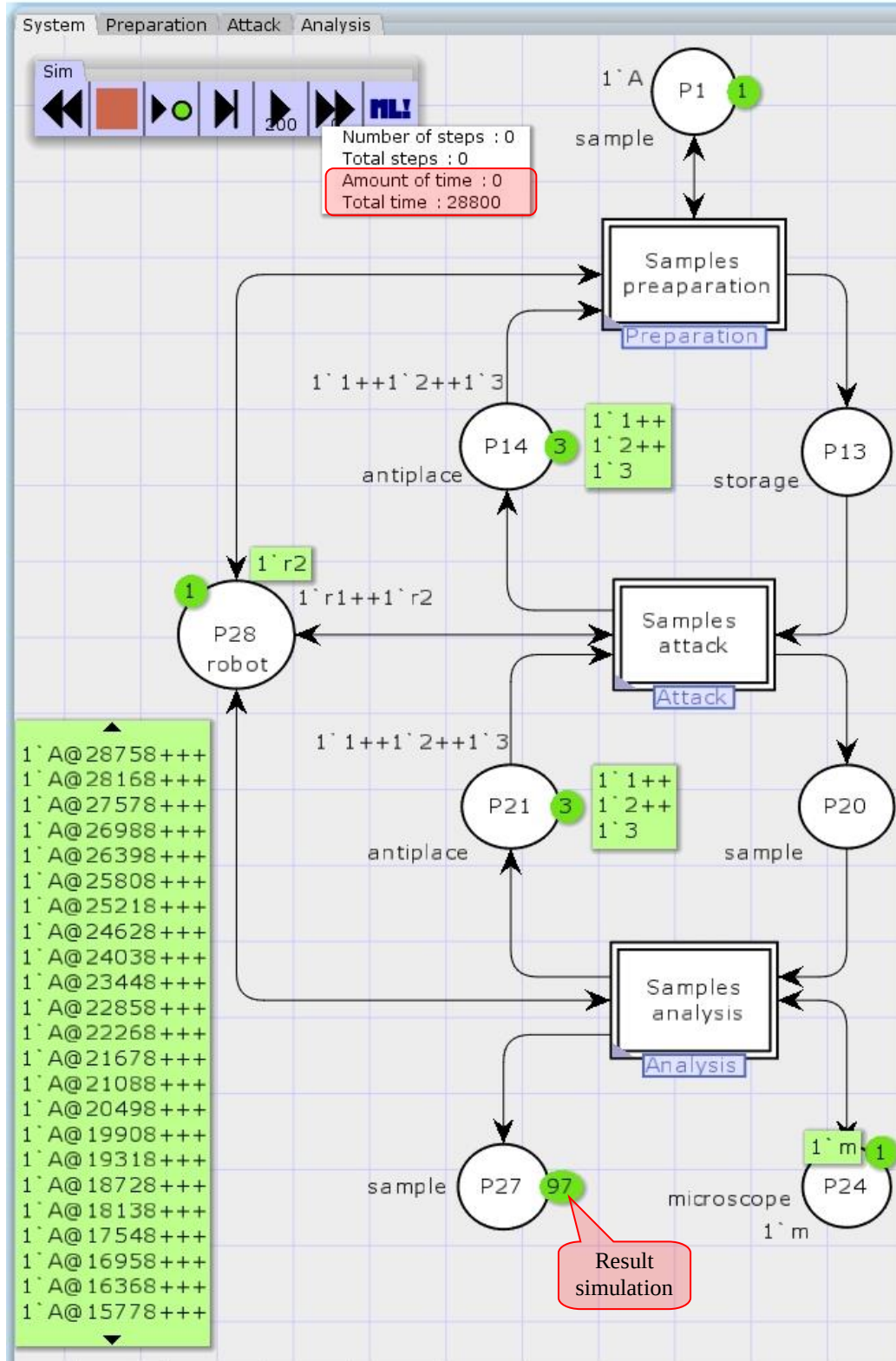


Figure 29. The main model with timed colored Petri nets with complex colors. [13]

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 29 shows the sub-model for the analysis of metallographic sample.

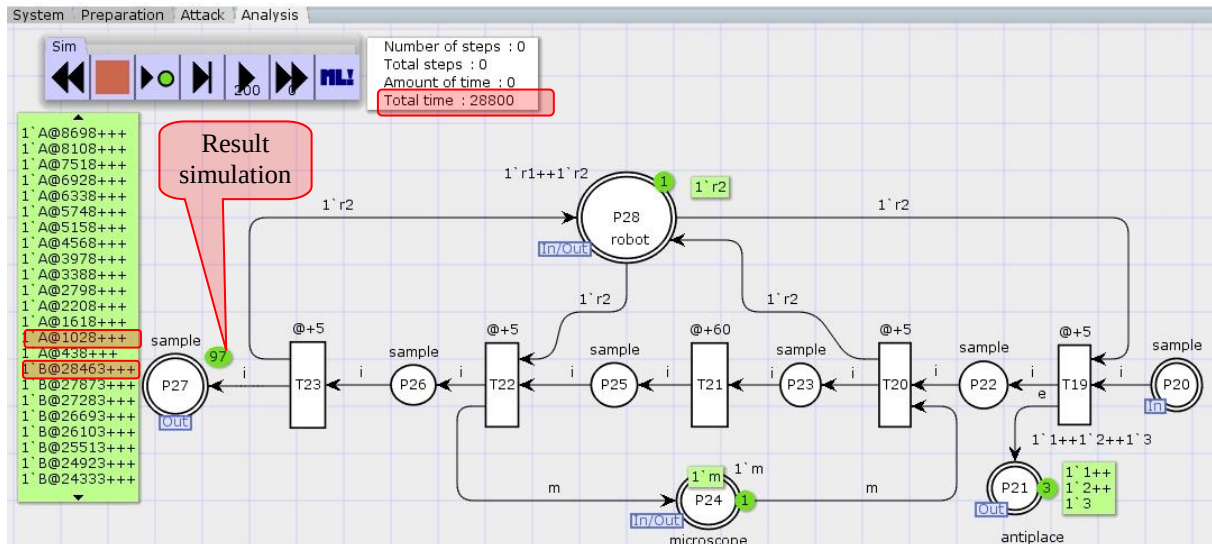


Figure 29. Sub-model of the system for the analysis of metallographic samples - complex colors [13]

For simulation, a time interval of 8 hours (28800 sec) is considered. The simulation duration is set in the *Simulation* window. During the simulation, 2236 steps were performed. 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.

It can also be noted that during the 8 hours a number of 97 samples were analyzed.

4. The Flexible Manufacturing System A007 model colored Petri Nets

4.1 The Flexible Manufacturing System A007. Components [14]

The flexible manufacturing system A007 of Industrial Engineering Department of Oradea University is shown in Figure 31. The cell is composed of: *Power station* (1); *Evacuation station* (2); *Lathe CNC CONCEPT TURN 55* (3); *Control equipment (FANUC or SIMESS) of milling machine* (4); *Milling machine CNC CONCEPT MILL 55 (May)*; *Control equipment (or FANUC SIMESS) the lathe* (6); *Mitsubishi RV-2AJ robot* (7); *Handle the moving robot* (8)

Flexible manufacturing system of Industrial Engineering Department Laboratory (SFF A007) is intended for processing cylindrical parts which have surfaces that are obtained by milling operations (Figure 30).

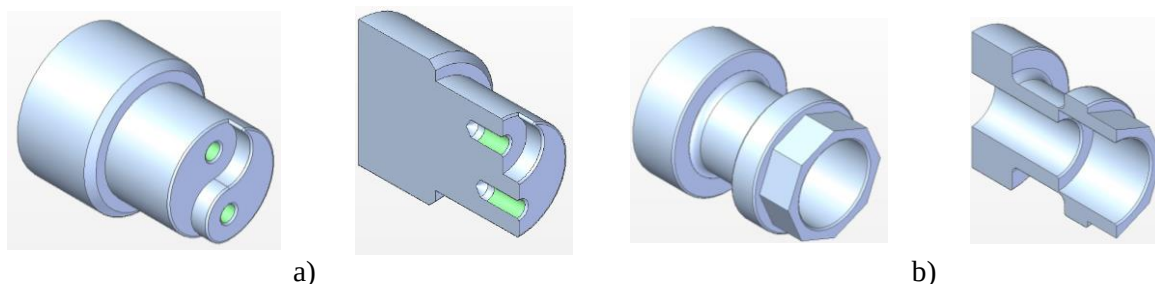


Figure 30. Types of parts that can be processed in the flexible manufacturing system [14]



Figure 31 *The Flexible Manufacturing System A007*

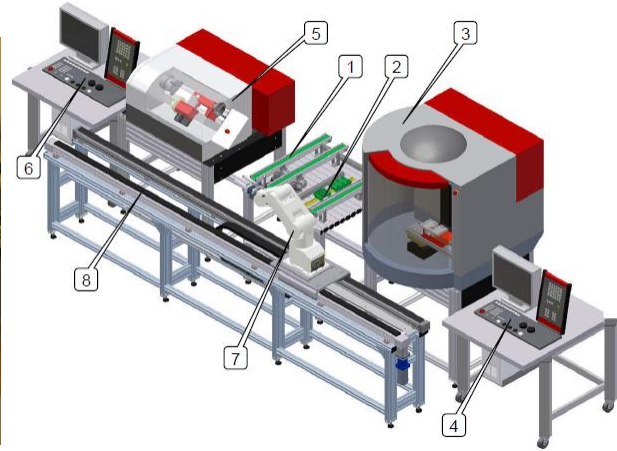


Figure 32. *The Flexible Manufacturing System A007. Components*

4.2. Model 1

A version of route that the piece can traverse the system is: the piece is positioned by the installation whip in place where it will be processed by the robot, this brings the piece in input position if the CNC program is load.

The piece is clamped in the lathe to be processed by the program. After processing, the robot take the piece from the lathe (CNC CONCEPT TURN 55) and brings it to the milling machine (CNC CONCEPT MILL 55), with the condition that the milling machine is not 0. The piece is attached to the device and processed by the program. After processing, the robot take a piece moved it to EI (exhaust installation finished parts). The Conveyor transfer finished parts in the storage.

Model 1 is built with Petri nets colored with complex colors. The complex color used is called complex and has three components: *piece*- P1 (means the generic part), *history* (means the place where the piece is at a given time) and *position* (position of the part in the manufacturing load, in batch);

$$\text{Complex} = \text{product piece} * \text{history} * \text{position} \quad (11)$$

Table 6 shows the values that the history component can take and their significance. These values are also important from the perspective that the robot is the component that connects the component subsystems of the manufacturing system and the part. Thus, it is necessary to know the previous state of the part in order to know where the part should be transferred by the robot.

Table 6. History component values [14]

History value	Signification
0	The part is in the Filing Station
1	The part was taken from the filling station, to be loaded on the CNC lathe CONCEPT TURN 55
2	The part was unloaded from the CNC lathe CONCEPT TURN 55, and will be loaded on the CNC milling machine CONCEPT MILL 55
3	The part was unloaded from the CNC milling machine CONCEPT MILL 55 and is deposited in the evacuation station
4	The piece is in the batch of the 12 pieces that must be evacuated from the system

The position component takes values from 1 to 12 and defines the position of the part in the batch launched in production.

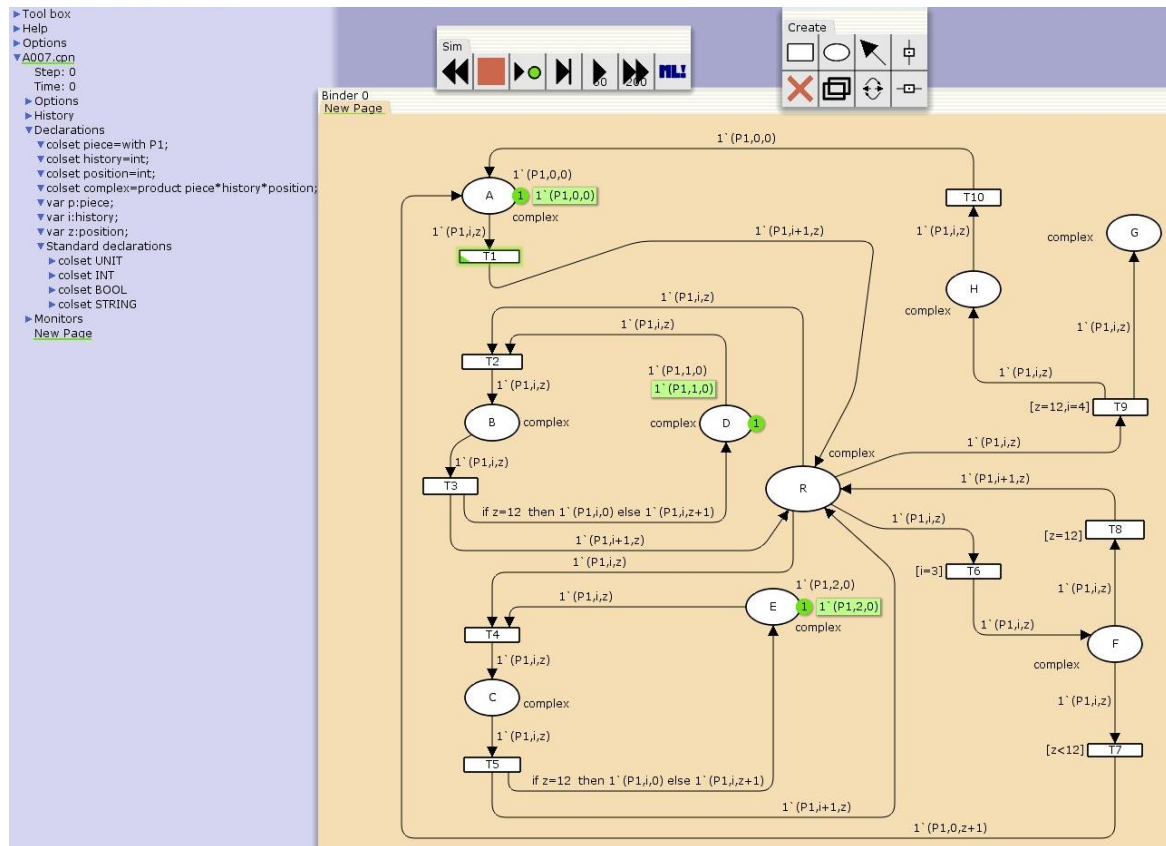


Figure 33 Model with colored Petri nets [14]

4.3. Model 2 [15]

This model was designed for the case in which the systems process the parts of figure 34:

- 1) two cylinder parts (figure 34a and figure 34b), these will be processed on CONCEPT TURN 55 CNC lathe;
- 2) two prismatic parts (figure 34c and figure 34d), these will be processed on CNC milling machine CONCEPT MILL 55.

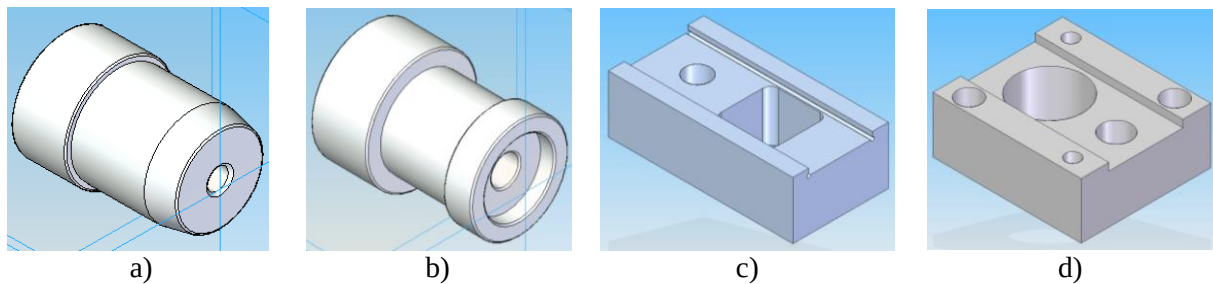


Figure 34 The parts that will be processed on the fabrication cell [15]

Each of the four parts, that will be included in the manufacturing process has a timing, if we consider a referral moment $t_0 = 0$. Therefore: Part 1 (first cylinder part – figure 34a) is the part that comes first in the cell; Part 2 (second cylinder part- figure 34 b) is the fourth part that comes into the cell; part 3 (figure 34 c) is the second and part 4 (figure 34 d) is the third part that comes into the cell.

Another important parameter in the evaluation of a manufacturing system is time processing. The processing time of part 1 on CNC lathe is 7 minutes, the processing time of part 2 is 9 minutes, the processing time is 18 minutes for part 3 and part 4 is processed in 21 minutes.

Timing will be developed from three perspectives:

- 1) Color timing (marks)
- 2) Arcs timing.

The simulation time associated to colors are used to highlights the arrival of parts in the system. Thus, we define the simulation time (P1, M1) @ 0; (P3, M2) @ 400; (P4, M2) @ 1450 and (P2, M1) @ 2000 (figure 35).

The timings associated to transitions are used to define the processing time. The transition which shapes the processing of the part is transition T2. To this transition was associated in fact four timings, one for each part. Actual value of the timing at a time, is the result of the instruction if: @ + (if (p, m) = (P1, M1) then 420 else if (p, m) = (P2, M1) then 540 else if (p, m) = (P3, M2) then 1080 else 1260. It has been considering the second to be unit measurement.

The timings associated to arcs was defined to show the manipulation times corresponding to Mitsubishi RV-2AJ robot. To the variable (function) which load the arcs: P7→T1; T2→P7; P7→T3 si T5→P7 it was associated the simulation time r @+8.

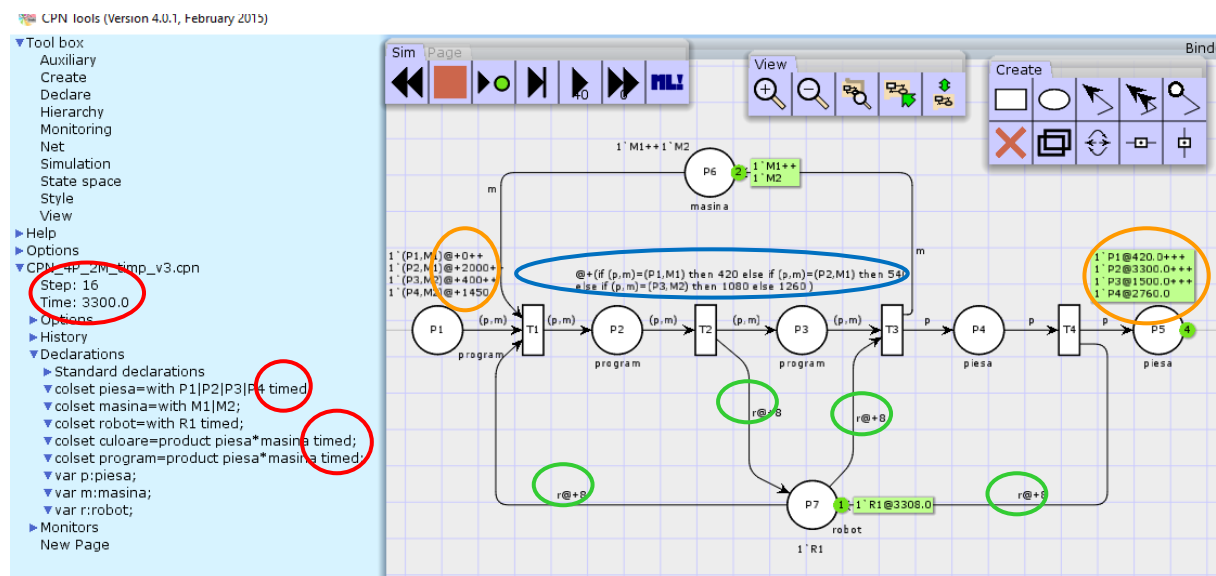


Figure 35. Timed colored Petri Net model, after simulation [15]

Considering that the information associated to model is built with colored Petri nets it is simulate the cell processing of the four parts. It can be see the end of processing times of each part: P1, 420 seconds; P2-3300 seconds; P3-1500 seconds; P4-3300 seconds. It also can evaluate the total functioning time of the robot: 3308 seconds (figure 35).

Simulation involves the execution of 16 steps; the number of executions transitions is 16.

5. Conclusions

Modeling and simulation with Petri nets are powerful tools for evaluating system performance. The paper presented how Petri net models have been developed for a wide variety of manufacturing systems: manufacturing lines in the textile industry, assembly lines in the consumer goods industry, automated lines in the detergent industry and robotic welding cells in the industry auto. Generalized hybrid timed Petri nets were used for these models.

The paper also presented how the same system can be used with several types of Petri nets. The modeled system was the robotic cell for the preparation and analysis of metallographic samples. The first model variant was a model with timed Petri nets. This is a very complex model with many elements (positions, transitions and arcs). The simplification of the model was achieved by switching to colored Petri nets with simple colors and then colored Petri nets with complex colors. The use of

hierarchical colored Petri nets (the third modeling variant) allowed a structural organization of the model by considering the component subsystems of the cell. This type of model facilitates the monitoring of the cell's functioning through the submodes that make up the main model.

Colorful Petri nets with complex colors offer various model solutions for the same system. This was demonstrated by the development of the two models associated with the flexible manufacturing cell A007.

Future research will follow the development of models with colored fuzzy Petri nets and stochastic Petri nets.

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