Evaluation of the performance of an automated metallographic samples analysis system by means of Petri Nets modelling

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Abstract. This paper presents the results of the research about the automation of the metallographic samples preparation and analysis processes. At the University of Oradea the authors designed and made an automated metallographic samples preparation and analysis system. This automated system can achieve polishing, attack by reagents and metallographic analysis. The flexible cell (the automated system) is made of two subsystems. The first subsystem, which is served by an industrial robot, performs the polishing and the sample surface assessment. The second subsystem, also served by an industrial robot, performs the reagent attack and finishes the metallographic analysis in order to determine the microstructure of the sample. The authors have designed a timed Petri nets model in order to assess the performance of the automated system and to identify the possible bottlenecks. The model is made for the case that the system is required to analyse two kinds of samples. The sequences performed by the industrial robots are modelled by transitions with associated timings that are equal to the real time periods taken by the robots to execute the corresponding actions. Other activities, such as grinding polishing, finishing polishing, reagent attack, washing, microscope examining, have been also modelled by means of transitions. The execution of a transition (the completion of a real sequence) is possible if certain conditions are met. These conditions are modelled into the Petri net by means of positions. The number of samples that can be analyzed in a certain time period can be determined by simulation.

1. Introduction
In the last years, great amounts of research have been carried out in the field of automation of specific activities and testing in biology and chemistry laboratories, material sciences etc. 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 Hombrechtikon System Engineering (HSE) [1], Highres Biosolutions [2], or in the field of material science we can give Picoquant [3] or SaxsLab (Xenocs) [4]. In 2018 the Canadian Institute for Advanced Research published the article “Integration of AI and robotics with materials sciences will lead to new clean energy technology” [5] which states: “Artificial intelligence and robotics
combined with material sciences and other advanced methods could dramatically speed up development of new materials for all clean-energy technologies.”

Reference [6] presents measurement operations from capturing an image up to generations of quantitative description of a structure as a report are actually performed by several evident actions that confirm the name of the product.

Two different techniques of fractal analysis were used to calculate the fractal dimensions are proposed in [7]. In the first method, the fracture surface morphology was utilized, and in the second method, the roughness profile of the fracture surface was utilized in order to calculate the fractal dimension.

In the field of metallography systems have been developed which contain 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.

Paper [8] presents an automated serial sectioning system with metallographic polisher, robotic arm, ultrasonic cleaner and Inverter Microscope. The authors analysed different aspects of this subject in previous work [9].

In this paper we highlight the importance of designing of such automated systems using state of the art computer methods like Petri nets.

2. 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). The layout of the designed cell is shown in figure 1. Two subsystems can be seen:

- subsystem $S_1$, which prepares the metallographic samples;
- subsystem $S_2$, which performs the metallographic analysis.

![Figure 1](image_url). The layout of the automated system (flexible cell) for the preparation and analysis of metallographic samples.
The following components of the automated system can be seen in figure 1:

- samples polishing posts: $Slf_1, Slf_2$;
- 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: $Ro_1, Ro_2$;
- 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 $Slf_1, Slf_2, Sp1, Us1, M1, St01$ of subsystem $S1$ are served by robot $Ro_1$;
- posts $R1, R2, Sp2, Us2, M2, St21, St22, St23, St31$ of subsystem $S2$ are served by robot $Ro_2$.

Figure 2 shows an overall view of the automated system (flexible cell) for the preparation and analysis of metallographic samples. The metallographic samples are entered into the system by means of storage device $St01$.

![Overall view of the automated system](image)

**Figure 2.** Overall view of the automated system (flexible cell) for the preparation and analysis of metallographic samples.

The samples preparation stage consists of polishing, surface assessment and reagent attack. This stage is divided between the two subsystems in the following manner: polishing (figure 3) and surface assessment (figure 4), performed by subsystem $S1$, are served by $Ro_1$, and reagent attack, performed by subsystem $S2$, is served by $Ro_2$.

The polishing of a metallographic sample is performed in several steps. The actual processing of the sample is always followed by washing and drying at posts $Sp1$ and $Us1$. 
The storage devices $St_{11}$, $St_{12}$ and $St_{13}$ act as interfaces between the two subsystems. Once the metallographic sample is processed, the robot $Ro_1$ places it in one of these storage devices, from where the robot $Ro_2$ brings it to the second subsystem.

In the subsystem $S_2$, served by robot $Ro_2$, the metallographic analysis is fully performed in order to assess the microstructure of the metallographic sample. After the sample has been transferred from subsystem $S_1$, the reagent attack is performed at one of posts $R_1$ or $R_2$, and then the sample is always washed and dried at posts $Sp_2$ and $Us_2$.

The final stage of the sample’s route in the automated system consists of the metallographic analysis at post $M_2$. The storage devices $St_{21}$, $St_{22}$, $St_{23}$ hold the sample if post $M_2$ is busy. When post $M_2$ is free to use, the metallographic sample is transferred there and the metallographic analysis is performed (figure 5).

After the metallographic analysis, the sample is taken out of the system by means of output storage device $St_{31}$ (figure 6).

The layout of the flexible cell was designed in such manner that robots $Ro_1$ and $Ro_2$ are able to access the posts of subsystems $S_1$ and $S_2$ that they serve.
3. The realization of the generalized timed Petri nets model

3.1. Making of the model
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 1.

Table 1. Positions and transitions of Petri nets model.

| Nr. | Symbol | Type | Meaning | Characteristics |
|-----|--------|------|---------|-----------------|
| 1.  | P1     | Pos. | Ro1 is free | m₀(P1)= 1 |
| 2.  | P2     | Pos. | S001 holds sample A | m₀(P2)= 1 |
| 3.  | T1     | Tr.  | Ro1 grips sample A | d₁= 5 sec. |
| 4.  | P3     | Pos. | Ro1 holds sample A in its grip | m₀(P3)= 0 |
| 5.  | T2     | Tr.  | Ro1 transfers sample A to S1f1 | d₂= 2 sec. |
| 6.  | P4     | Pos. | Ro1 placed sample A to S1f1 | m₀(P4)= 0 |
| 7.  | T3     | Tr.  | Coarse grinding sequence (S1f1) | d₃= 120 sec. |
| 8.  | P5     | Pos. | Ro1 takes sample A polished on S1f1 | m₀(P5)= 0 |
| 9.  | T4     | Tr.  | Ro1 transfers sample A to S2f2 | d₄= 2 sec. |
| 10. | P6     | Pos. | Ro1 placed sample A to S2f2 | m₀(P6)= 0 |
| …  | …     | …    | …       | …              |
| 75. | P40    | Pos. | Confirmation – Ro2 has sample B from S912 | m₀(P40)= 0 |
| 76. | P41    | Pos. | Confirmation – Ro2 has sample B from S913 | m₀(P41)= 0 |
| 77. | T36    | Tr.  | Ro2 has one sample B (logical transition) | d₉₀= 0 sec. |
| 78. | P42    | Pos. | Confirmation – Ro2 has one sample B | m₀(P42)= 0 |
| 79. | T37    | Tr.  | Ro2 transfers sample A to R1 and processes it | d₉₁= 12 sec |
| 80. | P43    | Pos. | Ro2 has sample A processed by R1 | m₀(P43)= 0 |
| 81. | T38    | Tr.  | Ro2 transfers sample A to R2 and processes it | d₉₂= 12 sec |
| 82. | P44    | Pos. | Ro2 has sample A processed by R2 | m₀(P44)= 0 |
| 83. | T39    | Tr.  | Ro2 transfers sample A to Sp2 and washes it | d₉₃= 12 sec |
| 84. | P45    | Pos. | Ro2 has sample A washed | m₀(P45)= 0 |
| 85. | T40    | Tr.  | Ro2 transfers sample A to U2s and dries it | d₉₄= 12 sec |
| …  | …     | …    | …       | …              |
| 153.| P79    | Pos. | Sample B (S23) was examined at M2 | m₀(P79)= 0 |
| 154.| T75    | Tr.  | Ro2 grips sample B (S21) from M2 | d₉₅= 5 sec |
| 155.| T76    | Tr.  | Ro2 grips sample B (S22) from M2 | d₉₆= 5 sec |
| 156.| T77    | Tr.  | Ro2 grips sample B (S23) from M2 | d₉₇= 5 sec |
| 157.| P80    | Pos. | Ro2 has sample B (S21) examined | m₀(P80)= 0 |
| 158.| P81    | Pos. | Ro2 has sample B (S22) examined | m₀(P81)= 0 |
| 159.| P82    | Pos. | Ro2 has sample B (S23) examined | m₀(P82)= 0 |
| 160.| T78    | Tr.  | Ro2 evacuates sample B (S21) | d₉₈= 5 sec |
| 161.| T79    | Tr.  | Ro2 evacuates sample B (S22) | d₉₉= 5 sec |
| 162.| T80    | Tr.  | Ro2 evacuates sample B (S23) | d₉₉= 5 sec |
| 163.| P83    | Pos. | Storage device S31 – samples B | m₀(P83)= 0 |

In fact, the Petri nets model consists of two sub-models (figure 7): sub-model for samples A (coloured blue) and sub-model for samples B (coloured 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 7. The timed generalized capacity Petri nets model of the automated system.
The capacity net characteristic is given by the fact that some positions have limited capacity – there is a maximum number of marks that can be found at that particular position at a given time. One such example is shown in figure 8 where position 35, which models the fact that robot R2 is free, features capacity 1.

The generalized characteristic of the net is given by the fact that there are arcs with loading greater than 1. Thus, arcs that start from position 30, which describe the loading degree of storage devices St21, St22 and St23, have loading 3 and are inhibitor arcs (figure 9). This solution is imposed by the fact that, in the real system, robot Ro2 cannot grip any metallographic samples from buffer storage devices St11, St12 and St13 when storage devices St21, St22 and St23 are full.

![Figure 8](image1.png) **Figure 8.** The definition of the capacity of the position that models the fact that robot Ro2 is free.

![Figure 9](image2.png) **Figure 9.** The definition of loading of the arcs that start from position 30, which model the constrain referring to the fact that storage devices St21, St22 and St23 are full.

The model is designed in such manner that potential conflicts are avoided. The number of samples that can be analysed in a given time interval can be found by simulation.

### 3.2. Simulation

A time interval of 8 hours (28800 seconds) is considered for simulation. The simulation duration is set in window “Simulation” (figure 10).

![Figure 10](image3.png) **Figure 10.** Setting of simulation duration; results of simulation.

![Figure 11](image4.png) **Figure 11.** The evolution of the busy/free states of robot Ro2.
The simulation shows that 47 samples A (position 67) and 47 samples B (position 83) have been processed and analysed (figure 10).

Graphs that show the evolution of the position mark can be attached to every position in the model. Figure 11 shows the graph that describes the states of robot Ro2, which can be free (value 1) or busy (value 0).

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.

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 12);
- for sample B, the discrete transition T_B has been added, with 900 second timing and position Sample B (figure 12);

![Figure 12. Modelling of the inputs of the system – version 2.](image)

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.

4. Conclusion

Modelling and simulation give us the possibility to analyse the operation of automated systems. This paper has presented a new use of Petri nets for the modelling of an automated system for preparation and analysis of metallographic samples. Timed, generalized and capacity Petri nets have been used. The model has been used to assess the performances of the automated system by means of simulation. Two situations have been studied: alternative input of the metallographic samples and input of the samples at given time intervals.

The simulation showed the number of samples in both examples, taking into account an 8 hours time interval. Also, the simulation showed that no bottlenecks or other unwanted events occurred during the operation of this automated system.

The next research will take into account the use of coloured Petri nets in order to make the model of the automated system for preparation and analysis of metallographic samples. This new approach will give a greater degree of flexibility to the next models.
5. References

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