# EVALUATION OF OPERATIONAL RELIABILITY IN INDUSTRIAL SENSORS CONTROL SYSTEMS VIA STOCHASTIC PETRI NETS (SPN)

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**Abstract.** The present paper describes the application of Stochastic Petri Nets (SPN) for analysis, modelling and evaluation of the operational reliability in industrial control systems. The SPN are applied for reliability modelling and reliability assessment in an industrial extruded polystyrene (XPS) grinding device. Some specific Petri net-based models of normal and abnormal control systems behaviour are developed and respectively applied under real operational control of an XPS-grinding device.

**Keywords:** operational reliability, industrial control systems, stochastic Petri Nets

## 1. Introduction

During the recent years, the modelling, the evaluation and the prognosis of the operational reliability in a reparable industrial equipment remains one of the main targets of reliability engineers and scientists, who develop methods and systems for Reliability Analysis and Reliability Evaluation (mainly via Fault Diagnosis) [1, 2, 3, 6, 8]. In general, such types of reliability studies are focused on the operational reliability of the industrial equipment, since this is the most important and cost effective stage in the equipments life cycle [2, 4, 6, 8].

One of the most advanced methods, that, could be developed and applied for modelling, analysis and evaluation of operational reliability in industrial control systems is the Petri Net approach, which has proven to be a really valuable tool systems and devices [5, 9, 10, 11].

In general, so advanced, and highly-performing tools as are the Stochastic Petri Nets (SPN), find their application mainly in the area of evaluation and real-time control of the operational reliability in industrial complexes, for optimal and adaptive control of industrial processes, as well as for on-line fault diagnosis with continuous and real-time evaluation of the systems states [5, 7, 9, 11].

The present paper describes the application of Stochastic Petri Nets for analysis, modelling and evaluation of the operational reliability in industrial control systems. The SPN are applied for reliability modelling and reliability assessment in extruded polystyrene grinding equipment (XPS-grinding equipment) via development and application of some specific Petri net-based models of normal and abnormal control systems behaviour under real operational conditions.

## 2. Sensors control system of industrial XPS-grinding equipment – structure, capabilities, operation

The industrial *XPS-Grinding equipment* is designated for grinding of XPS waste, as well as for grinding of XPS final products, which do not conform to the appropriate quality and technical characteristics. The *XPS-Grinding equipment* is one of the main modules of an *XPS-Recycling system*, that represents the fourth general product line of an already built and operated "Technologic and Logistical Complex for Manufacturing of Extruded Polystyrene (XPS) products".

All logistical structures and operations, as well as all essential technologic processes are developed in details in [1]. The XPS industrial complex is developed under the US Export Import Bank (US Ex-Im Bank) financing programme, and is located near the town of Varna, Bulgaria.

The general view of the grinding system, (subjected to the actual study), is presented at Figure 1.

Figure1. General view of industrial XPS-Grinding system (subjected to the actual study)

The control of the XPS-grinding and crushing processes is effectuated via basic *sensors control system*, which consists of *Dually Connected Sensors system* (DACS-system), *one programmable microcontroller*, and supplementary measuring and connecting devices. The basic DACS-system is designed to control the temperature range of the XPS-grinding and crushing processes (in order to avoid the non-desirable "sticking" of the grinded XPS-particles), as well as the evolutions of the grinding shafts. The microcontroller is designated to perform all necessary calculations that are needed for analysis and treatment of all data bases, (supplied by the sensors) and to generate the necessary *control actions*. The reliability structure of the basic DACS-system is presented at Figure 2. The structure consists of two sensors $S_T$-1 and $S_E$-2 (respectively for control of the temperature range and the shaft evolutions in the grinding chamber), which are connected in parallel (by the reliability criteria), and serially connected microcontroller (MC) – please see Figure 2.

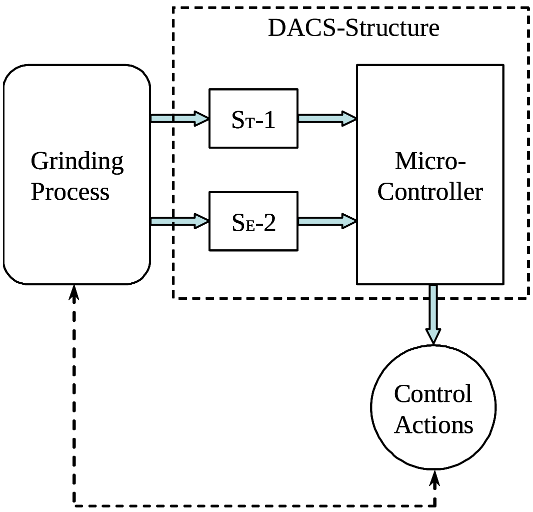

Figure 2. Structure of the DACS control system for XPS-grinding equipment

Since the XPS products, that should be submitted to crushing and grinding have various technological characteristics (due to the fact, that, the XPS final and waste products are multilayered and are composed by various layers with different parameters, please see [1]), the grinding processes, performed via the XPS-grinding equipment are rather *complicated*. In order to obtain an ***error recovery*** and/or ***fault tolerance*** of the control systems structure and respectively a ***higher level of the operational reliability*** in the entire systems structure – a ***Redundant Control Systems structure*** was developed and built in the XPS-grinding equipment. The developed Redundant Control Systems structure (RECS-structure) is presented at Figure 3. The RECS-structure is based on analytical redundancy via adaptive filters and predictive models that are capable to provide fault tolerance (and even failure recovery) against sensor failures for a restricted time period, after a failure occurrence.

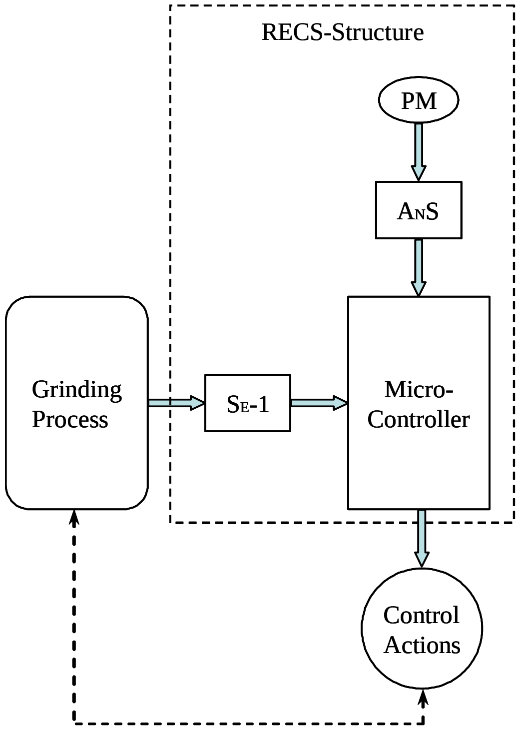

Figure 3. Structure of the RECS control system

The fault tolerance of the RECS-system, and respectively the enhancement of its operational reliability can be effectuated via a replacement of the failed sensor by its *Predictive Model* (PRM) *output*, that is generated by the detection filters of the *Analytical Sensor* (AnS). The PRM is however to generate an alternative outputs for a restricted period of time periods. The length of these time periods can vary for each particular PRM developed.

## 3. Development and application of Stochastic Petri Nets for development of reliability models and evaluation of the operational reliability in DACS and RECS structures

In order to obtain an *adaptive design* of the *reliability models*, that can be applied in both kinds of control systems developed (respectively with DACS and RECS structures), a particularly powerful and flexible method shall be applied in this study – the ***Stochastic Petri Nets*** (SPN).

A **Petri Net** (**PN**) can be defined via the following relation,

$$\mathbf{PN} = \{\mathbf{P}, \mathbf{TR}, \alpha\} \tag{1}$$

where **P** represents a set of ***places***;
**TR** is a set of ***transitions***;
$\alpha = \alpha_i \cup \alpha_0$ is set of ***direct arcs***,

where

$$\alpha_i \subset (\mathbf{TR} \times \mathbf{P}) \text{ and } \alpha_0 \subset (\mathbf{P} \times \mathbf{TR}). \tag{2}$$

If any **PN** contain features (symbols), then it is called a *featured* **PN**, [9]. The state of a featured PN is defined by the number $\mathbf{s_i}$ of features that are contained in each PN place $\mathbf{p_i}$. A *featured* (a marked) **PN** is then defined via the relation,

$$\mathbf{PN} = \{\mathbf{P}, \mathbf{TR}, \alpha, \mathbf{S_0}\} \tag{3}$$

where $\mathbf{S_0} = (\mathbf{s_{01}}, \mathbf{s_{02}}, \ldots, \mathbf{s_{0n}})$ is the *initial featuring* (marking) in the PN, [9, 11]. It should be noted also, that, each accomplishment of a transition modifies the distribution of the features over the places, thus generating a new featuring (marking) for the **PN**.

In the **PN's** ***graphic presentation*** *the features (the marks) are drawn as black dots.*

If to each transition (**TR**) in the **PN**-structures is associated a particular number, that, indicates *the time delay* "**T**" between the *enabling* and the *execution* of **TR**, then the developed **PN** is modified as a *Timed Petri Net* (TPN) structure, defined via the following relation,

$$\mathbf{PN} = \{\mathbf{P}, \mathbf{TR}, \alpha, \mathbf{S_0}, \mathbf{T}\} \tag{4}$$

where $\mathbf{T} = \{\mathbf{T_1}, \mathbf{T_2}, \ldots, \mathbf{T_S}\}$ represents the set of time delays, associated with the **TR**.

In cases when, in each transition of the TPN, only *random time variables* (with exponential distribution) express the time delay from the enabling to the execution of the transition, then the developed TPN converts to a *Stochastic Petri Net* (SPN), [9].

The **SPN** is thus expressed via the relation,

$$\mathbf{SPN} = \{\mathbf{P}, \mathbf{TR}, \alpha, \mathbf{S_0}, \theta\} \tag{5}$$

where $\theta = \{\theta_1, \theta_2, \ldots, \theta_S\}$ is respectively a set of random time variables, that are associated with the **SPN** transitions.

The reliability evaluation of DACS and RECS systems structures, can then by effectuated via specially developed SPN reliability models.

The structures of the created *SPN reliability models* for the already developed DACS and RECS control systems are respectively presented at Figure 4 and Figure 5.

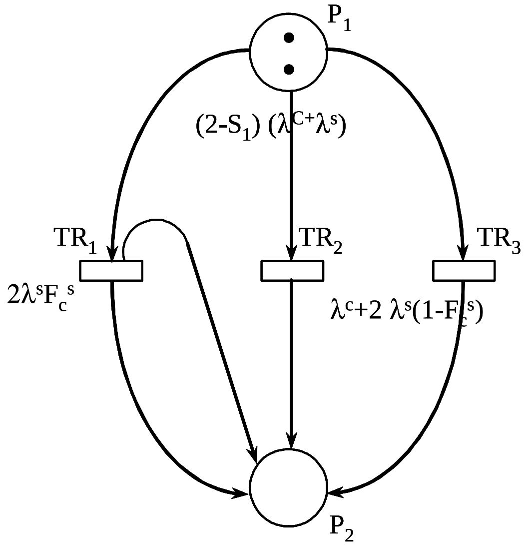


Figure 4. PN model for DACS structure of XPS-control system

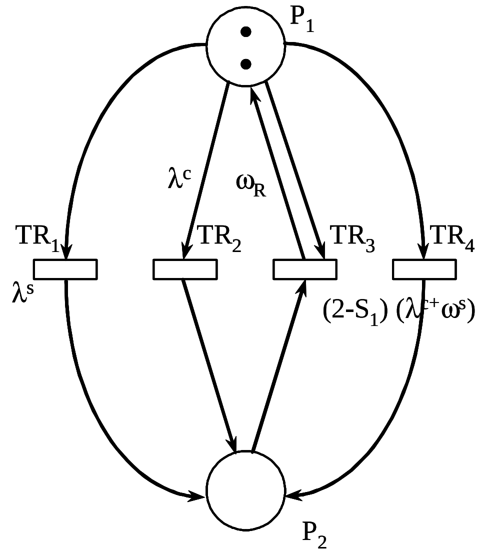


Figure 5. PN model for RECS structure of XPS-control system

The SPN reliability model, developed at Figure 4, as two sets of places ($\mathbf{P_1}$ and $\mathbf{P_2}$) and respectively three transitions ($\mathbf{TR_1}$, $\mathbf{TR_2}$ and $\mathbf{TR_3}$) and two features.

The modelling relations are as follows:

1. For the **SPN** place $\mathbf{P_1}$:
   - $\mathbf{s(P_1)} = 2$: Both sensors and the microcontroller operate correctly (no fault and/or failure in the system);
   - $\mathbf{s(P_1)} = 1$: One of the sensors and the controller operate correctly (the other sensor is in fault/failure);
   - $\mathbf{s(P_1)} = 0$: The systems is in failure.

2. For the **SPN** place $\mathbf{P_2}$:
- $\mathbf{s(P_2)}$ = 0: The system operates correctly (no faults and/or failures in the system);
- $\mathbf{s(P_2)}$ = 1: A fault and/or failure in sensor SE-1 (the material sensor);
- $\mathbf{s(P_2)}$ = 2: Both sensors or the controller are in failure, resulting in a failure of the entire system.

3. For the transitions $\mathbf{TR_i}$ in the **SPN**:
- $\mathbf{TR_1}$: Failure in the sensor $S_T$-1;
- $\mathbf{TR_2}$: Failure in the sensor $S_E$-2 or failure in the microcontroller;
- $\mathbf{TR_3}$: Failure in the microcontroller.

The SPN reliability model, developed at Figure 5, has also two sets of places ($\mathbf{P_1}$ and $\mathbf{P_2}$) and respectively four transitions ($\mathbf{TR_1}$, $\mathbf{TR_2}$, $\mathbf{TR_3}$ and $\mathbf{TR_4}$) and two features.

The modelling relations are as follows:

1. For the **SPN** place $\mathbf{P_1}$:
- $\mathbf{s(P_1)}$ = 2: Both sensors and the microcontroller operate correctly (no fault and/or failure in the system);
- $\mathbf{s(P_1)}$ = 1: The analytical sensor ANS operates correctly (the material sensor SE-1 is in fault/failure);
- $\mathbf{s(P_1)}$ = 0: The systems is in failure, since both sensors or the microcontroller is in failure.

2. For the **SPN** place $\mathbf{P_2}$:
- $\mathbf{s(P_2)}$ = 0: The system operates correctly (no faults and/or failures in the system);
- $\mathbf{s(P_2)}$ = 1: A fault and/or a failure in sensor SE-1 (the material sensor);
- $\mathbf{s(P_2)}$ = 2: The system is in failure, since both sensors or the controller are in failure.

3. The meaning of the transitions $\mathbf{TR_i}$ in the **SPN** respectively is:
- $\mathbf{TR_1}$: Repairing of the material sensor $S_T$-1;
- $\mathbf{TR_2}$: Failure in the material sensor $S_T$-1;
- $\mathbf{TR_3}$: Failure in the microcontroller;
- $\mathbf{TR_4}$: The analytical sensor $A_N$S can not longer treat the information data without the operation of the material sensor $S_T$-1.

The evaluation of the *operational reliability* **R(t)** of DACS and RECS structures is presented at Figure 6. The generated results are quite similar for the two system types.

However, a relatively significant difference can be observed for a failure rate $\lambda^C = 1/2000$. For the present case, the operational reliability of a RECS structure is better then the DACS structure *in the time interval* [0, 700]. In *the time interval* [700, ∞) the operational reliability of a RECS system is much better, then the reliability of a DACS system.

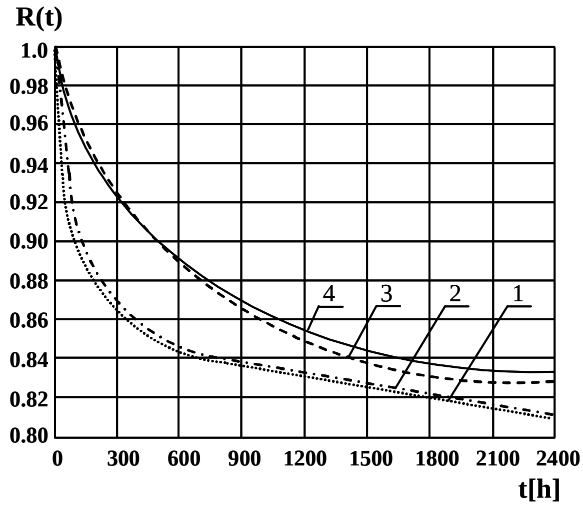


Figure 6. Operational reliability of DACS and RECS structures
1 – DACS-structure, $\lambda^C = 1/2000$; 2 – DACS-structure, $\lambda^C = 1/1000$; 3 – RECS-structure, $\lambda^C = 1/1000$; 4 – RECS-structure, $\lambda^C = 1/2000$

## 4. Conclusions

4.1. Reliability models of an XPS-grinding control system are developed as a Dually Connected Sensors System (DACS) and a Redundant Control System (RECS). The DACS structure consists of two sensors, connected in parallel, and one serially connected microcontroller. The RECS-structure is developed as an analytical redundancy system and is based on adaptive filters and predictive models that are capable to provide fault tolerance (and even failure recovery) against sensor failures for a restricted time period, after a failure occurrence.

4.2. Enhanced Stochastic Petri Nets (SPN) reliability models of the DACS and RECS control systems are developed and applied for the evaluation of the systems operational reliability R(t).

4.3. The developed models, structures and techniques are applied for reliability evaluation in an industrial XPS-grinding system, under real operation conditions, thus providing fault tolerance and reliability enhancement of the entire recycling technologic system.

### References

1. Dimitrov, K.D.: *Razrabotvane na tehnologicino-logisticen complex za proizvodstvo na termo-izolatzionnii izdeliea ot ekstrudiran penopolistiren (XPS)* (*Technologic and logistical complex for manufacturing of extruded polystyrene (XPS) products*). HC’TECH 2005, Sofia, 2005 (in Bulgarian)

2. Dimitrov, K.D., Danchev, D.: *Nadejnosti na mashini i sistemi* (*Reliability of Machines and Systems*). Ed. Technica, Sofia, Bulgaria,1999 (in Bulgarian)
3. Dimitrov, K.D.: *Model-based fault diagnosis in a waste-processing industrial system via casual graphs*. RECENT, Vol. 10 (2010), N$^{o}$ 2(26), July 2009, p. 101-105, ISSN 1582-0246, Brasov, Romania
4. Dimitrov, K.D., Nurkov, D.I.: *Experimental Platform for Process Modeling, Simulation and Analysis of Technical Conditions and Fault Diagnosis*. RECENT, Vol. 11 (2010), N$^{o}$ 1(28), March 2010, p. 23-28, ISSN 1582-0246, Brasov, Romania
5. Dhallin, J., et al.: *Application des réseaux de Pétri a la commande-contrôle de processus en sécurité*. AP II - 1987, N$^{o}$ 21 (in French)
6. Ligeron, P., et al.: *La Fiabilité en Exploitation – organisation et traitement des données*. Lavoisier Technique et Documentation, Paris, 1998 (in French)
7. Kretsovalis, A., Mah, R.S.H.: *Effect of redundancy on estimation accuracy in process data reconciliation*. Chem. E. S., Vol. 42, p.2115-2121, 1997
8. Ljing, L.: *From data to model: A guided tour*. Control ’94, p. 21-24, 1994
9. Peterson, J.A.: *Petri Net theory and the modeling of systems*. Prentice Hall Inc., 1991
10. Pinch, E.R.: *Optimal Control and the Calculus of Variations.* Oxford University Press, 1993
11. Zhou, M.C., Dicesare, F.: *Adaptive design of Petri Nets controllers for error recovery in automated manufacturing systems*. IEEE SMC 1989, Vol. 19, N$^{o}$. 5


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