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Modelling the production systems in industry 4.0 and their availability with high-level Petri nets

F. Long*, P. Zeiler**
B. Bertsche***

**Graduate School of Excellence advanced Manufacturing Engineering, University of Stuttgart, Stuttgart, Germany; Institute of Machine Components, University of Stuttgart, Stuttgart, Germany, (Tel: +49-711-685-66697; e-mail: fei.long@ima.uni-stuttgart.de)*
***Institute of Machine Components, University of Stuttgart, Stuttgart, Germany, (e-mail: peter.zeiler@ima.uni-stuttgart.de)*
****Institute of Machine Components, University of Stuttgart, Stuttgart, Germany, (e-mail: bernd.bertsche@ima.uni-stuttgart.de)*

Abstract: Industry 4.0 offers a new possibility to achieve a flexible and efficient production. Special features in industry 4.0 bring new challenges and have not been considered in the modelling yet. In this paper, extended coloured stochastic Petri nets (ECSPN) are used for modelling the production systems in industry 4.0 and their availability, in order to support the analysis and optimization of availability as well as of the supporting resources. Three models of ECSPN are built and simulated using a software REALIST to model interactions and self-organisation. Finally, the modelling results are explained.

Keywords: availability, production system, Petri net, ECSPN, industry 4.0, interaction, self-organisation.

1. INTRODUCTION

Production systems have been developed first from craft production into classic industrial production at the beginning of the 20th century, after that into lean production in the mid-twentieth century, and then into adaptable production in the past ten years (Rauch 2013). A well-known production system is the Toyota production system (Ohno 2009). Today, digital production (Westkämper et al. 2013) has participated in production systems. A very recent and important trend is to combine and connect production systems in industry with the "internet of services and things" in order to achieve a highly flexible and efficient production (Kagermann et al. 2013). Industry 4.0, a future project in the high-tech strategy of the German federal government, is a new approach to achieve these goals. Initiated by the future strategy program "industry 4.0", it is assumed that this trend could lead to the fourth industrial revolution (Kagermann et al. 2013). This trend can also be observed in other countries and all over the world. Combination and connection with "cyber-physical systems" and "internet of services and things" in production systems lead directly to the necessary changes and updates of the production systems. For this reason, the production systems in industry 4.0 have some special characteristics, which bring new challenges and requirements to the modelling and analysis of the production systems and their availability. In order to receive realistic results, the modelling methods should be able to consider the special characteristics of production systems in industry 4.0.

The existing conventional modelling methods such as Markov Models and Petri nets (Bertsche 2008, Pozsgai 2006) can be used to model production processes and repairable systems. They could also be used to model the production systems in industry 4.0 and their availability. According to the special characteristics of production systems in industry 4.0, these methods are evaluated in the early work (Long et al. 2015). The evaluation shows that Petri nets have unique advantages and are more suitable than other methods to simulate the production systems in industry 4.0. Petri nets were used as a graphical modelling formalism for state-discrete systems (Petri 1962). In recent decades, they have been continually developed and are increasingly used for realistic modelling in production technology and reliability engineering. The high-level Petri nets, coloured Petri nets CPN (Jensen 1996), use special coloured tokens to describe various information and to consider different states. Based on the CPN and the extended stochastic Petri nets (ESPN), the extended coloured stochastic Petri nets ECSPN (Pozsgai & Bertsche 2004; Pozsgai 2006) were developed with various functions, in order to simultaneously consider different states and describe stochastic processes.

In (Fasth 2011), ten methods for redesigning, measuring and analysing production systems such as DYNMO++ and Systematic Production Analysis are described. These methods can be used to model the structure of production, production processes etc. However, they cannot model stochastic processes that are crucial for the analysis of reliability and availability. ECSPN can simulate not only the general aspects of production systems such as structure and workflow, but also stochastic processes, various states of production processes and their changes, and the properties such as queues, priority, and guide function (Pozsgai 2006). These capabilities could be used to simulate the special characteristics of production systems in industry 4.0, e.g.

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flexibility and self-control. Therefore, it is worth studying the potentials of ECSPN to simulate the production systems in industry 4.0.

In a previous work (Long et al. 2015), the potentials of various modelling methods for the analysis of production systems in industry 4.0 are compared and evaluated. The ECSPN were evaluated as one of the most powerful methods and are therefore applied in this paper for further studies. The ECSPN are applied for the investigation of the interaction between productivity and availability. Furthermore, one fundamental aspect of production system in industry 4.0, the self-organisation, is studied based on two example applications.

The purpose of this paper is to introduce the applications and potentials of ECSPN for realistic availability modelling of production systems in industry 4.0. In Section 2, Petri nets, especially ECSPN and its properties, are described. The special characteristics of production systems in industry 4.0 are briefly introduced in Section 3. The applications of ECSPN and their modelling results are explained in Section 4. At the end of the paper, a short summary is given.

2. MODELLING METHODS

Petri nets allow a graphical representation of systems. This makes it possible to analyse complex systems in an easy way. The features such as causality and conflict can be graphically represented with Petri nets, therefore, they are particularly suitable to describe the behaviours of complex systems (Trost 2008). In this section, Petri nets and ECSPN are presented.

2.1 Petri nets

Petri nets were published as a method for modelling of concurrent discrete systems by Carl Adam Petri in 1962 (Petri 1962). This method consists of four basic elements: place, transition, arc and token. The places are pictured as circles. They describe possible states of a system or its components and can contain tokens. The transitions, which are pictured as squares, represent the activities that change the values of the states and can therefore model the dynamics in a system. The arcs indicate the connections between places and transitions and represent the flow of the tokens by arrows. They map the logical interrelations and show the structures of models. The tokens are pictured as filled out circles. They describe the specific values of the states.

At first there were only low-level networks, e.g. Condition-Event-nets (Reisig 1982). Over the last few decades, a number of enhancements have been introduced with the stochastic Petri nets (SPN). In SPN, each transition has a constant switching rate. The switching time is assumed as exponentially distributed. The generalized stochastic Petri nets (GSPN) provide two types of transitions. In addition to the time-bound transitions, timeless transitions are allowed, which switch immediately after activation. With the extended stochastic Petri nets (ESPN), any general distribution can be assigned to each transition to determine the switching time. Besides exponentially distributed and deterministic response times, other distributions can also be used. The CPN, which were developed in (Jensen 1996), provide special coloured tokens that can carry different information. Therefore, depending on the token colour and value, different states can occur in the network.

2.2 ECSPN

ECSPN were developed based on CPN and ESPN by Pozsgai (Pozsgai & Bertsche 2004; Pozsgai 2006). In addition to the properties of queues and ESPN, several additional attributes are included. ECSPN provide elements specially prepared for the modelling of state behaviour with ageing, the degree of renovation, the inspection strategy and operational cost. The modelling aspects, which can be considered by ECSPN, are introduced in (Zeiler & Bertsche 2014).

ECSPN use single-server and multi-server transitions. In comparison with multi-server transitions, single-server transitions have the benefits of clarity and accuracy to analyse interactions in complex systems. Therefore, single-server transitions are used in this paper. In SPN and ESPN, enabling memory and age memory are used as switching processes of transitions to describe the switching delay. Based on these two switching policies, ECSPN introduce a new switching method of age influence to consider the aging process. In this paper, the enabling memory is used.

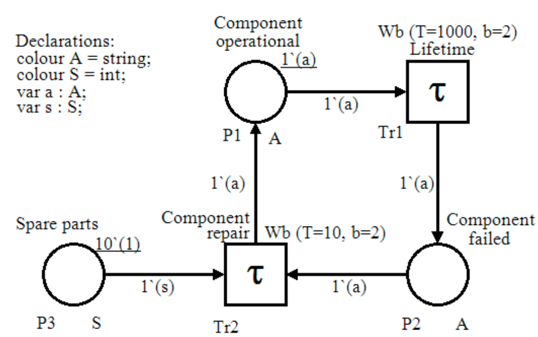

Fig. 1. An example of ECSPN.

A model of ECSPN for a repairable component is shown in Fig. 1. It consists of three places and two timed transitions. The states of component are presented as “operational” and “failed”. The transitions simulate the life time of this component and its maintenance time. At the beginning, the state of the component is shown with initial marking “operational”. The transition Tr_1 is activated with the initial marking and fires after a delay, which means the component fails. After the fire, the token in the place P1 is deleted and a new token is created in the place P2. With the new token, the transition Tr2 is activated and can fire after a repair delay. This deletes one token in places P2 and P3 and then creates a new token in place P1. The lifecycle starts again. The percentage of time, which the token in the place P1 occupied, is equivalent to the availability of the component. Places P1 and P2 have the colour A with datatype of “string”, while P3 has the colour S with datatype of “int”. The variables a and s are associated with different colours. This information is described in the declaration on the top left of the diagram.