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IFAC PapersOnLine 50-1 (2017) 5680–5687

Modelling the flexibility of production systems in Industry 4.0 for analysing their productivity and availability with high-level Petri nets

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Abstract: Industry 4.0 is characterized by a strong individualization of products under the conditions of a highly flexible production. The customer-oriented production leads directly to complex flexible production systems, which need to be modelled and optimized. Analysing the availability of flexible production systems in Industry 4.0 aims to reduce the risks of unexpected machine failure and thus resulting losses, and subsequently to support the optimization of production systems. Extended coloured stochastic Petri nets are used in this paper to build a model for modelling a flexible production system with three machines. The results show that flexible production can be simulated with this model.

Keywords: availability, production system, Petri nets, Industry 4.0, flexible, individualization.

1. INTRODUCTION

Over the last few centuries, the production systems have developed first from a craft production into a classic industrial production, then into a lean production and finally into an adaptable production (Rauch 2013). Thereby, lean production is widely used in the industry to enhance efficiency at growing product varieties (Brettel et al. 2014). With the rapid development and popularization of internet, digital production (Westkämper et al. 2013) is gaining more and more in importance. Recently, Westkämper and Löffler (2016) proposed a new concept. They consider production as a system. Individualization is one of the eight most important current global megatrends, which have a direct impact on production (Westkämper and Löffler 2016). Five visions and concepts of future factories are described in their work. They are adaptable production, networked production, digital production, learning production and sustainability in the life cycle of the production (Westkämper and Löffler 2016). These concepts of future factories point to the development direction of production systems in Industry 4.0.

With the increasing market saturation, the markets transformed into buyers markets, which forced manufacturers towards product differentiation (Brettel et al. 2014). The increasing demands for individual customer-specific products not only gradually draw the attention of manufacturer, but also quietly affect their production strategies. Due to the increasing global competition, customized products and rapid time-to-market become the focus of many companies (Brettel et al. 2014). For the manufacturer diverse product variants in various batch sizes need to be produced in an efficient way. However, the strategy of mass production cannot meet all these demands. In order to fulfil the demand of individualization, customer-oriented production need to be implemented, which leads directly to complex flexible production systems. It is a great challenge to optimise the production systems to achieve a highly flexible and efficient production. Industry 4.0 is a future project in the high-tech strategy of the German federal government and offers a new possibility to achieve this goal (Kagermann et al. 2013). Kagermann et al. (2013) indicated that Industry 4.0 will involve the technical integration of Cyber-Physical Systems into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. Brettel et al. (2014) discussed various research topics of Industry 4.0 and indicated that individualized production has a strong connection with the topics related to industry 4.0. On the other hand, Industry 4.0 will be characterized by a strong individualization of products under the conditions of a highly flexible production (Monostori et al. 2016). Therefore, flexibility is a basis of production systems in Industry 4.0 to realize individualization.

Availability is a crucial parameter for the objective characterization of the performance level of production systems. Numerous studies have investigated the availability of complex systems. The research of Loganathan et al. (2016) shows that most studies investigated constant failure and repair rates based on Markov model. Loganathan et al. (2016) used Semi-Markov model to analyse the availability of manufacturing systems. This model allows to take variable failures or repair rates into account. Various elements at different hierarchical levels of the system are considered in

10.1016/j.ifacol.2017.08.1118

the model. However, flexibility and its influence on productivity and availability is not analysed in their work. Flexibility is still a barrier for modelling the production systems and analysing their productivity and availability.

Petri nets are further developed and increasingly used for realistic modelling in production technology and reliability engineering. In Martinez et al. (1987) coloured Petri nets are used to model the coordination subsystem of a Flexible Manufacturing System (FMS). Barad and Sipper (1988) proposed a three-step approach to use Petri nets as a design representation of an FMS for comparing different systems on a flexibility basis. Petri net modular structure is used to model interrupted activities for evaluating the routing flexibility. Zhou et al. (1999) used Petri nets for modelling, simulation and control of flexible manufacturing systems. In Bashir et al. (2016), Petri nets are used to solve deadlocks in FMS with a minimal supervisory structure. Hernández-Martínez et al. (2016) proposed an approach for the modelling and supervision implementation of the coordination of standard Flexible Manufacturing Cells using Petri Nets. Their models contain the information about the availability and capacity of storages and equipment mixed with the process tasks and its logical precedence conditions.

In last decades, researchers have mainly studied the design and measurement of flexible manufacturing systems. The flexibility in production systems cannot yet be realistically modelled. Moreover, analysing the productivity and availability of flexible production systems based on realistic modelling of flexibility in production systems has not yet been investigated. In this work, a model of extended coloured stochastic Petri nets (ECSPNs) is built to model the flexibility of production systems with three independent machines. Compared to the models of a system with fixed structure, this ECSPN model can simulate flexible structures and thus flexible production processes. Diverse combinations of machines can be modelled, in order to model the production of various variants with different processes. In Section 2, literature review is given. Then, the modelling methods Petri nets and ECSPNs are briefly introduced in Section 3. Furthermore, the flexible model of ECSPNs is explained in Section 4. The results are shown in Section 5. Section 6 discusses the use of the flexible model in real production. Finally, a short summary is given.

2. LITERATURE REVIEW

2.1 From mass production to mass personalization

With the development of the production systems, the production strategy has evolved from mass production (MP) to mass personalization. At the end of the eighteenth century, the first mass production by machines led to the first industrial revolution. In the late nineteenth century, academia and industry paid much attention to mass customization (MC) and considered it as a major strategic initiative (Gilmore and Pine 2000). Pine (1993) defined MC as producing personalized products at a price similar to that of MP. MC can be offered via product and process variety. Daaboul et al. (2011) evaluated product and process variety with a value metric based approach to analyse their impact on customer perceived values in order to find the best balance between variety and complexity for designing MC. In customization, customer needs are identified by marking analysis. Based on different customer needs, customers are classified into different market segments. Tseng et al. (1996) described the design for mass customization (DFMC), which reuses proven design among product families to configure various product variants through modularity.

In recent years, implicit properties such as personal taste and experience play an increasingly important role in the shopping. Tseng et al. (2010) considered personalization as one of the major drivers for the next transformation of the global economy. With the aim to satisfy customers as individuals by offering personally unique products with positive user experience effectively and efficiently, Tseng et al. (2010) introduced design for mass personalization (DFMP). Customer needs with product variety can be matched through reusing various elements of design and manufacturing (Tseng et al. 1996, Jiao et al 2007). Based on one-to-one interactions with the customer, personalization can be realised through stimulating customer inherent needs (Tseng et al. 2010).

2.2 Review of flexibility

Bahrami (1992) defined flexibility as the ability to precipitate intentional changes, to continuously respond to unanticipated changes, and to adjust to the unexpected consequences of predictable changes. As a critical measure of total manufacturing performance, flexibility ensures the cost-efficiency and effectiveness of manufacturing process, in which customized products can be produced without sacrificing either objective (Gupta and Somers 1992). Sethi and Sethi (1990) considered manufacturing flexibility as a complex, multidimensional and difficult-to-synthesize concept. They defined flexibility in manufacturing as the ability to reconfigure manufacturing resources so as to produce efficiently different products of acceptable quality (Sethi and Sethi 1990). Flexibility was firstly considered as a trade-off against efficiency in production and dependability in the marketplace. Until late 1960s flexibility could be extended to large-scale production without sacrificing efficiency. Flexible manufacturing with computer and information technology enables the efficient batch production of multiple products.

In last decades, numerous studies have investigated the flexibility in production and manufacturing systems (Buzacott et al. 1980, Buzacott 1982, Browne et al. 1984, De Meyer et al. 1989, Sethi and Sethi 1990, Gerwin, D. 1993). De Meyer et al. (1989) defined four dimensions: quality, dependability, cost-efficiency and flexibility as competitive priorities in manufacturing, while flexibility is considered as the highest dimension. For a company, a minimum level of quality, dependability and cost-efficiency was required to become flexible. De Meyer et al. (1989) investigated the manufacturing strategy of the large manufacturers of Europe, North America and Japan in 1986. To cope with the shortening product life cycles and increasing market/demand