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Technical Paper

Simulation of matrix-structured manufacturing systems

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ABSTRACT

Increasing product variety, shorter product life cycles, and unknown future demands for each product type are key challenges of manufacturing companies. This paper describes the concept of matrix-structured manufacturing systems (MMS) which aims at providing high operational flexibility and scalability. The main goal of MMS is to eliminate a constant cycle time by providing redundant work stations for same operations as well as a flexible product routing. This enables to avoid starving and blocking and to achieve high system utilization while producing multiple product types with unknown demands and high volumes. The paper explains the main principles, elements, and control strategies of MMS and presents a simulation approach for the evaluation of MMS configurations. A case study shows the application of the simulation approach and how it can be used in the planning of MMS. The results reveal that a MMS configuration can lead to better utilizations of the exemplary manufacturing system in comparison to a sequential assembly line configuration.

1. Introduction

Manufacturing companies in general are opposed to various trends such as growing global competition, more individualized customer demands, new technologies and rapid technological progress, as well as strict environmental regulations. These trends lead to an increase in product variety, shorter product life cycles, uncertain and fluctuating demands, as well as higher cost pressure. The general manufacturing paradigm shifted from mass production to mass customization and more individualized products [1] (see Fig. 1). However, traditional manufacturing systems (MS) configurations such as sequential assembly lines or cellular job shop layouts struggle in handling either a high product variety and fluctuating demands or high production volumes. On the one hand, mixed-model assembly lines are in particular effected by different processing times of different products. The variations in processing times can cause starving or blocking of work stations and lead to an unbalanced utilization of resources [2]. A solution to this balancing problem becomes increasingly difficult if more product variants with significant differences in required work steps and processing times are introduced to the assembly line. On the other hand, cellular job shop layouts are able to handle a high product variety but are not capable of efficiently producing high volumes [3]. The resulting challenge for manufacturing companies is to establish a MS which is able to produce high volumes of products with a high variety and uncertain demands. This requires MS which provide the necessary degree of flexibility and scalability to offer specialized products according to a changing demands.

This paper presents an agile MS configuration concept for discrete manufacturing which allows using a sequential material flow structure for high volumes of multiple product types with sequential process steps. The proposed so-called matrix-structured MS (MMS) are able to react to changing market demands, produce a wide range of different products, allow the introduction of new products to the current set of products, be scaled to different output volumes as well as to handle layout and process reconfigurations. This can by achieved by eliminating a constant cycle time and allowing a flexible product routing. As a result, the MMS concept combines the advantages of a sequential flow line (handling high volumes) and a cellular job shop layout (handling high product variety) [4].

In a MMS, work stations are capable of performing different tasks and work packages for different product types. Work packages can be processes on different work stations which enables to avoid starving or blocking. Product instances are transported autonomously through the MMS making decentralized decisions such as selecting the next suitable work station. Consequently the product routing is not predetermined. The selection of a work station can be based on predefined and individual optimization objectives such as short transportation time/distance, short lead

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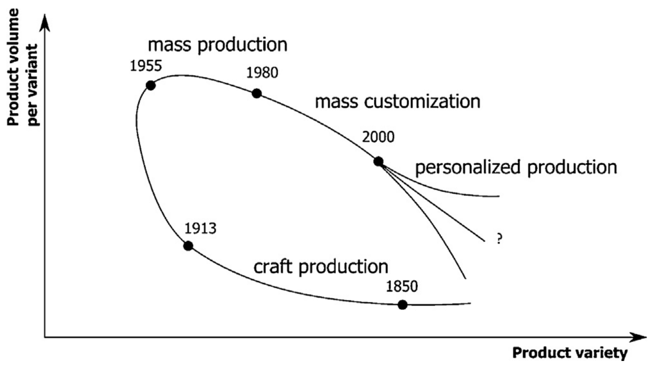

Fig. 1. Trend to mass customization according to Koren [1].

time, or high total system utilization. This leads to a dynamic and stochastic system behavior increasing the complexity of planning tasks. As a consequence, production planners need supporting tools for the prediction of the behavior of a MMS. Simulation can help to answer the question whether a MMS configuration is feasible and suitable for the manufacturing of a given set of products. This is important since a MMS configuration differs significantly from traditional assembly lines making it almost impossible to test MMS within an actual production environment without taking the high risks of corrupting the current production. However, it was found that commercial simulation software for manufacturing systems does not offer the required functionality for modeling MMS. This is why the development of a suitable simulation model was pursued. The remainder of this paper provides theoretical background about flexibility in MS, describes the concept of MMS in detail, presents the developed simulation tool for the evaluation of MMS, and demonstrates the application and advantages of a MMS in a case study.

2. Background

2.1. Flexibility in manufacturing systems

The challenges caused by high variety and uncertainty has been addressed in industry and research by the development of reconfigurable MS (RMS) and flexible MS (FMS) [5–7]. RMS are scalable in capacity or functionality through reconfiguration of hardware and software in order to be able to respond to a change in market demands or regulations [8,9]. FMS usually provide various forms of flexibility and can react to changes of products or the introduction of new product types. However, FMS are not able to efficiently process multiple product types with altering demands at the same time. Furthermore, RMS and FMS are not able to quickly adapt to disturbances and the dynamic environment of a MS. They have to be stopped in order to react to changes or disturbances [10]. Thus, the responsiveness is limited by the capabilities of the centralized and hierarchical control strategy. At the beginning of the century the term agile manufacturing (AM) was introduced to describe MS which are able to quickly respond to unpredictable changes in the environment [11–13]. In the same context holonic MS (HMS) have been introduced as a new paradigm based on a concept for describing biological and social systems [14]. In a HMS the system elements such as products, work stations, machines, jobs or material handling devices (so-called holons) act as autonomous cooperative agents. HMS are multi-agent systems (MAS) allowing agents to make decentralized decisions [15,16]. This leads to an agile, self-regulating system behavior of HMS which is resistant to disturbances and enables an efficient use of resources [10,14,15,17]. However, there are still many unanswered questions regarding the design and implementation of HMS including the organization of decentralized control strategies, mechanisms of self-organization, automation applications, and definition of the dynamic MS behavior [14].

The goal of the German Industry 4.0 project initiative – referring to the fourth industrial revolution – is the development of intelligent factories and manufacturing systems by utilizing cyber physical systems (CPS, [18]) and digital technologies (e.g. internet of things) [19]. A similar initiative with the goal of developing the next-generation of collaborating manufacturing systems is the Intelligent Manufacturing Systems Program (IMS) [20]. Enabler toward achieving intelligent factories is the combination of advances in production engineering disciplines with innovative information and communication technologies into CPS. These new technologies will allow connecting machines, products, and supporting devices in order to achieve a self-regulating, self-organizing and robust MS.

2.2. Simulation of manufacturing systems

Simulation is an established method in industry and science which aims at representing or imitating a real world system over time [21]. For this purpose, an appropriate model is necessary to represent the system of interest. A comprehensive overview over recent simulation applications in manufacturing and business is provided by Jahangirian [22]. In manufacturing, simulation is widely used as a supporting method in designing, planning, analyzing, and optimizing of manufacturing systems. Negahban et al. provide an up-to-date review about simulation approaches particular for MS design and operation [23]. In this context, simulation enables testing of alternative system designs, control strategies and new system elements without acquiring them or disturbing the real system (supporting "what if" analyzes). Furthermore simulation helps to provide insight to a system with respect to its cause and effect relations and to make the system's behavior visible to all stakeholders [21,23,24]. In the context of FMS, simulation is further used for scheduling tasks [25] and to generate data for real-time control systems [26].

Simulation approaches in general can be distinguished regarding different characteristics [24]. As an example, simulation models can be static, representing a certain state of a system, or dynamic, showing the development of system over time. Also models can be based on deterministic inputs or include random variables for modeling a stochastic behavior. Furthermore, a differentiation can be made between discrete and continuous simulation models. In discrete models, variables only change at discrete points of time whereas variables in continuous models change continuously. Also possible are combined approaches [21,27].

The common simulation approach for the analysis of MS operation is discrete event simulation (DES) [23]. Passive entities (which represent e.g. products) move through a MS and trigger certain actions at discrete points in time. This approach is typically used for scheduling tasks, capacity planning, and bottle neck identification. Another approach is agent-based simulation (ABS) which focuses on decentralized modeling of individual object behavior in a defined environment [27]. Each system element acts individually based on its inherent logic (usually modeled with state charts) and interacts dynamically with other elements. The principles of the agent-based approach can also be used for modeling, simulation, and control of MS [28–33]. This is especially the case for HMS, in which system elements are considered as autonomous entities interacting with each other [15,34–40]. However, none of these published approaches and tools for HMS was found to be directly suitable for the simulation of MMS regarding all relevant planning problems within the process of MMS development as well as for an easy-to use application in industry.