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Technical Paper

Capacity management of modular assembly systems

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ABSTRACT

Companies handling large product portfolio often face challenges that stem from market dynamics. Therefore, in production management, efficient planning approaches are required that are able to cope with the variability of the order stream to maintain the desired rate of production. Modular assembly systems offer a flexible approach to react to these changes, however, there is no all-encompassing methodology yet to support long and medium term capacity management of these systems. The paper introduces a novel method for the management of product variety in assembly systems, by applying a new conceptual framework that supports the periodic revision of the capacity allocation and determines the proper system configuration. The framework has a hierarchical structure to support the capacity and production planning of the modular assembly systems both on the long and medium term horizons. On the higher level, a system configuration problem is solved to assign the product families to dedicated, flexible or reconfigurable resources, considering the uncertainty of the demand volumes. The lower level in the hierarchy ensures the cost optimal production planning of the system by optimizing the lot sizes as well as the required number of resources. The efficiency of the proposed methodology is demonstrated through the results of an industrial case study from the automotive sector.

1. Introduction and motivation

A recent trend in production management is that companies are pushed by competitive markets and by facing several challenges arising from the management of a great variety of products with shortening life-cycles and customer-expected lead times. These requirements have significant impacts on the applied production technology: the production systems have to follow the trends of the products' life-cycle in order to maintain the economies of scale meaning the balance between the expected throughput and the corresponding production costs. Therefore, the coordinated evolution (co-evolution) of products, processes, and production systems is required to continuously revise and maintain the system configuration, in order to withstand the disadvantageous effects of the external drivers [1]. Furthermore, economies of scope also have to be reached by the proper management of the product portfolio with respect to three main activities: design, planning and manufacturing [2].

Focusing on assembly systems, the above mentioned important business goals can be achieved by utilizing the modularity of the products as well as the flexibility of the applied assembly systems [3]. This can be done by reducing the variant-dependent components in the systems, and applying systems that are built up of universal modules [4]. Flexible and reconfigurable assembly systems can support the firms to fulfill the customer needs while keeping the costs on the lowest possible level, even in a turbulent market [5]. The advantages of these systems can be utilized only if the right balance among the different capacities is found. Considering the design of modular assembly systems, an important task is to find the most appropriate system configuration that provides the desired production rate on the lowest possible cost [6]. Besides the proper physical structure of the applied system, there is an obvious need for the efficient production planning and control that supports the application of flexible and reconfigurable systems [7]. In case of assembly technology, system configuration and production planning processes strongly rely on each other, therefore, they are often combined in a common methodology [8].

The paper introduces a novel method for the management of product variety in assembly systems, by applying a new framework developed to enable the periodic revision of the capacity allocation and the system configuration. The framework has a hierarchical structure to support the capacity and production planning of modular assembly systems, both on a longer and shorter time horizons. On the higher level, a system configuration problem is solved to assign the product families to dedicated, flexible or reconfigurable

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resources, considering dynamic factors like uncertain order volumes. At the lower level of the hierarchy, it ensures the cost optimal production planning of the system by optimizing the lot sizes as well as the required number of modules. An important open question of this field is the consideration and prediction of the future-realized costs, characterizing the investments and operation of a certain system configuration. The substantial contribution and novelty of the paper is realized in the approximation of the costs – including cost factors affected by the dynamic reconfiguration processes – by prediction models that are applied in optimization models supporting higher level configuration decisions. Moreover, nonlinear interactions among the assembly processes of different products are also tackled by introducing additional decision variables (product subsets are determined with statistical models), keeping the linearity of the models while capturing the underlying interactions among the processes. This results in a production management framework with ongoing reconfiguration decisions at both strategic and tactical levels, enabling the minimization of the overall costs, relating to production and investments.

The structure of the paper is as follows. In Section 2, a literature review is provided, summarizing the state-of-the-art of modular system and the related capacity management methods. In Section 3, the production environment – considered in the paper – is described, highlighting the operation of the systems with the related costs and decisions. Section 4 provides a problem statement with the respected objectives, decisions and constraints. Section 5 introduces the proposed solution with the description of the hierarchical decision framework and its elements. Then, a real industrial case study is provided in Section 6 to evaluate the efficiency of the proposed methodology, compared different, most commonly applied rule-based solutions.

2. Literature review

Considering large product portfolios, the efficient management of assembly systems is a crucial financial issue, as product lifecycles are shortening, the number of variants is growing and traditional assembly systems are composed of variant-dependent components, thus they are usually unable to adapt to the changes cost-efficiently [9,4,10]. Therefore, the application of flexible and reconfigurable assembly systems should be considered, in order to achieve the economy of scale [11]. According to Wiendahl et al., flexibility and reconfigurability are specific to certain factory levels, therefore the term changeability is introduced as an umbrella concept that encompasses many aspects of change within an enterprise [12].

2.1. Comparison of dedicated, flexible and reconfigurable resources

Production technology has three main paradigms regarding the structure, management, and focus of the applied resources: dedicated (DMS), flexible (FMS), and reconfigurable manufacturing systems (RMS) [13]. There are no definite boundaries and specifications that categorize the above systems, however, dedicated systems are usually characterized by lower investment and higher changing costs, whereas flexible systems have the opposite characteristics [14]. Reconfigurable systems are in between them by offering a reasonable solution with relatively lower investment and changing costs. In the paper, a comprehensive capacity management approach is proposed, focusing on modular assembly systems. These systems consist of modular assembly lines that are designed to perform sequential assembly operations. The structure of the lines relies on the process-based alignment of assembly modules. Based on the structure of the modules, one can distinguish among dedicated, flexible and reconfigurable assembly lines. In order to characterize the different types of modules, some important concepts have to be clarified first, concerning the structure and operation of the system:

- *Modules* are the building blocks of modular assembly systems that are capable of performing specific types assembly tasks (e.g. screwing station, pressing station etc.). From structural point of view, one can distinguish among dedicated, flexible and reconfigurable modules from each types. Modular design is a commonly applied technique for assembly systems, since it enables to build different system configuration from blocks with standardized features (often referred as "*plug and produce*" modules [12,15]).
- *System configuration* refers to the design, selection and alignment of the system elements (e.g. modules). Given a certain product, more configuration alternatives exist that are capable of producing the product. Therefore, different performance measures need to be considered when selecting a system configuration: investment cost, quality, throughput, scalability and conversion time.
- *Reconfiguration* refers to the procedure when the physical configuration of the assembly system is modified, e.g. the alignment of the modules is changed in order to build a new assembly line and produce different product.

Dedicated, flexible and reconfigurable paradigms have advantages and disadvantages, therefore, the application of the different assembly lines is a crucial point when discussing the efficiency and economy of the assembly system. Several papers compare the three paradigms of production systems, however, the rest of them concentrate mostly on manufacturing processes [16,17,4]. Some of the characteristics summarized in the papers are valid for assembly systems as well, however, they have some specific features. Therefore, a brief introduction of the three types of assembly systems is provided.

Dedicated assembly lines are designed for assembling a certain product in high volume that is relatively stable. Due to the inflexible design of the dedicated modules, they can be operated economically only if the production volumes remain high and relatively constant, as the redesign and ramp-up of a modified or new dedicated module often entails high costs. Dedicated lines are usually automated, and equipped with a conveying system, therefore, the required human labor content is relatively low.

Flexible assembly lines are capable of assembling different, but relatively similar products by the adjustment of fixtures and tools (e.g. changing the bit and torque range on a screwdriver). They consist of flexible modules that are designed for performing a specific assembly task (e.g. screwing) of more product types, that are assembled in a medium/higher volume that can slightly fluctuate over time. As flexible modules are fixed on the shop-floor, they do not enable physical reconfiguration, and the scalability of the system is very low. Some flexible line is based on a hybrid assembly approach, where automated devices are combined with human labor, and the modules can be exchanged in a short time. Such modular systems are the combination of the flexible and reconfigurable paradigms, and suitable for quickly varying products and quantities, as the investment costs are lower than that of a highly automated system. Due to the higher level of flexibility, the risk of a bad investment is quite low [12].

Reconfigurable assembly lines are capable of producing more product families, by applying changeable fixtures and adjustable equipment. The modular structure enables to change the configuration of the system with relatively low effort, and scale up or down the capacity according to the order stream. When applying mobile, dockable workstations, the reconfiguration procedure