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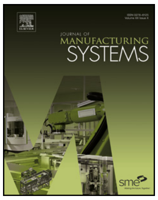

Car sequencing for mixed-model assembly lines with consideration of changeover complexity

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ABSTRACT

Implementing mass customization can inevitably lead to a large product variety, which makes the assembly process in mixed-model assembly lines (MMALs) very complex. In this paper, the concept of product variety induced changeover complexity, as one major source of uncertainty in mixed-model assembly, is proposed. Three types of changeover complexities measured using information entropy are presented. As the negative impact of changeover complexity on the performance of a MMAL can be reduced by selecting a suitable model sequence, a bi-objective car sequencing problem taking it into account is proposed. The problem is aimed at finding a model sequence with the minimum number of violating sequencing rules as a primary criterion, and the minimum level of total changeover complexity as a secondary criterion. A lexicographic approach based on ant colony optimization (ACO) is applied to solve the problem. Computational experiments show that both objectives can be effectively addressed using the presented ACO algorithm.

1. Introduction

Mixed-model assembly lines (MMALs) are nowadays widely implemented in various industries (e.g., automotive, electronics, and furniture) to manufacture varying models of a common base product in intermixed product sequences. In a MMAL, setup times and cost can be considerably reduced by means of applying flexible workers and machinery [1], which makes mass customization feasible. Aimed at providing customized products at near mass production cost [2], the strategy of mass customization may however inevitably lead to a large product variety. For instance, the number of product variations offered by firms in the European automotive sector ranges from several hundred to almost astronomically high numbers [3]. Although it is generally agreed that mixed-model assembly systems are capable of coping with the complexity arising from product variety, the influence of product variety on assembly process cannot be completely eliminated.

The impact of product variety to assembly systems has drawn extensive attention from both industrial practitioners and academic researchers. For instance, MacDuffie et al. [4] investigated the effect of five product variety measures on productivity and quality using data collected from 57 automobile assembly plants worldwide. The study revealed that the impact of the five measures was generally much less than expected according to conventional understanding. However, parts complexity, an intermediate type of product variety, was found to have a persistent negative impact on productivity. Based on an empirical study using data from a General Motors assembly plant and simulation analyses, Fisher and Ittner [5] claimed that option variability (but not mean option content per car) increases overhead hours, rework, inventory, and the excess labor capacity for buffering against variability on a work station. There are some other studies reporting undesirable impact of product variety on the performance of MMALs (e.g., [6–8]). In fact, it is nearly impossible to remove the undesirable impact when the strategy of mass customization is employed. Besides, the assembly process in mixed-model assembly systems can become very complex as product variety grows [9,10], which could possibly result in substantial negative impact on the performance of MMALs.

Various measures of manufacturing complexity can be found in the literature [9,11]. They were developed to quantify the level of complexity in different settings such as machining, assembling, job shops and supply chain (e.g., [12–15]). Shannon's Information Theory/Entropy [16] has been one of the most widely used approaches to modeling and measuring manufacturing complexity. First devised by Shannon in 1948, this approach uses information entropy to measure the unpredictability or uncertainty of an event in a communication system. In general, the more the uncertainty, the higher the complexity. Recently, researchers attempted to mea-

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sure the manufacturing complexity related to MMALs with the aid of information entropy. Based on an information-theoretic entropy measure called "operator choice complexity", Zhu et al. [17] developed models of product variety induced manufacturing complexity in MMALs, resulting from operators' choice making processes of various assembly activities such as part choice and tool choice. The measure and models were later used by Zhu et al. [18] in determining the order of assembly tasks in MMALs with the objective of minimizing the system complexity. Additionally, Wang and Hu [19] extended the complexity measure to assembly systems with parallel and hybrid configurations, and studied the impact of complexity on performance of assembly systems with different configurations using a throughput model. It was shown that variety induced complexity influences the station reliability and in turn impacts the throughput of mixed-model assembly systems.

Busogi et al. [20] pointed out the potential impact of option similarity on an operator's performance. Hence, they proposed another information entropy based measure of complexity, which considers both option counts and option similarity. Zeltzer et al. [21] also presented an entropy-based complexity measure at the workstation level, which not only assesses the unpredictability of tasks assigned to a workstation during assembly but also incorporates the variability of each task duration at the station. The measure was used in workload balancing and manufacturing complexity levelling in MMALs. It should be noted that the model sequence in which cars are assembled on a MMAL directly impacts the work overload and manufacturing complexity at each workstation [21], however, none of the measures developed in the above research work relates manufacturing complexity with actual production sequences.

Sequencing MMALs determines the order in which a given number of product models are launched within a planning horizon, e.g., one day or one shift. Generally, there are three alternative sequencing approaches in the literature [1], i.e., mixed-model sequencing (e.g., [22,23]), car sequencing (e.g., [24,25]), and level scheduling (e.g., [26,27]). Each of them pursues one of the two basic goals of either minimizing work overload or leveling part usage, which is due to the fact that the model sequence determines the labor utilization and the material usage rates at various stations in a MMAL. However, neither of the objectives is concerned with the assembly complexity which however can be detected by operators. Consider an operator responsible for installing a specific part or parts at a workstation [5], which is commonly seen in automotive manufacturing. Parts typically come in several versions, e.g., different specifications or colors. He or she may experience some complexity during work as different parts/components and different installation procedures could be needed. Thus, with more variations of car models, options, and parts, the operator would require more time and mental effort to search and select the correct part, and install it on a car with a specified model-option combination requiring a particular assembly procedure. Based on a study at 36 stations from an operator perspective, Mattsson et al. [28] reported that among three areas, work variance generally contributes the most to perceived production complexity. Huang and Inman [29] also claimed that increasing the variety of model, option, and part/component in automotive assembly could possibly affect seven of the 17 Gilbreth's work elements. As a result, the chance of the operator making mistakes such as misuse of wrong part and incorrect installation becomes greater with higher product varieties. Therefore, it can be seen that product variety determined in product design is a major contributor to assembly complexity. On the other hand, the level (or the magnitude) of assembly complexity also relies on the frequency of sequence-dependent model changeovers. In general, more frequent changeovers of assembly tasks tend to incur more randomness or uncertainty in dynamic manufacturing and possibly more quality issues such as misbuilt parts. Apparently, there is no need for sequencing cars in a mass production environment with only one model assembled (e.g., the Ford T-model in the 1930s), as the complexity induced by product variety does not exist. Therefore, in order to mitigate the negative impact of product variety, we suggest minimizing assembly complexity be considered in sequencing MMALs.

Unlike level scheduling with the objective of leveling part usage, both mixed-model sequencing and car sequencing approaches consider work overload minimization as their objectives. Mixed-model sequencing needs to explicitly take lots of operational data such as assembly times, worker movements, and station borders on a MMAL into account. This significant effort of data collection, however, can be avoided with car sequencing, which attempts to evenly disperse work-intensive options in model sequences by following a set of pre-determined sequencing rules. In this implicit manner, work overload minimization can also be achieved. Car sequencing has been applied in some automotive manufacturers such as Renault [30] and Nissan. In this paper, we propose a special car sequencing (CS) problem for MMALs with consideration of assembly complexity incurred by product variety, which addresses two sequencing objectives in a lexicographic order. The primary objective is the same as the objective of the optimization version of the standard CS problem. Meanwhile, reducing the assembly complexity perceived by operators is treated as the secondary objective. It should be noted that the secondary objective can also be considered simultaneously when mixed-model sequencing or level scheduling is applied.

The remainder of this paper is organized as follows. In Section 2, the concept of changeover complexity as a presentation of assembly complexity is introduced, and its three components, namely, the changeover complexities associated with independent features, bundled features, and influential features, are described in detail respectively. In addition, information entropy based complexity measures are developed. Next, the special CS problem considering changeover complexity is proposed in Section 3. Section 4 presents a bi-objective ant colony optimization algorithm for solving the problem. In order to test the proposed algorithm, computational experiments are conducted, and results are displayed and analyzed in Section 5. Finally, Section 6 concludes the paper. For convenience of presentation, cars are used as the products to be sequenced on MMALs, as the concepts and models depicted in this paper can be easily applied to other products requiring mixed-model assembly.

2. Changeover complexity in mixed-model assembly

A product usually has many features. For example, engine, transmission, wheel, tire, seat, sunroof, and air conditioning are typical features associated with a car. Furthermore, a product feature normally has multiple alternatives or options. For example, different audio systems are installed on the Ford Focus. In this study, a term *changeover complexity* is used to represent the assembly complexity related to product features with multiple options, which can be perceived by operators during assembly, while any feature with only one option is not considered in measuring changeover complexity. Assuming that each feature has a dedicated station in a MMAL, parts/components required by different options associated with a product feature are attached to products when they flow through the station. An operator who undertakes assembly tasks of a certain feature can perceive more randomness or uncertainty when more options pertaining to this feature are provided. This is partially due to the fact that he or she has more choices with respect to parts/components, tools, and operation procedures during the assembly [17,29]. Those choices, which are mainly determined in the processes of product design and assembly line balancing, account for the static aspect of changeover complexity. On the other hand, the changeover frequency of options (i.e., the operator's