Product variety and manufacturing complexity in assembly systems and supply chains

S.J. Hu (2), X. Zhu, H. Wang, Y. Koren (1) The University of Michigan, Ann Arbor, MI 48109, USA

CIRP Annals – Manufacturing Technology 57 (1), 45-48, 2008.

ABSTRACT

Mixed-model assembly systems and modular supply chains are enablers to high product variety. However, as variety gets very high, the assembly and supply processes can become very complex. In assembly systems, the complexity may cause human errors and in turn impacts system performance. The complexity also impacts supply chain configuration and inventory control policy. This paper proposes a unified measure and models of complexity to assist in designing systems with robust performances. Complexity is defined as an entropy function of product variety and models are developed to describe the complexity propagation in multi-stage assembly systems and multi-echelon supply chains. Applications of the models are presented for complexity mitigation.

1. Introduction

Mass customization has been the mantra for today's manufacturing [1]. It promises individualized products at near mass production cost. As a result of such paradigm change, the number of product variety offered by manufacturers has increased drastically. For example, BMW claims that ‘‘Every vehicle that rolls off the belt is unique’’ and the number of possible automobile variations in the to handle such high variety while at the same time achieve mass production quality and productivity. Mixed-model assembly systems and modular supply chains have been recognized as major enablers to handle the increased variety.

Various industries are practicing mixed-model assembly systems since they bring various benefits. For example, a mixed-model auto assembly line as shown in Fig. 1 not only can save investment cost by sharing multiple products in the same line but also absorb demand fluctuation.

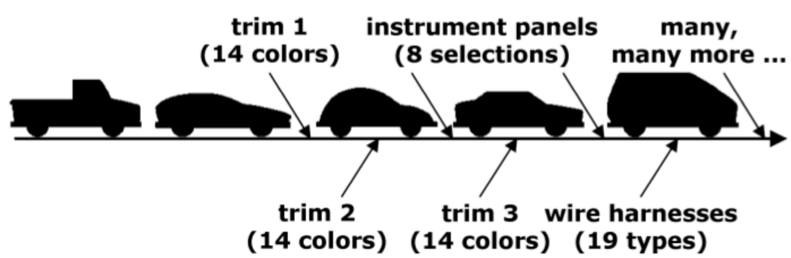

Fig. 1. Automobile mixed-model assembly line.

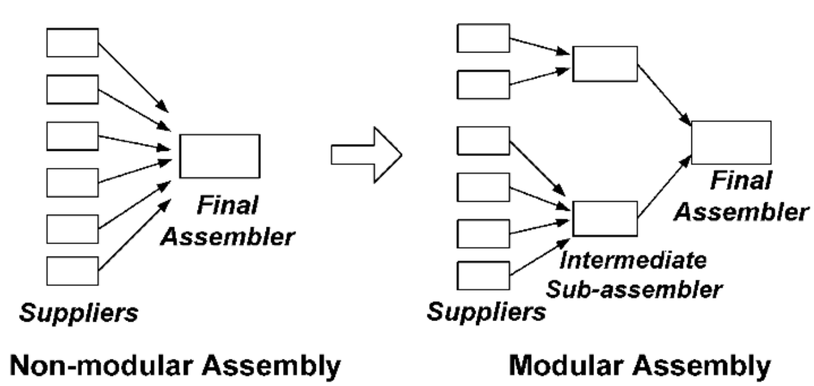

Fig. 2. Non-modular assembly to modular assembly supply chains.

The concepts of modular assembly supply chain and traditional non-modular ones are shown in Fig. 2. In the modular configuration, the final assembler apportions product modules to intermediate sub-assemblers instead of doing all the assembly work itself. As a result, only a few assembled modules will be delivered to the final assembler, which reduces the complexity of the final assembly process while shifting risk and responsibility to the sub- assemblers. Modular assembly has found applications in many industries, such as automotive and aerospace.

The high number of variety or build-combinations undoubtedly presents enormous difficulties in the design and operation of the assembly systems and supply chains. It has been shown by both empirical data and simulations [3,4] that increased product variety has significant negative impact on the performance (quality and productivity) in case of automotive vehicle production, including assembly and parts supply. One of the possible approaches to assess the impact of product variety on performance is to investigate how variety complicates the assembly process and supply chain operations. Some limited research has been done on assembly system and supply chain complexity. MacDuffie et al. [3] defined product mix complexity based on variety (product mix and its structure) and found significant negative correlation between complexity and manufacturing system performance through empirical study. Deshmukh et al. [5] defined an entropic complex- ity measure for part mix in job shop scheduling. Fujimoto et al. [6] introduced a complexity measure based on product structure using entropy for different stages of process planning. More recently, ElMaraghya et al. [7] applied entropy function to quantify the complexity of manufacturing systems and their configurations with examples in machining processes.

In supply chain, Frizelle and Woodcock [8] defined complexity as the variety and uncertainty associated with a system. Based on this definition, they classified the complexity of a supply chain system into structural complexity, which is associated with the variety embedded in the static system, and operational complexity, which is associated with the uncertainty of the dynamic system. Sivadasan et al. [9] developed an experimental methodology to study the operational complexity in a single supplier– customer system.

This paper proposes a unified measure of complexity by integrating both product variety and assembly process information, and then develops models for evaluating complexity in multi- stage mixed-model assembly systems and multi-echelon supply chains. The paper is organized as follows. In Section 2, we define complexity based on entropy and develop models for assembly systems and supply chains. In Section 3, system design methodologies based on the complexity models are discussed to enhance assembly system performance and determine optimal assembly supply chain configuration. Section 4 concludes the paper.

2. Definitions and models of complexity

In this session, we define a unified measure and develop models of complexity for assembly systems and supply chains based on product variety. We use an example to illustrate our modeling techniques.

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2.1. Mix and complexity

An example of a product family with its corresponding mixed-model assembly system and supply chain is illustrated in Fig. 3. The product has two components, A and B; each component has several variants (e.g., A_1 to A_3, and B_1 to B_2). The product structure can be represented by a product family architecture (PFA) diagram [10].

Fig. 3 illustrates all the possible variations of the customized products by combining the variants of each component. Here the maximal number of different end products is 6 (i.e., 3×2). Moreover, the product mix information is represented by a matrix $\mathbf{P}$, where p_{ij} is the demand (in %) of the jth variant of the ith feature. For instance, matrix $\mathbf{P}$ for the product in Fig. 3 is the following:

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & 0 \end{bmatrix}, \quad \text{where} \sum_j p_{ij} = 1, \ \forall i \tag{1}$$

In the mixed-model assembly process, one variant of every component is selected and assembled sequentially along the flow of the assembly line. For example, as depicted in Fig. 3, if A_1 is chosen for component A, and B_2 for B, the final product will be A_1B_2.

In the supply chain, two suppliers provide components A and B to the downstream assembler. Each element of the supply chain can provide a number of variants to the downstream assembler or customer. The final assembler provides six variants to the customers, A_1B_1, A_1B_2, A_2B_1, A_2B_2, A_3B_1, A_3B_2, which are the assembly combination from the variants provided by suppliers A and B.

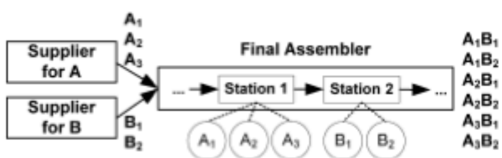

Fig. 3. An illustration of a mixed-model assembly line and supply chain.

Definition. Complexity is the average uncertainty in a random process i of handling product variety, which can be described by entropy function H_i in the following form:

$$H_i(p_{i1}, p_{i2}, \ldots, p_{iM_i}) = -C\sum_{j=1}^{M_i} p_{ij} \log p_{ij} \tag{2}$$

where p_{ij} is the occurrence probability of a state j in the random process $i, j \in \{1, 2, \ldots, M_i\}$, C is a constant depending on the base of the logarithm function chosen. If $\log_2$ is selected, $C = 1$ and the unit of complexity is *bit*.

2.2. Complexity in assembly system

Quite often, the mixed-model assembly process as shown in Fig. 3 is accomplished *manually*. Operators at every station must make correct choices among a number of alternatives according to customers' order. This process of selecting the right part is continued during the day. As variety increases, the operators face more uncertainty about making choices. This mechanism introduces complexity into the assembly task and in turn impacts assembly system performance. Therefore, complexity as defined in Eq. (2) characterizes operator's performance in making choices (thus *choice complexity*). Here p_{ij} in Eq. (2) refers to the probability of a choice taking the jth outcome in the ith choice.

2.2.1. Station level complexity

At a station, in addition to the part choice mentioned above, the operator may perform other additional assembly activities in a sequential manner. Some examples of these choices are fixture choice, tool choice, assembly procedure choice, etc. All these choices contribute to the *operator choice complexity*. At the station, we number the sequential assembly activities (such as part, fixture, tool, and procedure choices) from 1 to K, and write C_p in Eq. (3) as the total complexity of Station p.

$$C_p = \sum_{k=1}^{K} H_p^k, \quad k = 1, 2, \ldots, K \tag{3}$$

where H_p^k is the entropy computed from the variant mix ratio relevant to the kth activity at Station p.

As an example, in Fig. 3, we identify one assembly activity at Station 1, and two activities at Station 2. Specifically, we know from the process requirements that:

(1) At Station 1, one of the three components, A_1, A_2, or A_3, is chosen according to customer orders.
(2) At Station 2, one of the two components, B_1 or B_2, is chosen according to customer orders; also one of the three distinct tools is chosen according to the variant of component A installed at Station 1.

Therefore, the complexity values for the two stations are:

$$C_1 = H(P_{11}, P_{12}, P_{13}), \qquad C_2 = H(P_{21}, P_{22}) + H(P_{11}, P_{12}, P_{13})$$

2.2.2. System level complexity

Among the assembly activities, some activities are caused only by the feature variants at the current station, such as picking up a part, or making choices on tools for the selected part. The complexity associated with such assembly activity is defined as *feed complexity*. However, the choice of fixtures, tools, or assembly procedures at the current station may depend on the feature variant that has been added at an upstream station. This particular component of complexity is termed as *transfer complexity*. Hence, the total complexity at a station is simply the sum of the feed complexity at the station and the transfer complexity from all the

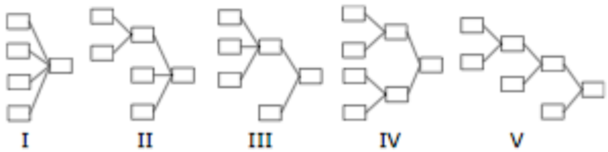

Fig. 6. Possible supply chain network with four original suppliers.

values in Fig. 5 is effective (because only the upstream task/station has influence on the downstream ones) for one particular assembly sequence, an optimization problem can be formulated to minimize the system complexity by finding an optimal assembly sequence while satisfying the precedence constraints. Please refer to Ref. [13] for details.

3.2. Optimal assembly supply chain configuration

Now we move from assembly system design to assembly supply chain design. As discussed in Section 1, modular assembly supply chain is a way to handle variety for mass customization at the enterprise level. The complexity model developed in Section 2 is a good means to studying supply chain complexity caused by product variety. It can be used to find the optimal assembly supply chain configuration. The procedure to find the optimal assembly supply chain can be divided into the following three main steps:

(1) Generate all possible supply chain configurations.
(2) Calculate complexity for each possible configuration.
(3) Compare the results and obtain the optimal supply chain configuration.

Among these steps, the first step is the most challenging. For example, given four original suppliers, there are five possible supply chain network configurations, shown in Fig. 6. For each of these possible networks, there are many possible supply chain configurations because the locations of each original supplier can be different from one configuration to another. For example, the network IV has three different possible supply chain configurations, as seen in Fig. 7.

The method of Webbink and Hu [14] for assembly system configuration can be modified for generating supply chain configurations. Wang et al. [12] developed a modified algorithm to generate all possible assembly supply chain configurations. After all the possible configurations are generated, the complexity of each configuration can be calculated by Eq. (7) and then the optimal configuration can be found by picking up the configuration with the smallest complexity value.

Based on the above algorithm, it can be shown that as the product variety increases, the optimal assembly supply chain configuration moves from non-modular assembly to modular assembly.

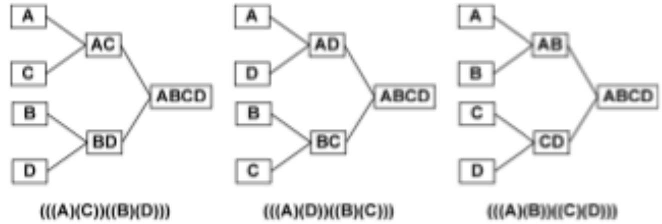

Fig. 7. Possible supply chain configurations for network IV.

4. Conclusions

This paper introduces a unified measure of product variety-induced manufacturing complexity for assembly systems and supply chains. Models are developed to characterize the propagation of complexity in multi-stage mixed-model assembly systems and multi-echelon assembly supply chains. Relationship is established between assembly system complexity and supply chain complexity. These models of complexity can be used to configure assembly systems and supply chains to ensure robust performance by mitigating complexity.

Acknowledgment

The authors gratefully acknowledge the financial support from the Engineering Research Center for Reconfigurable Manufacturing Systems of the National Science Foundation under Award No. EEC-9529125, and the General Motors Collaborative Research Laboratory in Advanced Vehicle Manufacturing, both at The University of Michigan.

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