Probabilistic Approach To Modular Assembly

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Abstract: Modular assembly is a common practice in many industries. The main motivation is to reduce assembly costs, improve reliability, reduce assembly time, and improve logistics and inventory management. The paper presents a methodology for assembly modularization that considers the probability for success of each assembly operation, as well as it cost. It shows that for any given assembly sequence, the expected cost is reduced when the assembly operations are divided evenly among the subassemblies. It also shows that when the process constraints require more operations in the initial subassemblies, it is recommended to sequence the operations in descending order.

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1. INTRODUCTION

The assembly process consists of a series of tasks in which components are connected together according to their functional relationships with other components. Large assembly processes are usually performed over several workstations that are connected by rigid or flexible transportation networks. Traditionally each station performs one or several assembly operations according to the process’ configuration and the resources requirements for these operations. In some cases, parts of the assembly operations are outsourced due to operational and economic considerations. The allocation of the components to the assembly stations is done according to the product structure that defines the relationships between the components, the sub-assemblies, and the parts. These relationships are often represented by a liaison graph that consists of nodes (representing the components) and edges (representing the relationships between these components).

Design For Assembly (DFA), originally proposed by Boothroyd (1982), is a methodology that aims at reducing costs and improving the expected success of the assembly process. Many models, technologies, and methodologies are based on DFA (e.g. Yoosufani et al., 1983; Corbett and Crookall, 1986), particularly in complex assembly systems. The complexity of the assembly can be expressed by explicit and unambiguous quantitative measures (e.g. the number of components and assembly operations) and/or by qualitative measures (e.g. the difficulty of the assembly operations, the expected completion time). Hinckley (1993) introduced the term assembly complexity index and states that “complexity is the least understood source of defects in the assembly process because of the difficulty of defining the relative measures of complexity.” Hinckley also proposed formulating the assembly complexity of the entire process by the probability that the assembly process is successful according to

\[ P_Y = \prod_{i=1}^{n} (C_k (t_i - t_0)^k) (1 - d_i), \]  

where \( P_Y \) – the probability that the entire assembly process is successful \( C_k \) – the level of quality control of the assembly operations \( (C_k > 0) \) \( t_i \) – the expected assembly time of assembly operation \( i \) \( t_0 \) – the expected assembly time of the basic assembly operation \( k \) – the sensitivity of assembly complexity to defects (k>1) \( n \) – the number of assembly operations \( d_i \) – the probability that the \( i^{th} \) operation is defect 0 ≤ \( d_i \) ≤ 1

Where the assembly process in already in operation, the expected times of the assembly operations in (1) can be measured directly; or the times can be estimated using one of the DFA methodologies or simulations at the process design stage. The probability for success of the entire assembly process, as given by (1), is a useful and objective measure for comparing various design alternatives.

In this paper, we extend the definition of the term assembly complexity by examining the effect of a failure in one assembly operation may have on previous operations. We further extend the definition of assembly complexity by formulating a probabilistic function for each assembly operation that determines the effect of a failure in one assembly operation may have (in a probabilistic sense) on previous operations. For example, a failure of an operation in a simple assembly process may require re-work of that operation alone. However, a failure of an operation in a complex assembly process may require repetition of several assembly operations that have already been completed, or even scraping the entire semi-finished assembly and starting from the first operation. This problem was originally introduced by Simon (1962) in his paper on the architecture of complexity.
Simon describes two watchmakers who design their own watches. Both watches consist of 1000 components. The first watchmaker aims to assemble the 1000 component in a single long process. However, each time the watchmaker is disturbed, the entire assembly process is repeated from the beginning. Assuming the cost of each assembly operation is \( C \) and the probability for successful completion of each assembly task without disruption is \( P \), the expected assembly cost of the entire process is given by

\[
\hat{C}_n = \sum_{i=1}^{n} \frac{C}{p_i} = \frac{C}{1-P} (\frac{1}{p_n} - 1).
\]  

The second watchmaker divides the same 1000 components into 100 subassemblies such that an interruption requires the repetition of the current subassembly alone. These subassemblies are assembled again in groups of 10 such that the total number of assembly operations is 1,110. However, the expected cost of assembling the watch by the second watchmaker is far less. For example, assuming a probability of 0.01 for disruption of each assembly operation and a homogeneous cost for all operations, the first watchmaker needs 20,000 more attempts to successfully complete the entire process, and the expected cost is 4,000 times higher.

The effect of a failure of a single assembly operation is determined by the *mutual dependencies* between the operations, and the severity of a failure is given by the *complexity index* - \( k \). Figure 1 illustrates this concept as a state diagram in which the assembly operations are the states and the edges between the states represent the transitions between the states given by the probabilistic effects of failure or success. In the example shown in the figure, the process consists of 4 assembly operations and a final state (5) that represents a successful completion of the entire process. Each operation has a probability for success given by the probabilistic transition to the succeeding operation. However, an operation may also have a probability for failure that requires re-work of that operation only, or re-work of previously completed operations. Defining \( p_{i,j} \) as the probability to move from assembly operation \( i \) to assembly operation \( j \), then \( p_{i,i+1} \) is the probability for a success completion of task \( i \) (and therefore continuing to the next operation \( i+1 \)). \( p_{i,j} \) defines the probability of failure in operation \( i \) that requires repeating only that operation, and \( p_{i,j} \forall j<i \) is the probability for a failure in operation \( i \) that requires re-work from operation \( j \). The *complexity index* of a failure in operation \( i \) is therefore given by \( k_i = t - j \). In practice, \( k_i \) represents the number of operations that need to be repeated in the case of a failure in task \( i \). Notice that a task may have several complexity indices (e.g. task 4) as there may be different types of failures, each with a different probability for repeating previous tasks. According to this definition, the complexity of a given assembly sequence \( P_k \) is given by \( O(P_k) = \sum_{i=1}^{n} k_i (max) \) where \( k_i (max) \) is the largest complexity index of task \( i \). In a *fully complex system* a failure at each operation requires repeating the entire process from the first operation such that \( k_i (max) = i \). In a *zero complex system*, a failure in a specific operation requires repeating the failed operation alone, and \( k_i (max) = 0 \forall i \).

In our previous work (Efatmaneshnik and Ryan, 2016) we presented a formulation for the construction of complex homogeneous systems by dividing the process into modules where each operation has an identical cost and probability for success. In Shoval et al. (2016(a)) we analysed the sequence of simple and complex heterogeneous assembly processes where costs and probabilities for success are different for each assembly operation. We used the Traveling Salesperson Problem (TSP) solver to determine the optimal assembly sequence of simple processes in which the probabilities for success are different for each assembly operation but costs are homogeneous, or when the probabilities are homogeneous and costs are different. For complex processes, where both costs and probabilities are different we showed that performing more complex operations (that have higher probability for failure or higher costs compared with other operations) at the beginning of the process decreases the expected assembly cost. We also showed that when the probabilities for success of the assembly operations are relatively close to each other, the more expensive operations should be deployed to later in the process (subject to the operational constraints).

In this paper we propose to use modularity in the assembly process in order to reduce the expected cost and increase the probability for success, given heterogeneous probabilities for success and costs of the assembly operations. Figure 2 illustrates this idea. In this figure there are 7 assembly operations (and a final state – 8 that represents the successful completion of the entire assembly process), each with a specific cost \( C_l \) and a probability for success \( P_l \). Given the heterogeneous probabilities and costs, and the mutual dependencies between all tasks, we analyse the effect of dividing the assembly process to subassemblies by adding three operations as shown in Fig. 2(b) that we call assembly break points. The goal of these additional operations is to interrupt the mutual dependencies in case of failures such that a failure of a specific assembly task affects previous operations only to the last break points. These break points can take place as operational buffers (e.g. mechanical couplers, electronic diodes), assembly stabilizers (e.g. additional fixtures and connectors), or as modules and subassemblies that can be executed independently from other assembly operations. According to this structure, all operations between two break points construct a cluster (module), and any pair of clusters is connected at a break point. Each break point is defined by two values - \( c_{BP} \) and \( p_{BP} \), representing the cost and probability of assembling the two clusters. It should be noted that the cost of assembling two modules is usually different from assembling two components, as it must consider the connections of all
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