Process Selection Using Variation and Cost Relations

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Process Selection using Variation and Cost Relations

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Abstract. Variations are inherent in all manufacturing processes and can significantly affect the quality of a final assembly, particularly in multistage assembly systems. Existing research in variation management has primarily focused on incorporating GD&T factors into variation propagation models in order to predict product quality and allocate tolerances. However, process induced variation, which has a key influence on process planning, has not been fully studied. Furthermore, the link between variation and cost has not been well established, in particular the effect that assembly process selection has on the final quality and cost of a product. To overcome these barriers, this paper proposes a novel method utilizing process capabilities to establish the relationship between variation and cost. The methodology is discussed using a real industrial case study. The benefits include determining the optimum configuration of an assembly system and facilitating rapid introduction of novel assembly techniques to achieve a competitive edge.

Keywords. Variation management, process selection, cost estimation.

1. Introduction

Product assembly is one of the most expensive areas of manufacture, and has been estimated to account for one third of the overall manufacturing cost [1]. As a result, industry is increasingly looking towards optimizing assembly systems to maximise the value of their products. One area in particular, assembly process selection, has a direct influence on both the cost and the quality of a final product. This is especially true in multistage assembly systems, common in the aerospace and automotive sectors. In multistage assemblies, undesired variations induced by assembly processes can propagate between stations. To select the best assembly techniques for a product requires an understanding of the link between variation and cost for each process, and the assembly system as a whole. This requires modelling of how variations are induced and propagated between stages are associated to the cost of achieving the quality level required. However, the relationship between variation and the final assembly cost is potentially non-linear and has not been well established by existing research. Therefore, determining the optimal multistage assembly configuration and rapidly introducing novel assembly techniques presents a significant challenge. To address this problem, a

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novel method of process selection by establishing the link between quality and cost is presented in the herein paper.

2. Literature Review

Early research in the area of variation management was carried out by the U.S. automotive industry, and was aimed at managing variation in multistage automotive body assembly systems. The theory of Stream of Variation (SoV) was subsequently proposed by Hu & Koren [2], which provided an effective methodology to predict and diagnose variation. Huang *et al.* [3] furthered SoV theory by integrating it with state space modelling, and utilizing it for diagnosis of multi-station manufacturing systems. Another important step in the development of the theory was accurately modelling process errors. Djurdjanovic & Ni [4] incorporated the dimensional errors of fixtures, locating and measurement datum features during machining operations into the SoV model. The ability of the SoV using state space modelling to accurately model the complex variation sources inherent in multistage systems has ensured that it has remained an active research area. Recent research however, has focused on incorporating geometric dimensioning and tolerancing (GD&T) factors into the model. For example, Kong *et al.* [5] developed a variation model to analyse size, bonus and floating tolerances, and Loose *et al.* [6] integrated GD&T for multistage machining processes. Tolerancing research also introduced the concept of process-oriented tolerancing into the SoV [7]. However, the link between variation and process selection has not been explored fully using the SoV theory. Specifically, the ability for the SoV to assist assembly system configuration requires further research.

Although the variation model for multistage assembly systems has been considered extensively, there has been significantly less research linking variation to cost. Research has instead focused on tolerance optimization against cost, with Etienne *et al.* [8] optimizing functional tolerances using a genetic algorithm and Zong & Mao [9] considering quality loss against manufacturing cost to allocate tolerances. However, optimizing tolerance allocation against cost can be developed further to optimize process selection against cost. Mirdamadi *et al.* [10] used an Activity-Based Costing model for cost estimation for variation management, moving towards this aim. Nevertheless, there is a significant gap in research for defining and arranging an entire assembly system to best compromise between quality and cost.

3. Methodology

The overall aim of the methodology is to determine the most cost effective system of processes to ensure all Key Product Characteristics (KPCs) of an assembly are kept within predetermined specifications. KPCs are defined as assembly features that affect the quality of the product, such as its performance, reliability, manufacturability, fit or assembly. The proposed methodology consists of three main steps. Firstly, the assembly system to be evaluated is defined, KPCs are identified and linked to Key Control Characteristics (KCCs). The effect of processes on the KCCs are then modelled using the SoV method, to assess the capability of the assembly to deliver the desired assembly quality. Finally, a time or cost model, related to each process, is derived for the assembly and assessed. The three steps of the methodology can then be iterated to improve the overall assembly system and individual processes. Alternatively, two or more assembly systems can be compared using the methodology to determine which solution is more suitable for a given product. Figure 1 illustrates the proposed methodology using a flowchart, with the three main steps divided into more specific sub steps.

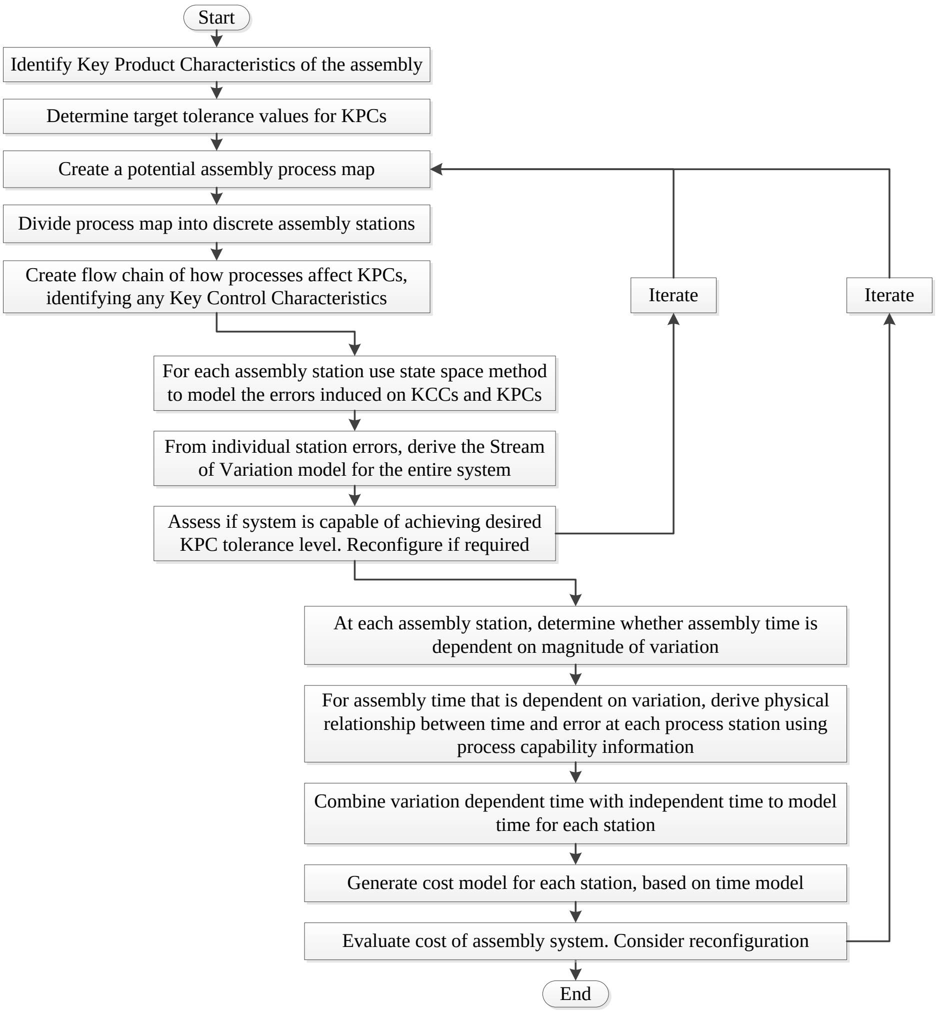

Figure 1. Methodology Flowchart.

The first step is to identify the KPCs of the manufacturing and assembly process. These are the features of the assembly that must have limited variation in order to ensure satisfactory performance of the product. Once identified, the allowable GD&T specification must be defined for each KPC feature to ensure the desired quality level. This tolerance value will subsequently be used to assess the capability of all proposed assembly systems. Potential assembly system can now be generated. The assembly process map must be detailed enough to divide into all the individual stages that make up the system. This is to ensure accurate and representative SoV and cost models can be created later in the analysis. It is important to consider that each stage of the assembly process can be classified into one of three categories; those that induce variation, those that manage variation and those that have no effect on variation. At this point it is useful to create a flow chain to map how each processes affects the variation level at the KPCs. It is likely that the variation of additional features must also be controlled as they have a direct effect on KPCs. These are named KCCs [11]. It is critical that all errors induced that have a direct or indirect influence on the variation at the KPCs are identified, and later included in the SoV model.

Having determined a number of KPCs which must be held within tolerance, and generating a potential assembly system for consideration, the next stage of process is to evaluate the ability of the assembly system to achieve the target quality specification. This is done by modelling using the state space method and SoV theory. Firstly, for each assembly station the errors induced on KCCs and KPCs must be modelled. This includes errors introduced at that stage, errors carried over from the previous stages and errors propagated onwards to later stages. These errors are all to be mathematically captured into a state space model. This is completed for all stations in the multistage assembly system. The series of state space equations generated can then be chained together to form the SoV model for the entire system. The stream of variation model ensures that processes are not considered in isolation, and quantifies all upstream and downstream effects on the system. The ability of the proposed assembly system to achieve the desired tolerance at each KPC can now be assessed. If the system is not capable it can be reconfigured with processes that induce less variation. Alternatively, additional processes to manage variation and bring them back to within specified limits can be used, such as shimming. Once an assembly system has been confirmed as being capable of achieving the required quality, the cost implications can then be addressed.

The final stage of the methodology is the development of the time model, and subsequently the cost model. Assembly time can be either dependent or independent of the magnitude of variation at each station. To generate an accurate time model, the relationship between variation dependent time and the error level at each station must be derived. This should be done using process capability information, to a detailed level. Information that should be captured includes the number of passes of a machine required to complete an operation for a given level of error. The dependent time can then be added to the independent time, which does not change regardless of the amount of error at that station to produce the total time for each station. Once the time model is established at each station, it can be expanded to generate the cost model. This is done by relating, for example, labour costs and overheads to the variation dependent times, and including any amortised capital costs of required machinery. In a similar way to the SoV model, the stream of costs can be combined together to estimate the total cost required to output each KPC at the desired quality level. At this point the assembly system can once again be evaluated and reconfigured if required. Alternatively, comparable studies between alternative assembly processes can be completed to allow decision making between a number of different assembly arrangements. The methodology can also be used to assess both the quality and cost implications of new assembly processes and techniques.

4. Industrial Case Study

In order to test the proposed methodology, a typical real world aerospace problem was selected. This problem consisted of an aircraft spar and hinge bracket assembly. The KPCs were identified and are highlighted in Figure 2. A target tolerance was assigned to each KPC, and the assembly process was divided into discrete process stations. It was found from industrial experience that there is a large variation from the manufacturing process which exceeds the allowable tolerance of the KPCs. Errors accumulated from previous manufacturing and assembly stages, which can be predicted and sources diagnosed using the SoV model, results in the necessity of a variation management stage that requires excess variation to be removed. In order to eliminate this problem, variation management processes were considered to bring variation down to acceptable levels.

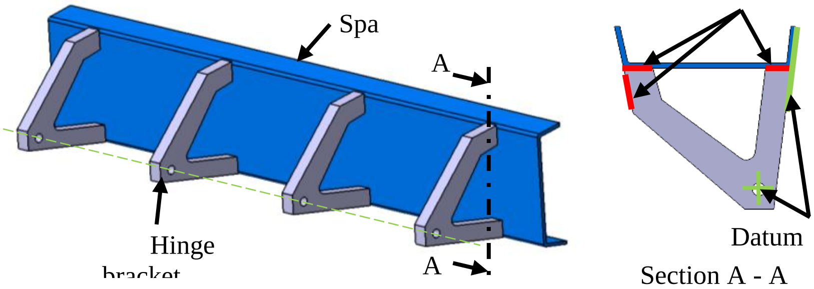

Figure 2. Typical aerospace spar and hinge bracket assembly, showing isometric and side views.

The first process considered was shimming. Due to variations between the spar and the hinge bracket, shims are used to fill any gap between the hinge bracket and the spar. This shimming process was found to be sufficiently capable of reducing the variation at the KPCs to within the allowable tolerance defined. Therefore, the time and cost implications of shimming were considered next. A nonlinear relationship was found between variation and time of assembly. The main reason for this is the distinct changes in shimming material used depending on the level of variation, and thus the size of gap to be shimmed. For example, for very small gap liquid shimming is sufficient and is a quick process. However, for larger variations peelable polymers are required. These shims often have to be modified and adjusted, and therefore take considerably longer to install. To physically model the difference between these two types of shimming process, MOST activity modelling [12] can be utilised. This process satisfies the quality requirements of the assembly, and the manual nature of the process however means that the majority of the cost comes from labour costs alone. However, it was found through analysis to be a very time consuming manual process. As a result, it is beneficial to consider a second variation management process to evaluate against shimming.

One alternative process for consideration is an adaptive fettling [13]. For this process to be used, all hinge brackets must be manufactured oversized, and then accurately milled down to match the variations on the CFRP spar. This process therefore has very different characteristics compared to shimming, however it was found to also be capable of removing the level of error required to bring the KPCs within tolerance values. The time analysis can then be conducted, and it is found that a very different nonlinear relationship is present between variation and time for this process. The level of variation influences the process time in two ways. Firstly, there are distinct stepped increases in time at certain threshold values of variation. This is due to the milling machine requiring more than one pass to remove the material required to bring the KPC within tolerance. Secondly, the amount of material to be removed by each milling pass, and therefore the time taken to do each pass, can be modelled as mathematical equation between variation and time, as is presented by Groover [14]. It was found that for all error values, the fettling process is a more rapid method of removing variation but with additional capital costs. The time model can then be expanded to include cost. Once the large capital expenditure of the milling machine is considered, an informed decision can be taken to determine which assembly system is the most economically viable solution.

5. Conclusions

A methodology to facilitate process selection by relating variation and cost is proposed. This consists of a SoV model to model process induced variations during the assembly process, and a cost model which utilises process capability to mathematically relate error level to time, and subsequently cost. By using the suggested methodology, the assembly system can be configured to achieve a desired quality level at the lowest cost and assembly time. The proposal provides a method to compare and select the most suitable processes. The proposed method was illustrated using a real world industrial example.

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