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Process chain modeling and selection in an additive manufacturing context

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ABSTRACT

This paper introduces a new two-dimensional approach to modeling manufacturing process chains. This approach is used to consider the role of additive manufacturing technologies in process chains for a part with micro scale features and no internal geometry. It is shown that additive manufacturing can compete with traditional process chains for small production runs. Combining both types of technology added cost but no benefit in this case. The new process chain model can be used to explain the results and support process selection, but process chain prototyping is still important for rapidly evolving fields like additive manufacturing.

Introduction

The benefits of additive manufacturing (direct generation of tool paths, geometric freedom, multi-material parts, functionally graded materials, etc.) [1,2] combined with their historical limitations (geometric precision, surface quality, material availability, material properties, etc.) led to an early industrial focus on applications that required small numbers of complex parts that were either not possible or not cost effective to produce using conventional means. However, as both additive and traditional manufacturing technologies evolve, it is becoming more difficult to choose whether to use AM or a traditional process, and to choose which AM technology to use [3]. It is also becoming more beneficial, and therefore necessary, to choose if and how to combine additive manufacturing and traditional process technologies in a given context and process chain.

Proper selection and optimization of process chains is important for product quality, process performance, and production efficiency [4–6]. However, it is a difficult task that requires “material, shape and process” to be “considered simultaneously” [7]. Process planning is sometimes considered to be a problem of requirements and information gathering [5,8,9], knowledge and information management [5,10–13], or decision making [3]. However, these perspectives are based on an assumption that all required information can be obtained. Process capabilities and costs are often local and constantly changing. In addition, the demands on those capabilities are constantly increasing. For example, the ongoing trend toward miniaturization and thus micro/nano manufacturing pushes “all technologies to [their] limits” [14]. Similarly, the increasing “focus on precision manufacturing” places ever-growing demands on “replication precision and quality” [15]. Therefore, the suitability of any process technology for a new product in a rapidly growing field may be impossible to know a priori. This can leave designers and manufacturing engineers with no choice but to treat process planning like a traditional design problem where multiple concepts must be generated, promising candidates identified, and prototypes produced to gather sufficient information to make a decision (e.g. [16]).

In addition, the rate at which technology and consumer choice is evolving requires production systems to be more flexible and responsive than ever. Thus, it can be valuable to consider different stages of a product’s life (introduction and initial ramp up, mass production, end of life, etc.) as well as future product variations during process planning, especially when the initial demand or market growth is difficult to predict. In this case, the goal may not be to select one process chain but to select an appropriate process chain for each stage of a product’s marketable life.

This paper introduces a new approach to modeling manufacturing process chains to support process selection, concurrent engineering, and design for manufacturing in the early phases of conceptual and detailed design. This approach is used to consider the role of additive manufacturing technologies in process chains for the small-scale production of a redesigned part with micro scale features and no internal geometry.

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Conceptual modeling of manufacturing process chains

In the literature, process chains are often shown as simple linear sequences (e.g. [17–21]). However, all manufacturing processes are defined by the interaction of various artifacts. The main artifact (the product) is designed and therefore sets the requirements for production. Standardized artifacts, such as manufacturing equipment, impose constraints on the manufacturing process and affect the quality of the final product. Custom supporting artifacts (specialized tools, jigs, fixtures, patterns, etc.) may also need to be designed and produced. These supporting artifacts are subject to the requirements of the product and the constraints of the standard artifacts in the system. They add new requirements and constraints to the overall process chain. They add cost and increase the lead time for the project. And, they have the potential to introduce or reduce errors in the production and therefore affect the quality of the product.

A two-dimensional process chain model

In order to compare process chains, it must be clear how many artifacts will be designed, how each artifact will be produced, and how each artifact affects and is affected by the others. To visualize these artifacts and their interactions, we propose a two-dimensional (2D) process chain model. In this model, each artifact to be produced occupies one horizontal row. The process chain to produce that artifact is written as a standard block diagram within the row. The inputs to each block are either raw materials or existing workpieces and the outputs are either new workpieces or the final artifact for that row. A vertical arrow indicates the entry of one artifact into another's process chain. The convergence of multiple artifacts can also be indicated using standard logic operators such as those described in [22]. The logic operator is the preferred representation because it emphasizes the fact that constraints imposed by the upstream artifacts may produce emergent requirements that affect the downstream processes.

Fig. 1 shows a 2D process chain for a system with two artifacts. The first is a tool that is produced with a series of three processes. The second is a product that is produced with a single process using the tool. Fig. 2 shows a 2D process chain for a system with three artifacts: a tool, a fixture, and a product, each produced with a single process. Fig. 3 shows an alternate version of the process chain in Fig. 2 using a logic operator.

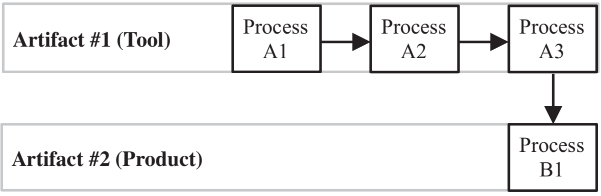

Fig. 1. Example process chain for a product produced with one process using one tool that was produced with three sequential processes.

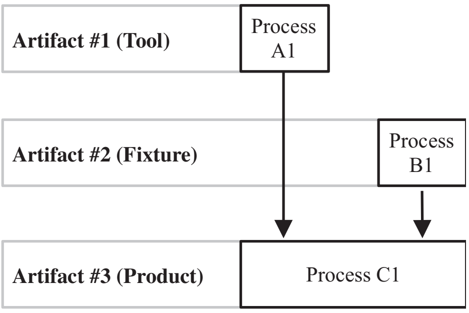

Fig. 2. Example process chain for a product produced with one process using one tool and one fixture that were each produced with one process.

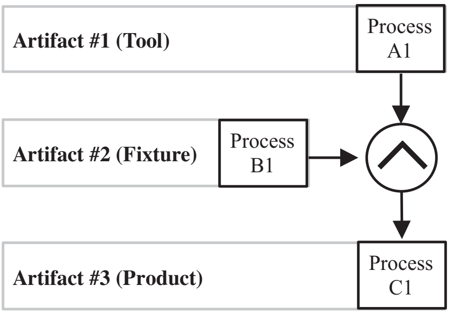

Fig. 3. Alternate representation of process chain shown in Fig. 2 using a logic operator.

Degree of detail needed in a 2D process chain model

The degree of detail needed in each process chain depends on the context and on the needs of the designer or manufacturing engineer. To support process selection, it is important to include all processes and sub-processes that can substantially impact production time, quality, and cost. For example, pre- and postprocessing steps (raw material/workpiece preparation, cleaning, sprue removal for injection molding, support removal for additive manufacturing, etc.) should be included.

To improve clarity and usability, similar processes should be grouped when possible. For example, it would be better to include one block per CNC program in a machining-based process chain, rather than one block per tool or tool path. This will also help to differentiate between machine time/cost and operator time/cost.

Finally, to ensure a fair basis for comparison, the processes that are included or excluded from the process chain model should be the same across all process chain options. For example, if tool path generation and machine set up is included in a machining-based process chain, these must also be included in the corresponding process chain for additive manufacturing.

As with all design tools, two-dimensional process chains should be constructed with as much detail as necessary, but no more.

Evaluating 2D process chain models

The structure of the 2D process chain model is intended to help designers to qualitatively compare production concepts. For example, all processes and handling operations increase the time and cost of production. All other things being equal, a longer process chain will have a higher cost and a longer production time than a shorter process chain. Similarly, a process chain with less automation will usually have a higher cost, longer production time, and more variability than a process chain with more automation.

Every process in a process chain adds value but can also introduce errors into production. Similarly, handling a part between processes can damage it. Thus, the overall risk to an artifact and the cost of scrap increases with the length of a process chain. All other things being equal, a longer process chain will have a higher risk and a higher cost of scrap than a shorter process chain.

Added value and risk are not necessarily evenly distributed along a process chain. Process chains with the riskiest operation(s) earlier in the process chain will have a lower cost of scrap and should be preferred to those that have the riskiest operations last. Similarly, finishing operations that create precision surfaces and features should be late in the process chain where they can reduce or eliminate earlier errors and will be at a lower risk for future damage.