Axiomatic Design for Understanding Manufacturing Engineering as a Science

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Abstract

The objective of this work is to advance the understanding of manufacturing engineering as a scientific discipline in the context of axiomatic design. Scientific disciplines have a few, simple self consistent rules that can be applied to a wide range of problems. Manufacturing engineering includes a wide range of processes and systems without a clear unifying foundation. Two top FRs for the design of any manufacturing process or system are proposed: maximize value added, then minimize costs. The similarities with value engineering are acknowledged. The application of maximize and minimize FRs are discussed in process, business, and societal contexts.

Keywords:
Axiomatic Design, Manufacturing Engineering, Manufacturing Science

1 INTRODUCTION

The objective of this work is to discuss the development of manufacturing design as a scientific discipline through the application of axiomatic design. Scientific disciplines are distinguished by a few simple laws or rules that can be applied to solve a wide variety of problems that define that discipline. Manufacturing is, of course, a technological discipline. It relies on scientific findings and the scientific method. Nonetheless manufacturing is lacking a common, simple technological foundation, composed of a few, simple, recognized laws, which would make it a true scientific discipline. This discussion is aimed primarily at the design of manufacturing processes. The discussion could be extended to the design of manufacturing systems as well.

The establishment of manufacturing as a scientific discipline with rules that are common to all manufacturing processes would be important. Such a scientific discipline would be easier to understand, learn, teach, and apply to solving manufacturing problems [1].

Text books on manufacturing processes tend to be like encyclopedias e.g., [2-3]. The text books contain sequential descriptions of individual manufacturing processes, arranged by some kind of taxonomy, which is usually based on what is being done to the material, e.g., remove, add, deform, etc.. The text books include different approaches to solving problems related to the processes. However, there is usually no attempt to connect the approaches used to solve the different kinds of problems. There appear to be no laws that are common to the process descriptions.

The application of lean principles [4-5] to manufacturing systems promotes an approach to the design of manufacturing systems based on value stream mapping and cost reduction that has been effective in improving the return on manufacturing operations. Lean, which was based on the Toyota production system (TPS), has been applied to many production and product systems (e.g., [6]), regardless of how similar their situation might be to Toyota's. Lean is largely constrained to system level design.

Suh [7] (p. 318) discusses a generalized design for flexible manufacturing systems, stating that the top FR is to maximize return on investment (ROI). Two DPs are proposed: (a) a system to produce components at a minimum cost, and (b) a system to provide a high-quality product that meets customer needs. Solution (a) works well when there is unlimited demand, as for Ford's early cars. Solution (b) applies when there is an overcapacity of production facilities; therefore it is the desirability of the product that determines success. This approach explicitly recognizes different environments for manufacturing. It also recognizes a high level general objective: ROI. Suh's decomposition leads to many of the same principles common to Lean manufacturing. Suh's discussion is limited to the system level of manufacturing.

The effective application of axiomatic design to multi-functional design problems depends on a good decomposition. Generalized decompositions, as Suh proposes in the section of his book [7] on the design of flexible manufacturing systems, can be useful for advancing design solutions. The approach here is to look for a universal decomposition which would be sufficiently generalized that it would be appropriate for solving any level of manufacturing design problems. This generalized decomposition should be able to transcend system and process design. Lean should be one solution, when it is appropriate. The solution should be applicable throughout a continuum from detailed manufacturing process design to abstractions of manufacturing systems, because both processes and systems must be part of manufacturing science. The decomposition should be capable of encompassing all of the manufacturing discipline which must include processes as diverse as machining and weaving. The functional requirements in such a universally useful decomposition could also be considered laws or axioms for manufacturing science.

2 METHODS

The method discussed here for the development of manufacturing axioms is to identify commonalities and generalize. Manufacturing can be defined as the process of transforming resources to produce a product that meets human needs. Human needs equates to value. To be effective, manufacturing must also provide a return on investment. The commonalities should relate to value and return. The development should include extending these principles to the details of the process level.

2.1 Process perspective

The most interesting problems in text books on manufacturing processes address force calculations and material behavior. The approaches to solving these problems do have some common roots, such as, force balance, analytical geometry and mechanics of materials. These solutions are certainly useful for the design of machines and tools that can transmit the loads necessary to perform the processes.

Usually in text books on manufacturing processes there is no recognition of the commonalities in the approaches to the solutions of manufacturing process problems. More importantly there is no discussion of the larger context in which problems in process design should be solved. Engineers working on process design problems are machine builders. Fulfilling the need to solve these kinds of problems was a part of the motivation for the development of mechanical engineering which traces its origins to the industrial revolution. The industrial revolution largely starts in Germany, where the term for mechanical engineer is *Maschinenbauingenieur*, literally translated: machine building engineer.

Mechanical engineers, it could be argued, were the first manufacturing engineers. The collection of subjects that currently comprises mechanical engineering, including thermodynamics, heat transfer, fluid mechanics, stress analysis and mechanics, are what an engineer would need in a factory in the first decades of the industrial revolution. The engineer focused on solving detailed technical problems associated with supplying power and making reliable machinery. Taylor is well known for developing the methods to study efficiency at the beginning of the twentieth century and developing Industrial Engineering [8-9]. Technical and efficiency problems continue to be issues that need to be addressed.

Early in the industrial revolution some products were in such demand that all cars could be black. The human need was keen and market competition not so fierce. Black cars had enough value that product differentiation was not necessary for success. In such a business climate certain metrics can develop, such machine tool usage, which are not applicable in other business climates. These kinds of metrics are not sufficiently universal to be the basis of manufacturing axioms.

2.2 Recognizing useful commonalities

Consider the nature of scientific laws. The science of mechanics is governed by Newton’s laws. These describe the relationship between forces, masses and motion. Newton’s laws cannot be proven. Examples of consistency with the laws do not constitute a proof. The laws are recognized because no one has seen a violation of them, at lease within an accepted field of applicability. Newton’s laws are obeyed by mechanical systems. They apply to planets and to objects on earth. Therefore, there is no evaluation of goodness of mechanical systems based on how well they obey Newton’s laws. All Mechanical Systems obey Newton’s laws perfectly. The same thing cannot be said about manufacturing. Manufacturing relies on people who make choices. Manufacturing is not constrained by unbreakable laws as is mechanics.

Because a spectrum of manufacturing from good to bad exists, manufacturing laws would need to be different than Newton’s laws. Manufacturing laws would be closer to the axioms that Suh [10] has proposed for design. A spectrum of good to bad designs can and does exist. Suh states that good designs conform to two axioms, maximize the independence of the functional elements and minimize the information content.

Suh’s Axiomatic Design [10], in addition to defining the best design axiomatically, suggests how to solve design problems. Designing the process for the solution to design problems is itself a design problem. The top functional requirement (FR0) is to create the best design. The corresponding design parameter (DP) is a system to apply axiomatic design. FR1 and FR2 would be to maximize the independence of the functional elements (1st axiom) and to minimize the information content (2nd axiom). DPs 1 and 2 could be the applications of axiom one and axiom two, respectively. This approach could be applied at all levels of the design decomposition.

Suh states that the first axiom must be satisfied before the second [10]. That suggests that the design matrix for the design process is a lower triangular matrix. This means that the application of axiom one can influence the compliance with axiom two. Several of the theorems address this point of solutions to axiom one influencing axiom two ([7] p. 60-64).

In developing axiomatic design, Suh [10] studied existing designs to find the commonalities, proposed candidates and eventually narrowed them to the two axioms mentioned above. Womak et al. [4-5] essentially followed that route to develop lean manufacturing by studying Toyota. The development method here is to consider manufacturing in the context of axiomatic design.

Similar to design, manufacturing is a human creation with good and bad instances. Unlike mechanics and like design, manufacturing is not required to follow manufacturing laws. The laws would be what distinguish good manufacturing from bad. The general top FRs for systems for designing manufacturing process should include lean [4-5] and return on investment [7] and be applicable at the detailed process level. The number of FRs should be a minimum ([7], p. 60, Corollary 2).

3 RESULTS

This work proposes two FRs that can be applied to all manufacturing problems from the details of the process to the abstraction of manufacturing systems.

FR1 – maximize the value added to the product

FR2 – minimize the cost in the production process

Similar to the design axioms, FR1 must be applied first. There are legitimate costs that are necessary for the value adding processes. If minimizing the cost were to be the satisfied first, then the potential to add value could be eliminated. The corresponding DPs could be stated generally as systems to control the value added and systems to control costs.

4 DISCUSSION

An important question should relate to cost and the independence of the FRs. Cost is usually a constraint in product design because it cannot be decoupled from the other FRs [10]. Certainly there are costs that are necessary for producing value. Costs are therefore implied in FR1, so it might be argued that the FRs are not independent and cannot be independently satisfied and therefore this decomposition violates Suh's axiom one for independence. We might then restate FR2 as minimize the cost of the non-value-adding activities. The risks with this restatement are that value-adding activities, like conventional machining, discussed below, would not be scrutinized sufficiently, and that larger kinds of costs, like the cost to society of non-sustainability, would be ignored.

The terms maximize and minimize can be criticized in a design process because there are no clear limits, which means that there is no clear end to the process. FRs should define the objectives, or targets, for the design solution. No-cost manufacturing is not a realistic objective. "Control" or "provide" could be an alternative terms for both "maximize" and "minimize" in these and similar situations. Target values and tolerances could be set based on business analysis. Providing targets and tolerances would remove the frustration of never reaching infinite value or zero cost. Stating that something is an FR implies that it should be provided and controllable. Minimize and maximize provide a clear sense of the desirable direction. With any of the terms, a reasonable approach is to indicate target values and functional tolerances for the FRs as part of the design process. These targets and tolerances could be adjusted with each product and process design cycle.

What is proposed here, on an abstract level, has similarities with what can be found in the literature on value engineering and target costing. The emphasis in this paper is that the upper level should be applied to the smallest details of the process as well as to the manufacturing organization in a decomposition hierarchy based on axiomatic design. This important literature on value engineering and cost targeting provides useful themes for further hierarchical decompositions in the application of these principles to axiomatic design. Details of these applications are left to future work.

The intent here is to use the domains and decompositions inherent to axiomatic design in order to link value to the customer, starting with customer needs, through functional requirements to design parameters (e.g., physical features) and the processes to create them. These value links establish a two dimensional value chain that extends horizontally across the domains and vertically through the hierarchical decomposition.

Lean uses a process of value stream mapping that is essentially material based and follows the transformation of resources. Within axiomatic design a value chain analysis is established traceable to customer needs and functional requirements.

Costs are meant to include waste and investment. Clearly a means for reducing cost is to reduce waste and investment, provided that the desired value can be achieved.

Waste as a cost could be considered in a broad sense. Consider byproducts of manufacturing, such as carbon emissions. Legally, there are constraints on what can be discharged. Ethically, there could be constraints that go beyond the legal constraints. The first canon of engineering ethics is to hold paramount the health, safety and welfare of the public. Certain emissions resulting from certain production processes are harmful to the environment, and are damaging to the health, safety and welfare of the public. What are the ethical obligations of engineers involved with the design of these processes?

4.1 Application to Processes

The value in machining is often creating a surface with the desired roughness in the desired location. The costs in machining have little to do with creating this surface. Most of the cost in energy and tooling is in the formation of chips. The processes referred to as material removal are appropriately identified from the cost perspective, although perhaps not so appropriately from the value perspective.

The application of the proposed FRs could lead to precision castings and forging, which require less material removal. Another avenue suggested by the proposed FRs would be to minimize the energy required for material removal.

A kind of value chain analysis could be applied to processes. This would link value at the customer level, or customer needs with specific features created by the processes. The aspects of the process, which require resources, should be compared with the features at the detailed end of the value chain. The resource expenditures should be consistent with the creation of value.

5 CONCLUSIONS

Two top level FRs have been proposed for application to all manufacturing processes and systems:

1) Maximize the value added
2) Minimize the cost

The proposition is that these could also be axioms to be used as a foundation for manufacturing science.

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