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AXIOMATIC DESIGN OF MANUFACTURING PROCESSES CONSIDERING COUPLING

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ABSTRACT

Axiomatic design theory is applied to manufacturing process design. Different configurations of design domains and decompositions are considered here in order to provide options for maintaining independence while addressing the development of new products and manufacturing processes. The development of metrics and criteria for the process design is described as part of a complete design of the process variables. Value and cost are considered in the context of manufacturing. Tool design can be considered to be an extension of the manufacturing process as a means of meeting special, new processing needs.

Keywords: Axiomatic Design, Manufacturing, Process, Coupling, Surface roughness specification

1 INTRODUCTION

The objective of this paper is to advance axiomatic design (AD) theory [1] to improve manufacturing process development (MPD) within the context of new product development (NPD). Here, development is intended as a broader term than design. Design is the only part of development that is considered here. Design is the focus of this paper and used in a narrow sense intended only to encompass those activities that are integral parts of the decomposition in the axiomatic design process. Fully considered MPD would include the design of manufacturing processes and systems. In this paper, the focus is on the manufacturing process design, while recognizing that it is not always clear where or how to draw the distinction between manufacturing processes and systems. Drawing this distinction precisely is not particularly important to this discussion.

This paper addresses definitions and metrics for process variables and the coupling that occurs in some NPD-MPD situations. The manufacturing processes that are considered here could be applicable in the broadest range of those processes that perform value-adding transformations that satisfy customer needs (CNs).

AD provides a system for developing design solutions starting with CNs. Functional requirements (FRs) and constraints (Cs) are developed from the CNs. However, users of AD often focus solely on the functional and physical domains, without considering the process domain, i.e., how things are made. The design process then often stops with satisfactory fulfillment of the FRs by the design parameters (DPs). The process domain, and its elements, the process variables (PVs), are often ignored.

Consideration of the functional and physical domains is, at a minimum, required in AD to understand the relations between FRs and DPs. Extending this to consideration of the process domain, which would include the PVs, deserves more attention. This brings MPD into NPD. This is important because good MPD facilitates wealth creation and is essential to economic competitiveness.

Rigorous compliance with AD tradition in the formulation of design elements has not always been followed by some of the most skilled users of AD. For example, FRs should begin with a verb and be stated in the imperative [1]. However, valuable contributions have been made while ignoring this formality [2, 3]. Nonetheless, in teaching and developing axiomatic design, it can be useful to apply more formality in the formulation of FRs, DPs, and PVs. This would include specifying metrics and tolerances and quantitative relations between the elements.

Suh includes the process domain in the design solution and shows DP-PV interactions in the process matrix [1]. An approach to modifying DPs and FRs to reduce DP-PV coupling, by combining design and process matrices, is addressed briefly by Suh (128-131) [1].

Several types of coupling were considered by Brown [4], attempting to be collectively exhaustive with respect to relations between FRs and DPs. However, there is nothing in that work that addresses coupling between DPs and PVs or coupling that arises in the MPD as a result of constraints in the NPD.

Issues with coupling that interfere with maintaining independence can develop during the process of getting from NPD to MPD. MPD can be subject to coupling which results from the formulation of FRs and selection of DPs in the NPD. MPD can be coupled by decisions made during the NPD. For example, some coupling in the MPD can originate with the specifications that the DPs use for surface roughness characterizations that do not respond independently to the adjustment of individual process parameters. This is seen in the case of designing shaft surfaces for rotating lip seals [5]. There are product specifications made by the product designers that are typically beyond the influence of the manufacturing process engineer, such as, the specification of

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surface roughness parameters. MPD could benefit from approaches for dealing with these kinds of product specifications that cause coupling in the process design.

NPD in this work is intended for end-use consumer products. These are products that produce value for the consuming customer only. This value is intended to be consumed by the end user, rather than sold. It is also not intended to produce additional value that can be sold. Its value and use ends with the consumer.

Manufacturing processes and tools for facilitating manufacturing could also be considered as a type of product. It is special in that the primary function in MPD and related tool development is to create value in another, different product [6] that can be sold. In these formulations of a design problem, the manufacturer would be the consumer, although not an end-use consumer. Therefore, MPDs and manufacturing tool design could also be considered a kind of product in applying AD.

In this paper the term NPD will be used in a more limited sense that excludes all MPDs. This would also exclude important things that should be part of the complete development of a new product, like the development of new tools for new products, which can't be produced by existing processes, or for reducing cost and waste on existing manufacturing processes. These will be considered under MPD here. Design for facilitating tool development (FTD) can also be considered separately.

The approach used in this paper to advance AD for improving MPD is to first consider how to configure the domains in order to reduce coupling, and then consider how to more rigorously define and measure the processes. This will be done in the context of the dual objectives of manufacturing, adding value, and reducing costs, as proposed by Brown [6] and critiqued by Thompson [7]. Note that the definition of costs and consideration of waste are left to the manufacturer. Only the decomposition process and decomps are considered here, to the exclusion of integration.

The term "decomp" is used here to mean the design decomposition, describing the breakdown of the design into its components, e.g., lists of FRs and DPs, as opposed to decomposition as the act of decomposing.

2 METHODS: CONFIGURING DECOMPS AND THEIR DOMAINS FOR MPD

Decomps and their domains can be configured in different ways to facilitate MPD. The MPD could be included directly with the NPD or considered separately. In the latter case, there is the opportunity to introduce new FRs for manufacturing. Only the NPD-FRs relate directly to the original CNs for the new consumer product.

In any case, each element, i.e., FR, DP, and PV, at each level should have a target value, a tolerance and an expression of its relation to the adjacent domains. The expression of this relation should be an equation. This equation could be developed from known, fundamental relations or by fitting data from experiments. The former is of course preferable from time and cost perspectives. These equations describe the FR-DP and the DP-PV relations and are used to construct design and process matrices.

2.1 MPD INTEGRAL IN 4-DOMAIN NPD

The configuration for addressing MPD within NPD has 1-decomp with 4-domains (1:4) as shown in Fig. 1. The dotted arrows from the customer domain indicate that there can be an influence of the CNs beyond FR0, on the lower level FRs. In this 1:4 configuration, the context is entirely new product development, as opposed to manufacturing. The MPD is supposedly done within the NPD decomp. This decomposition process occurs in a linear manner for each branch at each level, following an FR-DP-PV progression at each level of the zigzag [1].

At the leaf level, the most detailed level of the decomp, the manufacturing process for each feature should be specified in the PV, with a target and tolerance. This PV would be traceable through a value chain to an NPD-CN.

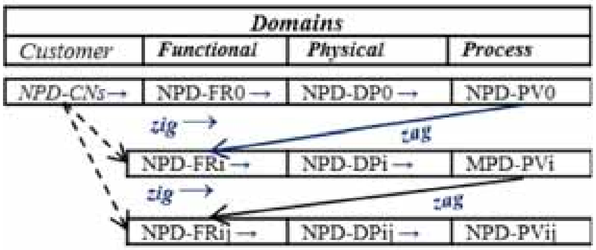

Figure 1. Zigzag decomposition with the customer-oriented single system, four domain (1:4) configuration. The zero level and top two levels with i and j representing the indices associated with different branches are shown.

In the case of the design of surface textures for shafts for rotating lip seals, the product specifications are currently standard, height parameters [5, 16, 17, 18]. The selection of these parameters and their tolerances has been developed through experimentation. They include specific ranges for average roughness, peak to valley height, and peak height. Supposing these are separate DPs, then the problem is that when one height parameter is adjusted, by changing a PV, the other two parameters change as well, and might go out of tolerance. Non-productive iterations might be required to adjust the process variables in an effort to bring all the surface roughness design parameters into tolerance simultaneously. This is a problem because there is no known system for this, nor is there any guarantee of, or test for, convergence.

In the 1:4 configuration this coupling, which is due to the specification of the roughness values for the texture design, should be addressed systematically during the decomposition. These kinds of coupling should become obvious when the target values, tolerances and relations between the elements are defined by equations and the resulting interactions are entered into the design and process matrices. In the course of maintaining the independence of the functional elements, which would be done level by level, this kind of coupling should be addressed during the decomposition.

The other kind of coupling that potentially would arise systematically from this configuration concerns the manufacturing costs. The value chain originates with the CNs and needs to be maintained throughout this NPD. The value chain also must extend through the manufacturing to the use of the actual product. Maintaining the value chain, starting

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with the customer and continuing through product and production development, is essential to successful design. That value should be satisfied by the FRs and fulfilled by the DPs, then produced by the PVs. The 1:4 configuration is focused on maintaining this direct value chain through the process design. However, it does not systematically allow for the control of manufacturing costs. The control of these costs has been cited as an essential part of successful manufacturing process design [6].

2.2 MPD WITH 3 AND 4-DOMAIN NPDS

Another configuration for addressing MPD is a 2-decomp 6-domain configuration (2:6) as shown in Fig. 2. This 2:6 configuration uses the first three domains -- customer, functional and physical -- in the NPD and then has a second decomp of the same three domains for the MPD. The decomposition involves taking the DPs from the NPD and using them, essentially, as special kinds of CNs, to develop FRs for the MPD. This configuration fits in with much of the current tradition of AD. Many users of AD and much of the literature on AD tend to stop at the physical domain.

Some MPD-CNs would maintain the value chain developed from the end-use customer NPD-CNs, which address the value-added criterion for manufacturing [6]. Additional MPD-CNs would be supplied by the manufacturer, acting as a customer. These would include the elements for controlling cost and waste thereby satisfying the second criterion for manufacturing [6].

The NPD and MPD decompositions might be done sequentially. This would provide a complete, finished view of the NPD for defining the needs of the manufacturing process. This could save iterations through the MPD when changes are made to the NPD. However, this kind of approach could design in costs during the NPD, costs that cannot be addressed in the MPD alone.

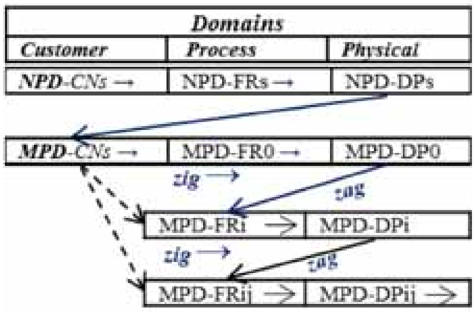

Figure 2. A representation of a 2-decomp 6-domain configuration to MPD from NPD. FTD could be constructed in a similar way from the MPD DPs.

The MPD-FRs address the MPD-CNs directly. Two types of FRs are expected: those that maintain the value chain that began with the NPD-CNs and those for reducing cost and waste. The MPD must establish the process variables that correspond to the NDP-DPs.

New, specialized tooling, FTD, could also be considered in an additional decomp, originating with the DPs of MPD in the same way, MPD is shown in Fig 2. The FTD-CNs would originate with the MPD-DPs. The process design then would not need to be constrained to existing tooling. For example, in some especially innovative projects, such as the development of manufacturing for integrated circuits in the latter half of the twentieth century, tooling for these processes did not exist and substantial, extraordinary tool design was done. Fixturing is an example of a more common tooling design problem that could require its own development. The FTD-FRs could be formulated either from the NPD-PVs or from the MPD-DPs or MPD-PVs.

In the 4-domain configuration, all process solutions link directly back to NPD-FRs. Independence is maintained in the 4-domain configuration across the functional, physical, and process domains by examining the design and the process matrices [1].

To better maintain independence during the zigzag decomposition in the 1:4 configuration, the NPD-FRs and the NPD-DPs could be adjusted or could change completely during the selection of the NPD-PVs. Sometimes, processes cannot be found that individually address specific NPD-DPs independently. In some instances, the NPD-DPs can be selected, and sometimes their corresponding NPD-FRs can be redefined to accommodate available processes [5].

Process solutions in the MPD stage of the 2:6 configuration can directly consider interactions within manufacturing systems, including multiple processes and surroundings, thereby promoting the maintenance of independence.

Consideration of the NPD-PVs in the context of a manufacturing environment could require additional FRs to satisfy the broader requirements of manufacturing. Independence in the 2:6 configuration is maintained in part through the definition of the MPD-FRs. However, one disadvantage is that this would remove the MPD sufficiently from the NPD-FRs, so that coupling with the PVs that originates in the NPD-FRs would not be so obvious and might not be addressed by changing NPD-DPs in the MPD stage, as in the 1:4 configuration.

A more elaborate, 2:4-, or 8-domain configuration, including both NPD and MPD PVs, could be used to address independence across all four NPD domains first, and then to consider interactions with the manufacturing systems in an independent MPD. This has the advantage of addressing NPD FR-PV coupling first. It has the disadvantage of requiring more work in the development of additional process domains, compared to the 6-domain configuration. Sometimes, the MPD-PVs might be obvious and not need to be developed.

2.3 FORMALIZATION OF PV DEFINITION

The discussion of this development will be in the context of the manufacture of mechanical parts. This could be extended to other kinds of design as well. Form and surface finish are NPD-DPs that are common to many mechanical parts. This discussion assumes that other important attributes, such as yield strength, are addressed in other branches of the decomp.

Formally, the NPD-PVs should start with verbs, like the FRs. PVs indicate actions, applications of energy to manufacture value-adding NPD-DPs, e.g., turn a cylinder or form threads.

The NPD-DPs in the 6-domain configuration that lead to the formation of the MPD-FRs must first be restated to begin

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with verbs, e.g., *manufacture* a cylinder or *create* threads. The MPD-DPs should start with a noun or an adjective. MPD-DPs might include a present participle modifying a noun, e.g., *turning* process or *forming* process. The MPD-PVs that relate to the NPD could look much like the NPD-PVs, e.g., turn on a lathe, or form threads with a tap.

Including tooling information in the MPD could avoid resorting to a formal FTD process in simple cases.

In the 6- and 8-domain configurations, there would be also FRs that relate to the manufacturing systems, e.g., maintain a material removal rate to control machining costs.

2.4 DECOMPOSITION RULES

Thompson [7] emphasizes the importance of including all the key stakeholders in establishing FRs. If this is done appropriately in the sole context of NPD, then the MPD and FTD stakeholders need to be included in one, all-encompassing, decomp. The PV decomps must provide a complete description of the processes, just as the FRs and the DPs must provide complete functional and physical descriptions [8].

And just as the FRs need to be considered in a solution-neutral environment from the point of view of the DPs [1], the DPs also must be selected in a solution-neutral environment from the point of view of the PVs. The FRs should not contain physical information [9], and the DPs should not contain process information. This would violate the distinctions intended for bimodal and tri-modal approaches. Therefore, “grind surfaces” is not a good MPD-FR, and “ground surface” is not a good NPD-DP. This consideration is important for the decomp to be valuable and creative.

3 METRICS, TOLERANCES AND RELATIONS BETWEEN THE ELEMENTS

Consideration of metrics in the design of manufacturing processes can improve the utility of AD. These metrics should be used to define targets and tolerances. Furthermore, quantitative relations between elements in the different domains should use these same metrics. Nonetheless, AD has been shown to be valuable without a formal definition of the metrics or a quantitative description of the relation between the elements in the domains. AD could be more valuable in some cases with metrics. It is not clear how to determine when the effort for quantification is merited. It is supposed that there is some kind of cost: benefit consideration that could be applied.

Metrics are domain specific. Metrics for the functional domain must relate to functional attributes, those for the physical domain to physical attributes, and those for the process domain to process attributes. For example, when designing a shaft for interfacing with a rotary lip seal, the FRs can relate to CNs for sealing and for the longevity of the seal. The functional metrics should relate to leak rates over time. The physical metrics would relate to the form and finish of the shaft. The process metrics should relate to how the form and finish are being created.

3.1 ENERGY PARTITION FOR PV METRICS

Because manufacturing processes involve the application of energy to perform value-adding transformations, it seems logical that the process metrics should relate to some kind of energy utilization.

Energy partition, where the process energy is doing work, e.g., material removal or surface modification, is discussed by Malkin in relation to grinding [10-12]. Acoustic emission can also be a metric for process monitoring [13], as can ultrasound [14]. In-process measurement has a rich history [15].

One intent of the process metrics could be to give an indication of how well the DPs are being generated. Similarly, the DP metrics should give an indication of how well the FRs are being fulfilled. Assessments of the process energies are distinctly different from the in-process measurements of NPD-DPs, which are also valuable [16]. The energies measured in process do not have to be those directly responsible for the transformations in order to be valuable, e.g., acoustic emissions.

3.2 TOLERANCES AND RESOLUTION

The resolution required for the metrics is based on the NPD-FR or the MPD-FR metrics and their tolerances, because that is what defines the success of the design solutions.

The requirements for the NPD-FRs should be mapped onto those for the NPD-DPs and NPD-PVs and then transferred appropriately to the MPD-FRs.

Directing the process work to accomplish the NPD-DPs in machining and grinding is currently done by defining the tool-workpiece interaction with the tooling, feed, speed, and depth of cut for many material removal processes. The parallels in additive manufacturing might logically include the energy used for bonding, as in selective laser sintering.

The overlap between the design range (NPD-DP tolerance) and the system range, or manufacturing capability, defines the common range [1]. MPD should seek to maximize the common range in order to comply with axiom two, thus minimizing information. The resolution of the process metrics should be good enough, relative to the common range, to control the process, maximizing the probability of keeping the process in the common range.

4 DISCUSSION

More work would be required to understand how to measure the energy partition in a process like tape finishing. During a single, short grinding operation, or hit, the energy partition on tape finishing can change. Because in tape finishing the same abrasive can remain in contact with the workpiece for a longer period of time than in other abrasive finishing operations, the abrasive tends to load with chips, and the process can transition from chip removal towards rubbing. With increasing contact time, relatively more of the energy goes into heating the workpiece and smoothing the surface than into material removal. Frequently, it could be easier to measure the DPs in process than the energy partition of the process. The heating of the workpiece will need to be compensated for in determining the form at ambient temperature. This would also influence the linearity of the

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DP-PV relation, especially if time of contact is the selected PV.

This process of determining the common tolerance band when adjusting a process parameter could be applied to any situation where there are several non-orthogonal, semi-redundant DPs that must be satisfied, and coupling needs to be overcome in the selection of the PVs and their values. Semi-redundant DPs must be also non-orthogonal. The converse is not true when the correlations are negative.

5 CONCLUSIONS

Design domains can be configured several ways to address manufacturing process development.

The most comprehensive approach would be based on developing process domains for new product and for manufacturing development, although, it is not clear when there is a good return on investment for this effort.

Metrics and quantitative specifications of tolerances and relations between elements of adjacent domains might improve value of the design, although it is not clear when this extra effort would be justified.

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