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Metrics for Developing Functional Requirements and Selecting Design Parameters in Axiomatic Design

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Abstract

This work studies the systematic use of metrics for developing design decompositions in axiomatic design (AD). The supposition is that a rigorous use of metrics will guide the formulation of superior functional requirements (FRs), and the selection of the best design parameters (DPs). Good FRs are essential for satisfying the customer needs (CNs). The metrics and equations relating FRs to their parents and to the corresponding DPs can be useful for complying with the axioms and for verbalizing FRs. Quantitative value chains, along with targeting and tolerancing chains, which start with the CNs, are proposed The use of adaptive designs, whereby a design solution can evolve to respond to changing circumstances, are also mentioned.

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1. Introduction

The selection of good functional requirements (FRs) is essential for design solutions that satisfy the customer needs (CNs). According to Suh, a design solution can be no better than its FRs [1]. This is true, limiting the result, no matter how well the axioms are applied after the FRs are developed.

The highest level FRs are based on CNs, which establish the value in the design problem. FRs translate the CNs into functional terms that can be used in engineering design. The CNs can be seen as the beginning of a value chain that extends through the FRs in the functional domain, to the DP solutions in the physical and process domains. The FRs continue this value chain, connecting to the design parameters (DPs) and the integrated solution. If everyone were to be using axiomatic design (AD) with equal effectiveness, then the competition to create the best design solutions would be to develop the best FRs. The best FRs are those that provide the best value for the customers. This must be captured in the formulation of the CNs and the development of the FRs.

The objective of this paper is to advance the techniques for teaching the development of FRs and the use of metrics for decompositions, starting with CNs. Parent and child and FR-DP equations are considered along with in the decomposition, se, tolerancing and adaptive, or evolutionary, designs.

This work is important because the fundamental supposition of axiomatic design is that proper application of the axioms leads to the best solution for a given design problem. The engineering design problem is defined by the FRs. Therefore a design solution can be no better than the FRs used to define the engineering design problem [1]. This view puts special burdens on developing FRs.

This work can also be important for learning and adopting AD. Failure of engineers to adopt AD often stems from difficulties with the formulation of good FRs. The hypothesis, proposed here, is that more rigorous attention to metrics throughout the decomposition will lead to better FRs and DPs and assist in assigning functional and physical tolerances and thereby improve the value of the resulting design solutions. This work advances the development of a systemic, quantitative determination of the quality of the FRs and DPs

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with respect to satisfying the customer needs (CNs). This could be an element in a larger algorithm to automate some of the axiomatic design process.

1.1 State of the Art

The process of developing FRs has been advanced by Thompson [2] for sorting out FRs from non-FRs and optimization and selection criteria. The concept that FRs must be collectively exhaustive and mutually exclusive (CEME) has been proposed previously [3]. And, Henley [4] has recently emphasized the usefulness of metrics in developing FRs.

There has been some work to develop techniques for improving the development of metrics for FRs. This work builds primarily on the need for CEME decompositions [3] and on metrics for FRs and how they should be used for verification of collectively exhaustive decompositions [4]. The requirements for a decomposition based on elementary combinatorics, set theory and partitioning, stating that the sum of the children must equal the parent have been developed and the importance of themes for verifying that a decomposition is CEME have been emphasized [3]. In addition the importance of semantics in the thought process while developing FRs and being able to argue convincingly that a decomposition is CEME has been presented [3]. Theses concepts also apply to the DPs. Henley [4] argues that the FRs should use metrics in order to establish that a decomposition is CEME. Henley also clarifies that the children are not required to simply sum to equal the parent, rather they can combine in any manner, in an equation, to equal the parent.

Thompson [2] dissects many things that have been used as FRs, sometimes by AD novices, and shows how in some situations there are several other FR-like entities that can be useful. These useful reclassifications include: non-FRs that describe the qualities or the character of what the design solution should be, and optimization criteria (OCs) and selection criteria (SCs) that are often indicated by the use of “maximize” and “minimize”. The OCs and SCs imply that there is a ranking that can be useful for selecting the best among candidate solutions. Ranking requires metrics and assigning values, of course. Thompson’s dissection of the FRs provides useful distinctions for intermediate and advanced AD users in addition to novices.

Thompson [5] presents a rigorous approach to considering the needs of customers and stakeholders. This is based on identifying several different stakeholders and stakeholder categories. This can be used to develop a check list that can be used to generate CNs that will be associated with FRs possibly at different levels in the decomposition. She also emphasizes the importance of being collectively exhaustive at this critical juncture in the development of the design solution, developing the initial FRs. Without recognizing the stakeholders, important CNs will be missed that would otherwise add value to the design solution. The missed CNs will probably lead to missed FRs and a less valuable design solution.

The mutually exclusivity i[3] is directly related to the independence axiom, which requires independence, i.e., mutual exclusivity, of the FRs. Different kinds of coupling have been examined [6]. FR-DP is the usual kind that is indicated by off-diagonal locations in the design matrix. FR-FR coupling can be more problematic because it might be less obvious. It results in a fully coupled portion of the design matrix corresponding the coupled FRs and could be mistaken for two instances of FR-DP coupling. However FR-FR coupling cannot be resolved by changing the DPs. Mutual exclusivity is required for compliance with axiom one and contributes to an axiomatic design process.

Metrics for the FRs have been emphasized in arriving at a design solution for play calling strategies in American Football [7]. Fixed and adaptive strategies are developed. The latter respond to changes in opponents’ strategies. In this instance it is shown that the having appropriate metrics improves the probability of success.

The intent of the design can be like the CNs and the design target has been called the equivalent in concept FRs [8]. This theory supposes that abductive reasoning, a logical inference using an observationally-based development method, to go from more abstract CNs to the more concrete concepts that are embodied in the FRs and then to the DPs. Liu and Lu [9] write about synthesis and analysis in axiomatic design and concept generation. They had good results for creating design solutions when compared with traditional brainstorming. Idea generation and validation are emphasized, although metrics and quantifying are not mentioned.

Matt [10] uses metrics in the development of the decompositions for the designs of manufacturing systems. Metrics specific to manufacturing, like takt time and units produced, are appropriately integrated into the decomposition.

Suh [11] introduces concept of the need for re-initialization in complex system design. This can be periodically or in response to a need that must be detected by monitoring. Matt [12] develops the theory and practice of re-initialization writing. A design solution can include the capacity to monitor and control complexities. These complexities reduce the probability of success, which address the fulfilment of axiom two. The design solution is adaptive in that it detects if a system range in manufacturing is deviating sufficiently from a prescribed range and can trigger a re-initialization. This is a kind of adaptive design solution.

1.2 Approach

The supposition here is that the selection of metrics improves the transition from CNs to DPs and to FRs. The use of metrics and mathematical relations, especially during the development of the decomposition, is considered in the context of ease and confidence of the quality assessment. This use of metrics is similar to Matt’s work [7e], although here it is examined systematically as part of the decomposition process. The assessment of the quality of the solution is related to the success of the solution in providing value, and to the verifiability of the value during the design process. The quality of a design process is also related to the capacity for teaching students to use AD to solve design problems effectively.

2. Methods

The methods used here are philosophical and experiential. They are rooted in practice with, and teaching of, AD. The techniques presented here for developing FRs and employing metrics have evolved during over 25 years of experience as a practitioner and teacher of AD. Some of the experience includes consulting with industry on design problems. Much of it comes from advising capstone engineering design projects and teaching a project-oriented graduate course on axiomatic design of manufacturing processes at Worcester Polytechnic Institute. The students in the course have been a mixed group of regular, full time students and part time students who, working full-time as engineers, bring industrial experience into the class. An objective in teaching full-time engineers AD is to provide them with something they can use immediately for their jobs. This has worked well. Most of the practicing engineers report that they have used AD at their jobs. This teaching experience provides opportunities to see a wide variety of interpretations, including misinterpretations, of proposed techniques and a range of applications and degrees of success. This is the feedback necessary for evolving the teaching methods.

2.1 Perspectives

The use of metrics has been driven by the need to verify the quality of the design solutions. Twenty-five years ago a qualitative development of decomposition was taught at WPI. This was complimented with a quantitative definition of the design matrix. Partial derivatives were used to illustrate the coupling terms. The column vectors were reviewed and exercises were assigned to find the reangularity and semangularity [1]. There were also quantitative problems on axiom two, similar to those suggested by Suh (1990). However, the zigzagging development of the design decompositions was almost always qualitative. The metrics for FRs and DPs, if they were added at all, were generally added after the decomposition was finished.

In the early years the decompositions tended to be small, usually not exceeding about twelve FR-DP pairs. The introduction of Acclaro (Axiomatic Design Solutions, Inc. www.axiomaticdesign.com) allowed for much larger decompositions. A design for one consulting project exceeded two thousand FR-DP pairs. Acclaro software facilitates zigzagging decomposition and construction of qualitative design matrices.

Verification of the quality of the decomposition of a design solution, for both FRs and DPs, is based on the CEME requirement. In the absence of metrics, this argument, can strive for a logical basis by using a theme to expand the parent into children. When it is non-quantitative it is difficult to verify. Many students simply declare that their decomposition is CEME. This is non-verifiable and clearly unsatisfactory.

The evaluation of the decomposition is not so much for academic grading. as it is for the designer to self-critique and self-correct and thereby improve the design. The evaluation should increase the likelihood that the design solution will successfully satisfy the CNs.

2.2 Generalities

The design hierarchy is developed as a decomposition of the design solution, top-down, in a zigzag manner. The objective is to satisfy the CNs. The upper levels act as constraints on the lower levels [1]. The lower levels need to be consistent with the upper level of the decomposition. The use of parent-child equations, discussed below, can assure this consistency.

The decomposition needs to be CEME to be valid, that is, an actual decomposition that is complete and potentially useful for a design solution that complies with the axioms.

The decomposition process starts with the customer needs (CNs), which should establish the value. The value must be maintained through the domains and down the hierarchy. Some parts of the CNs should be constraints, non-FRs, OCs, or SCs [2].

The designer must maintain a distinction between the functional and physical domains. The FRs should be stated in a solution neutral environment, so as to maximize the solution space for selecting DPs. If the FR contains physical information, the design solution space becomes limited and the best design solution might not be considered. Including physical information in the FR is contrary to the AD process.

Axiom one demands mutually exclusivity of the FRs. Axiom two clearly applies to the selection of the DPs, although it also could apply to how well the FRs can provide value to the customers. In a decomposition the children must be collectively exhaustive with respect to parents. FR metrics should be used [4] to verify this. Parent-child (in one domain) and design (between two domains) equations should be developed during the decomposition.

FR0 should start with the active verb for the thing you are designing. Avoid starting with “design” unless you are designing a design process. Starting FR0 with the word “design” is a frequent mistake with inexperienced users of AD. An FR0 like “design a bicycle” is only appropriate if the CN is something like “produce designs for bicycles”. There is another potential problem with an FR0 that mentions a bicycle. The word “bicycle” already suggests a physical design solution. Almost everyone thinks of two wheels and a frame when they see the word “bicycle”. If the goal is to discover if there might be something other than a bicycle for self-powered personal transportation or pleasant exercise, try “transport people under their own power” or “provide exercise with changing scenery”. In other words, the designer should start with the CN and formulate an FR that is completely void of physical information about the solution.

2.3 Design solutions with evolving strategies

Two kinds of solutions are considered here: fixed and adaptive, or evolutionary. Fixed solutions are adjustable and controllable to respond to a more limited and relatively static set of circumstances and only require adjustments to the value of the current DP. There are also evolutionary, dynamic or adaptive, design solutions that are intended to evolve new design solutions. These adaptive design solutions adjust to circumstances that are changing in a larger sense and require new DPs [7].

Examples of fixed, quasi-static design solutions might be some kinds of "continuous improvement systems", such as are used in lean manufacturing [7f]. These kinds of design do not require new DPs. The DP is a system that continuously strives for improvement and can satisfy CNs over long periods.

Evolutionary design solutions are intended to adapt to larger changes in circumstances that require new DPs. Evolutionary designs might be used to address changes in a competitor's strategy or product that could require some redesigning of the current strategy or product as initially designed. These kinds of adaptive solutions, for addressing larger changes in the circumstances or environment, need to include some kind monitoring to know when these changes are large enough to trigger a response.

An example of such adaptive designs that evolve to respond to changing circumstances is given for play calling in football where the other team changes their play calling strategy because the opposing team has changed theirs [6]. If both teams are using an adaptive strategy, then the quest would be to adapt, or evolve, faster than the competitor. This is a concept that is understood in many competitive endeavors.

In AD the ability to evolve by responding to changes in the environment or in an opponent's behaviour can be addressed by placing FRs at appropriate places in the hierarchy and branches. Typically these kinds of FRs would have the children to address monitoring, or measuring key indicators, analysing these measurements, and responding appropriately. Adaptation, or the ability to evolve, can be a top level FR or it can be distributed appropriately in the branches.

FRs that begin with terms like maximize or increase might be evolutionary if they have an appropriate solution decomposition. They also can be OCs or SCs [2]. If they are to be evolutionary then the design solution needs to include monitoring, analysis and response functions.

3. Results and Discussion

3.1. Leading with metrics

Deciding on appropriate metrics for the FRs before choosing the DP, even before verbalization, can be effective in developing superior FRs. The supposition is that metrics for the FR, or functional metrics (FMs), facilitates the verbal definition of the FRs and the application of the axioms. The metrics for the FR should indicate how well the CN is being satisfied. This would be different than how well the customer is responding or how sales are going. The FM should indicate what would be measured to see if this particular FR is fulfilling its intended function. It should be a measurement of the accomplishment of the function that the DP, the physical design solution will ultimately supply. The FM should be responsive to the question: what would you measure if you were tasked as an engineer to assure that that function was fulfilled.

The metrics can also be useful for discussing with customers and other stakeholders early in the design process to be sure that the design efforts are providing the intended value and avoiding unnecessary expenses.

Sometimes there is a tendency to propose that the metric is binary, that its mere existence is all that needs to be verified. The designer should be cautious in accepting binary verifications instead of measures of quality. To develop a more valuable, quantitative metric the designer needs to consider what might constitute more or less valuable versions of the solution.

3.2 Equations for the decomposition: design and parent-child

There are two kinds of equations that should be part of the decomposition: parent-child equations that show how the children combine to equal the parent, and design equations that show how the DPs relate to FRs. The former is a kind of intra-domain equation and the latter is an inter-domain equation.

Naturally, the writing of equations is facilitated by the selection of appropriate symbols for representing the FRs and DPs. These symbols should be chosen to be specifically related to the metric, as opposed to the more generic FR1, FR2, etc.

Writing specific design equations can be difficult at the higher levels in particular. This is because at these levels the FRs are more abstract and the upper level DPs often represent systems that are composites of many elements. The effort to write the upper level equations can assist in the decomposition by suggesting the detailed content of the upper level FRs and DPs. When it is not obvious what the details of the design equations should be, they can be left as unknown functions. Nonetheless these should attempt to specify all the symbols for all the DPs that will influence each FR.

The parent-child equations need to show how the children combine to equal the parent. Previously this combination has been referred to as summing [3]. The use of all the children in any kind of mathematical expression should be acceptable in the parent-child equations. In some situations plots or tables can be acceptable, although in no case can a parent be decomposed into only one child. There must be at least two children for each parent.

The language used to describe the children should be similar to that used to describe the parent. The child FRs and DPs should inherit critical attributes from the parent, this includes the phraseology.

3.3 Targets and Tolerancing

Knowing what should be measured, i.e., selecting the right metrics, is required for setting target values and tolerances. It is important to keep these distinctions clear. When asked to specify metrics students occasionally and wrongly provide the target values. Initial design decomposition can be accomplished with metrics and without determining the values for the metrics.

Often the target values and tolerances for the metrics should be determined during the decomposition phase. Sometimes when the required dimensions for a component are calculated it is discovered that it will not fit into the space allotted Sometimes it is discovered that a feature violates some other constraint. This kind of problem would initiate a change in the design solution that impacts the decomposition. Excessive calculation and design changes during detailed drafting (CAD) can be indications that the decomposition phase was not sufficiently quantitative.

Targets and tolerances can be understood for the CNs. These should be transferable to the FR and should be part of the development of the FR and its metric. If the design equation relating the FR and DP has been developed properly then the calculation of target values and tolerances in the physical domain should be straightforward. There should be a clear value chain for the physical tolerances on the detailed engineering drawings that connects through the functional domain to the customer.

3.4 Considerations for manufacturing process design

Manufacturing process design can be considered in a chain from FRs to DPs to PVs [1, 13], although here it will be considered separately as FRs for the manufacturing process to DPs [14]. The role of manufacturing is to create the required or desired value and control costs [13, 15]. Accomplishing these directives clearly benefit from appropriate metrics.

In fabricating mechanical parts there are universal concerns: achieving the desired form, or shape, i.e., large scale geometry, and the right surface texture, or roughness. In this view of manufacturing FRs and DPs it would be appropriate to design a manufacturing process where achieving form and surface roughness are ends in themselves. The larger picture would address why that roughness is needed, however this can be outside the scope of manufacturing process design.

This suggests two FRs: one for achieving the prescribed form, and one for achieving the prescribed surface roughness. The metrics for the form and texture FRs would be the probability of achieving the dimensional and the roughness tolerances. The appropriate metric could be repeatability. The measure for repeatability could be the standard deviation at some level of the hierarchy. From this the probability of success and information content could be calculated (Suh 1990). The FRs for achieving tolerances might be high level thereby applying to everything, in a kind of distributive manner, or they might be distributed throughout the branches.

In an adaptive design an adaptive FR could be called “control the variability” perhaps applying to a specific feature. The DP could be a “variability control system”. The DP might be intentionally vague at this point in the process of developing the decomposition. The design equation relating this FR and DP could be similarly vague. The designer would select variable names and write equations, like V = f(S), where V is the standard deviation and S is some physical measure of the control system or control device. The function might determined analytically and tested experimentally. An increase in variability could indicate wear or change in temperature and would trigger maintenance or improvement in temperature control.

4. Concluding remarks

A number of concepts relating to the use of metrics in the process of developing a design solution axiomatically have been discussed. Some of these concepts might seem obvious, although all have proved challenging for some graduate students over time. The experience has been that the emphasis on metrics improves the design process and elevates the comprehension. All of these concepts would benefit from further development and the publication of case studies using these concepts, such as done by Matt [12]. Specific steps should be laid out for the inclusion of metrics and integrated into a synthesis and analysis design development system, such as shown in Liu and Lu [9]. The systematic application of adaptive design systems that go beyond re-initialization [11. 12] to re-design, as used in play calling for football [7] for defining new DPs and possibly new metrics and FRs.

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