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A CLASSIFICATION OF PROCEDURAL ERRORS IN THE DEFINITION OF FUNCTIONAL REQUIREMENTS IN AXIOMATIC DESIGN THEORY

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ABSTRACT

The definition of functional requirements is one of the most critical and difficult steps in the Axiomatic Design process. This paper presents five classes of procedural errors made by both novice and expert designers during the definition of functional requirements in Axiomatic Design Theory. Each category is described in detail, the linguistic markers for the errors are identified, examples from the literature are provided, and strategies for avoiding these errors are suggested. The implications of these errors for design practitioners, educators, and researchers are considered. The paper ends with a discussion about the nature of requirements and future requirements research topics in Axiomatic Design Theory.

Keywords: Axiomatic Design, requirements process, functional requirements, constraints.

1 INTRODUCTION

The definition of functional requirements is one of the most critical steps in the Axiomatic Design (AD) process [Suh, 1990]. Functional requirements (FRs) represent both the "objective" [Suh, 1990] and the "intent" [Suh, 2001] of the designer. As such, they explicitly define the problem to be solved and guide its solution. The functional requirements also lay the foundation for all of the major steps in the Axiomatic Design process: decomposition, mapping between the design domains, the creation of design matrices, and the application of the design axioms. Thus, "a good design is not likely to result" without "an acceptable (or correct) set of FRs" [Suh, 1990]. Unfortunately, the correct definition of FRs is also one of the most difficult tasks in AD.

The requirements process defines the design problem through the elicitation, collection, evaluation, translation, and organization of information about the desired artifact and its stakeholders. Axiomatic Design Theory provides some structure and guidelines to facilitate this process. For example, the design domains define and separate customer, functional, physical, and process information. This helps to organize the requirements information and to differentiate it from the information (and information content) associated with various design solutions. The design hierarchies and decomposition process organize information based on its level of detail. And, both the design hierarchies and the design domains separate "what" and "how" information within and across the domains. However, Axiomatic Design offers only two categories for requirements information (functional requirements and constraints), leaving the designer with no guidance for how to process the remaining information. In addition, AD generally places the system boundary around the artifact and thus offers no methods for the classification of information related to the designer and the other stakeholders who will produce (or implement) and interact with the artifact.

The difficulties associated with learning to use Axiomatic Design Theory and with managing the information that falls outside its boundaries cause designers to make five types of procedural errors during the definition of FRs:

1. Mixing FRs with design parameters (DPs)
2. Mixing FRs with other types of requirements
3. Mixing the FRs of the various stakeholders and of the artifact
4. Mixing the FRs of the artifact and of related systems
5. Defining negative FRs

In this context, procedural errors are defined as errors that stem from an incorrect interpretation or application of Axiomatic Design Theory. Thus, this paper seeks to differentiate between 'true' FRs and information that has been labelled as such. The more subtle problems that can decrease the quality or utility of an FR such as fixation and bias, the presence of hidden or latent needs or assumptions, insufficient decomposition, and the premature loss of solution neutrality are not addressed in this work.

In the follow sections of the paper, each of the procedural errors is described in detail. The linguistic markers for the errors and their sub-types are identified. Examples from the literature are provided when available and strategies for avoiding these errors are suggested. Next, the implications of these errors for design practitioners, educators, and researchers are considered. The paper concludes with a discussion about the nature of requirements and future requirements research topics in Axiomatic Design Theory.

2 MIXING FRS WITH DPS

The differentiation between 'what' and 'how' information is "one of the most essential and unique features" of AD" [Lu and Liu, 2011a]. This distinction lays the foundation for solution-neutral thinking, which increases the "innovation possibilities" for new artifacts [Lu and Liu, 2011b]. However, learning to distinguish between 'what' and 'how' information and to apply the different types of information appropriately in Axiomatic Design Theory can be a challenge. The two perspectives are "easily confused … in real work applications" in part because an "upstream 'how' must also be viewed as a downstream 'what'" [Lu and Liu, 2011b]. This leads to "difficulties in carrying out the zigzagging procedures systematically" and results in "bad mixes of 'what' and 'how'" in design decompositions [Lu and Liu, 2011b].

In the early stages of the design process, these bad mixes of 'what' and 'how' information manifest as the presence of DPs or physical information in the high-level FRs. These errors can usually be identified by the presence or emphasis on a noun (a physical means of performing a function) instead of on the verb (the function that should be performed). The verbs 'to use' (i.e. 'The artifact should use [material, component, energy source, etc.]') and 'to have' (i.e. 'The artifact should have [component or feature]') are also commonly associated with these types of errors.

The conflation of FRs and DPs is the most problematic of the five classes of procedural errors and only one of two that is unambiguously incorrect. The presence of physical information in the FRs prevents the creation of a solution neutral design environment, violates the first axiom, trivializes the mapping process between the functional and physical domain, and otherwise undermines the foundations of Axiomatic Design Theory.

Fortunately, these are also the least persistent errors. The comingling of FRs and DPs is frequently observed in the early decompositions of designers who are still learning to use AD and who have not learned about functional thinking and solution neutrality from other sources. These errors result from a lack of understanding of the theory and are not an indication of AD's limitations. As a result, these errors tend to disappear as designers gain more knowledge about and experience with AD. They are almost never seen in the literature.

3 MIXING FRS WITH OTHER TYPES OF REQUIREMENTS INFORMATION

Requirements in AD are usually defined by mapping the customer needs (CNs) to FRs and constraints (Cs). However, additional types of requirements, including non-functional requirements (nFRs), selection criteria (SCs) and optimization criteria (OCs) are often needed [Thompson, 2013]. Classical Axiomatic Design Theory does not acknowledge these additional categories or provide any guidance on how to include them in the design process. This leaves designers with three choices: "classify all requirements information as [FRs] even if much of it is not functional in nature," discard all non-functional requirement information, or create a parallel classification for this information (Figure 1) [Thompson, 2013]. Most novice and intermediate designers recognize the importance of this additional information but are not sufficiently comfortable with AD to modify its methodological framework to suit their needs. As a result, they usually choose the first option and integrate this information into the FRs.

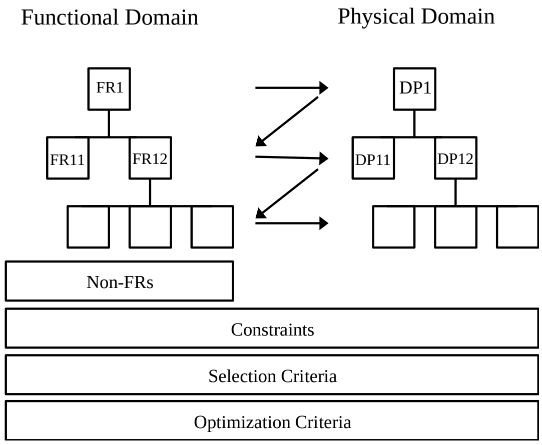

Figure 1. Expanded requirements categories for AD. Adapted from [Thompson, 2013].

3.1 MIXING FRS WITH NFRS

Non-functional requirements (nFRs) describe how the design should be (durable, easy to use, etc.) and specify the qualities or attributes that the artifact should have (inexpensive, light weight, etc.). As a group, they describe the "character" of the artifact and are needed to ensure that the artifact is accepted, liked, and used by its stakeholders [Roberson and Robertson, 2006].

Non-functional requirements influence the definition of the Cs, SCs, and OCs and the mapping of the FRs to DPs. They can also introduce the need for new functionality and new FRs in order to achieve the desired qualities. However, nFRs are more like CNs than true FRs. They rarely translate directly to a single physical feature and thus are not subject to the one-to-one mapping required by the Independence Axiom. As a result, mixing FRs and nFRs, disrupts "the mapping of the FRs to DPs later in the design process" and interferes with the application of the design axioms [Thompson, 2013].

While both FRs and nFRs rely on the presence of a verb in their definitions, nFRs can almost always be identified by the use of the verb 'to be' (i.e. 'The artifact should be [adjective]'). nFRs can also address the user's perception of the artifact – how it feels, looks, smells, tastes, etc. In these cases, the verb 'to be' is implicit rather than explicit.

The confliction of FRs and nFRs is commonly seen in novice decompositions. In these cases, the nFRs often greatly outnumber the 'true' FRs. However, these errors are rarely seen in expert decompositions. There are four factors that may contribute to this. First, nFRs are more important in industrial and product design than in engineering design. Since product design is more common in educational settings while experts tend to use AD more for engineering design, students have a greater need to define nFRs and more opportunities to conflate nFRs with FRs. Second, AD experts instinctively recognize the interference of nFRs with the FR to DP mapping process. Thus, they are more likely to create a parallel classification system for this information, while students are more likely to classify nFRs as FRs. Third, when making purchasing decisions, consumers tend to focus on the qualities of products and take the functionality for granted. Since students have been consumers for much longer than they have been designers, they also focus more on the qualities of an artifact than its functionality. Finally, functional and solution neutral thinking can be uncomfortable and unintuitive for new designers. The high ratio of nFRs to FRs (which sometimes reaches 100%) indicates that some students may replace FRs with nFRs to avoid engaging in functional thinking.

3.2 MIXING FRS WITH INPUT CONSTRAINTS

Input constraints (or "constraints in design specifications" [Suh, 1990 p. 39]) set a hard limit on the values of a quality or metric (cost, weight, size, operating temperature range, etc.). All design options that fall within those bounds are acceptable while those that fall outside cannot be chosen or included in the final artifact. Input constraints can usually be identified by the use of absolute limits or comparative words (at least, less than, greater than, equal to, etc.).

Errors that involve the conflation of FRs with input constraints are common in the Axiomatic Design literature and are regularly made by AD experts. For example, Suh's [2001 p. 43] 'functional requirements' for buying a house include a minimum and maximum commute time (FR1), a minimum quality for the local school system (FR2), minimum air quality (FR3) and a maximum housing price for a given square footage (FR4). These requirements are not related to the main function of a house (providing shelter). Instead, they define the qualities or attributes of acceptable houses and their locations. All houses that do not have these qualities cannot be purchased.

Similarly, Suh [1990 p. 30] defines FR2 of a microcellular polymer as "maintain toughness of the plastic part to equal or exceed that of the original part made of impact-grade polystyrene". This should also be a constraint. All new materials that do not have the required toughness cannot be selected for use.

Suh [1990 p. 39] acknowledges that it is "sometimes difficult to determine when a certain requirement should be classified as an FR or as a constraint". This confusion likely stems from the fact that classical Axiomatic Design Theory does not acknowledge the existence of non-functional requirements.

3.2.1 FRS VS. CONSTRAINTS IN CLASSICAL AD

In classical AD, constraints are defined as "the bounds on an acceptable solution" [Suh, 1990 p. 39]. FRs are distinguished from constraints by the fact that "a constraint does not have to be independent of other constraints and FRs" while the independence of FRs is mandated by the 1st Axiom. Constraints also "do not normally have tolerances associated with them, whereas FRs typically" do [Suh, 1990 p. 39].

3.2.2 DESIGN RANGE VS. CONSTRAINTS

The 2nd Axiom requires that all (lowest level) FRs have bounds on their acceptable values in the form of the design range. Otherwise, the information content of a given design cannot be calculated. If constraints specify the bounds on acceptable solutions and FRs are the only other category of requirements information, then constraints must specify the acceptable bounds of the FRs. This implies that each design range is composed of a pair of constraints.

However, if we accept that both function and non-functional requirements exist, then we may define the design range as the bounds on an FR and define input constraints as the bounds on a quality or an nFR. This definition is consistent with Suh's statement above since nFRs are not bound by the Independence Axiom.

3.2.3 TOLERANCES VS. CONSTRAINTS

In order to address Suh's second criterion, we must define tolerances. Tolerances specify the acceptable deviation from a specified value, typically in the form: value +/- tolerance. In order for a requirement to have a tolerance, it must have a target value as well as an upper and lower bound. Many nFRs (such as required operating temperature range) have both upper and lower bounds, but most will not have a target value. In contrast, every true FR must have both a target value and at least one upper or lower bound in order to apply the 2nd Axiom.

Based on this discussion, the 'FRs' listed above are still constraints since none of the requirements (commute time, school quality, air quality, price, and toughness) have a target value. They state only a single bound and a preference for values furthest from that boundary.

3.3 MIXING FRS WITH SCS, AND OCS

Selection criteria and optimization criteria help to determine which design(s) should be chosen and where to focus efforts to improve them. Unlike constraints, selection criteria imply a ranking. They direct the designer to choose the 'best' (lightest, cheapest, most robust, etc.) design according to the SCs. Optimization criteria specify which design parameter(s) to optimize (often in rank order). SCs and OCs can usually be identified by the use of superlatives (most, least, [adverb]-ist, etc.) or transitive verbs (minimize, maximize, etc.).

Errors that involve the conflation of FRs with SCs and OCs are also common in the Axiomatic Design literature. For example, Suh [2001 p. 20] defines FR2 of a refrigerator door as "minimize energy loss". "Minimize energy loss" implies a ranking between design options and should instead be defined as an SC or OC. To retain this sentiment as an FR, it would need to be rephrased as: "prevent energy loss" or "insulate the refrigerator".

Similarly, Shin et al [2011] propose eco-FRs of the form: consume the "minimal amount of material," consume the "minimal amount of energy," etc. These, too, represent SCs or ways to choose between design options, rather than a function that the artifact must perform. The final artifact may, in fact, consume both energy and resources. But it will do so as a by-product of performing its intended functions.

4 MIXING THE FRS OF THE ARTIFACT AND RELATED STAKEHOLDERS

Not all errors during the definition of FRs involve the conflation of different types of design information. Designers are also observed confusing the actions of the artifact with those of various actors. This manifests as a mixing of the FRs of the artifact and various stakeholders. It is most commonly observed with the two most important stakeholders: the designer and the user.

4.1 MIXING THE FRS OF THE ARTIFACT AND THE DESIGNER

Both novices and experts can be observed mixing the FRs (and other requirements information) of the artifact and of the designer. At the novice level, this is most commonly seen in the definition of constraints. Design students frequently list the constraints that limit their abilities to complete the design task (their limited domain-specific knowledge, the project budget, the project deadline, etc.) rather than the constraints on the final artifact (size, weight, cost, etc.).

At the expert level, the conflation of the artifact and the designer is most commonly seen in the highest level FRs. For example, Suh [2001 p. 353] defines FR1 of a microcellular plastic as "reduce the amount of plastic used". However, the plastic can only perform functions such as resisting forces, absorbing energy, resisting crack formation, and resisting crack propagation. The designer is responsible for choosing (and thus reducing) the amount of plastic used by the final artifact.

Similarly, Brown [2011] proposes that all manufacturing systems share two highest-level FRs:

FR1 = Maximize the value added to the product
FR2 = Minimize the cost in the production process

However, the highest-level FR of all manufacturing systems is probably better defined as: manufacture [artifact]. From a requirements perspective, minimizing and maximizing are ranking terms and could be translated into SCs or OCs. But, as written, these functions can only be performed by the designer.

4.2 MIXING THE FRS OF THE ARTIFACT AND THE USER

A less common and less obvious error is the conflation of the artifact and the user. For example, Suh [1990 p. 51] defines the two FRs of a manual bottle/can opener as:

FR1 = Open beverage bottles
FR2 = Open beverage cans

Manual bottle/can openers are classic examples of physical integration in AD and demonstrate how physical integration can be utilized without interfering with the application of the Independence Axiom. However, these simple devices are tools. They can be used (by a person) to open bottles and cans, but the only true functions that they perform involve resisting and transmitting forces and torques. This is similarly true for hammers and other simple tools.

Opening bottles and cans can be true FRs. For example, electric can openers actually open cans. Likewise, driving nails can be a true FR when designing a nail gun. But these types of FRs can only be defined for active machines and not passive hand tools.

Both novice and expert designers make these types of errors when applying AD. Ensuring that all FR definitions have a subject ('the designer', 'the user', or 'the artifact') could help to avoid the conflation of what the design should do and what the designer should do. But since this error is tied to the fundamental nature of functional requirements (which is still not fully understood), it is unlikely to eliminate them altogether.

5 MIXING THE FRS OF THE ARTIFACT AND RELATED SYSTEMS

Finally, experts are occasionally observed mixing the FRs of the artifact and of related systems. For example, in an earlier discussion of microcellular plastics, Suh [1990 p. 30] defines FR1 as "reduce the material cost by 20%". This could be interpreted as a mix of FRs and Cs (i.e. the material costs for the new artifact must be 20% lower or the concept cannot be considered). It could also be interpreted as a mix of the FRs of the artifact and the designer (i.e. the designer must reduce the material costs by 20%). But a better or more literal interpretation is that this is one of the functions that the company that produces the artifact must perform.

$FR1_{Business}$ = Increase profits
    $FR11_{Business}$ = Reduce material costs

Similar examples can be seen from Suh [2001 p. 318] and Brown [2011] who argue that the highest-level FR of a manufacturing system should be to "maximize the return on investment (ROI)". The use of the term 'maximize' implies the presence of an SC or OC. The statement could also be interpreted as a directive for the designer. But if taken literally, this is an SC and/or an OC for the business that owns and operates the manufacturing system. The highest level FRs and DPs for such a business might look like this:

$FR1_{Business}$ = Earn money
$DP1_{Business}$ = The Business
    $FR11_{Business}$ = Produce artifacts
    $DP11_{Business}$ = Manufacturing division
    $FR12_{Business}$ = Sell artifacts
    $DP12_{Business}$ = Sales division

The statements from Suh and Brown could then be interpreted as directives to optimize FR1.

In a rare counter-example, Shin et al. [2011] acknowledge the difference between the FRs of the company and the product. For example, they suggest that a software company might define "protect the environment" as an FR. They then observe that the corresponding DP ("tree planning program") does not have to be related to the software that the company develops and sells.

6 NEGATIVE FRS: A SPECIAL CASE

The final class of procedural errors involves the definition of 'negative FRs'. Negative FRs define what the design should *not* do. For example, 'the artifact should not harm the user'. This is the second class of errors that is unambiguously incorrect.

Most of the time, negative FRs are simply customer needs which have not yet been translated into the language of the designer. Like all CNs, these statements may contain FRs ('cut high volt power when electrical panel is open'), nFRs ('be safe'), input constraints ('surface temperature should not exceed 90F'), and selection and optimization criteria ('minimize risk to user while performing maintenance').

However, 'negative FRs' can also be true system constraints. System constraints are "constraints imposed by the system in which the design solution must function" [Suh, 1990 p. 39]. Unlike input constraints, which are "usually expressed as bounds on size, weight, materials, and cost," system constraints "are interfacial bounds such as geometric shape, capacity of machines, and even the laws of nature" [Suh, 1990 p. 39]. 'The artifact may not use fossil fuels' is an example of a system constraint.

Negative FRs regularly appear in the functional decompositions of novice designers. However, because 'negative FRs' are not true FRs (by definition), these errors are rarely, if ever, observed in the literature.

7 DISCUSSION

This paper has distinguished between errors made by novices and experts in Axiomatic Design Theory. This was done, in part, because this work has different implications for design practice, education, and research.

7.1 IMPLICATIONS FOR DESIGN PRACTICE

The implications of this work for professional designers and AD experts are limited. These individuals have typically reached the unconsciously competent stage of design. As a result, they naturally avoid errors that can impact their decompositions and the application of the design axioms. For AD experts, FRs act as mental placeholders for information. As long as the information is processed in the same way, the words used to convey that information are of little importance. These distinctions could matter if the experts are working in a larger design team where their decompositions will be used to communicate progress and to serve as documentation for future use. However, both AD experts and design experts in general should be able to recognize the intent behind the FR definition. Thus, these lapses in rigor are unlikely to cause problems in the design process or in the final artifact.

7.2 IMPLICATIONS FOR DESIGN EDUCATION

In contrast, the implications for Axiomatic Design education are significant. It is important for AD novices to have clear guidelines to direct the definition of their FRs. It is also important for design faculty members to have guidelines to identify errors in FR definition so they can provide feedback to their students. Finally, it is essential for students to have models for how to reformulate and improve their FRs.

Errors made by experts, especially in seminal texts, provide students with bad examples of how to perform design decompositions and could encourage them to make similar errors in the future. A clarification of requirements categories and how to define FRs could pave the way for more rigorous and consistent AD texts and teaching materials. This, in turns, should also increase the ease and efficiency of AD education.

7.3 IMPLICATIONS FOR DESIGN RESEARCH

Finally, these issues are important for design researchers. Expert errors might not be errors. Instead, they might represent different strategies employed by expert designers to work around the limitations of existing design theories. Alternatively, the miscategorization of these FRs as 'errors' could indicate faulty assumptions on the part of the design researcher (in this case, the author) and the limitations of his or her understanding of requirements and design information. In either case, identifying and studying expert 'errors' can stimulate discussion and help the design community as a whole to improve both our understanding of design and to improve and expand existing design theories.

8 FUTURE WORK

This work raises a number of questions about the nature of requirements and the relationship between AD and more traditional product and engineering design. First, it raises questions about the concept selection process in AD. Axiomatic Design Theory can be viewed as a way to model the relationships between various types of design information rather than a step-by-step design process to follow. As a result, the generation of competing design concepts is mostly neglected in the classic AD texts and concept selection is primarily governed by the two axioms. Further discussion is needed to determine if SCs are a valid and necessary category of information in AD or if their role is built into other aspects of the theory.

Similarly, the requirements categories presented in this paper (FRs, nFRs, Cs, SCs, and OCs) are derived from both AD and from other design texts. As a result, the relationships between these categories have not been fully established in the context of Axiomatic Design Theory. For example, in section 3.2 of this paper, Suh treats real estate constraints as functional requirements and then applies the second axiom these 'FRs'. This raises the question of whether FRs and constraints are really different types of information and whether or not the 2nd Axiom could or should be applied to other types of requirements.

In addition, in this work we define nFRs as a distinct category of requirements information. But it remains to be seen whether nFRs are more than CNs that have been carried over to the functional domain without being properly mapped to the 'true' requirements categories (FRs, Cs, etc.). If nFRs are found to be a valid requirements category, do they currently serve as a catch-all for other yet-undefined requirements information like Norman's [1988] signifiers and affordances? This, in turn, indicates that we should explore whether or not signifiers and affordances represent sub-categories of human-centered FRs.

Finally, in this work input and system constraints are differentiated based on their focus and level of granularity. (Input constraints are portrayed as focusing on nFRs and being more specific and quantitative while system constraints are portrayed as focusing more on high level DPs.) However, the major distinction between the two is usually based on the source of the constraint (does it come from within the design process or from an external source?). This raises questions about the definitions of these types of constraints, if additional categories of constraints are necessary, and if constraints should be decomposed in hierarchies with different levels of detail like other types of requirements information.

This work does not attempt to answer these questions. Nor does it claim to identify an exhaustive list of requirements research questions to explore. It only suggests that a more rigorous investigation of 'errors' in FR definition may lead both to these questions and to their answers.

9 SUMMARY AND CONCLUSIONS

This paper presented five classes of common procedural errors that are made by designers at all levels during the definition of functional requirements. It was observed that certain types of errors are more likely to be made by AD novices while others are more common from AD experts. Novice errors seem to result from a lack of understanding of the theory. As a result, these errors tend to disappear as designers gain more knowledge and experience with AD. They are not an indication of AD's limitations. However, expert 'errors' may be indicative of questions about the nature of design information and/or the limitations of existing design theories. It is suggested that a more rigorous investigation of expert 'errors' in FR definition may lead to the identification of new design research questions and their answers. This, in turn, may improve design education.

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