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WHERE IS THE 'WHY' IN AXIOMATIC DESIGN?

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ABSTRACT

Axiomatic Design (AD) Theory describes the design process as a mapping of 'what' to 'how' across four design domains. Every decision during this process is made deliberately, from the highest-level functional requirements to the lowest level process variables. However, it is unclear how and where to document that information within the AD framework. This paper investigates where and how the goals, motivation, values, and rationale of a design project – the 'why' – are, could, and should be specified within AD. It presents three options for where to find the goals and motivation (the highest-level 'why') of a design project. It explores the various 'whys' associated with the requirements and mapping and decomposition processes. The design domains are then viewed as a whole and a new model that defines the relationship between 'why,' 'what,' and 'how' information in AD is presented.

Keywords: Axiomatic Design, design rationale, product development, decomposition.

1 INTRODUCTION

In Axiomatic Design Theory, "a rigorous design approach must begin with an explicit statement of "what we want to achieve" and end with a clear description of "how we will achieve it"" [Suh, 2001]. The transformation of an "abstract intent (i.e. 'what') to a concrete instantiation (i.e. 'how')" [Lu and Liu, 2011a] that satisfies the perceived needs of the stakeholders is achieved through a mapping between the design domains and through the decomposition of information within each domain [Suh, 1990]. Every decision made during this process is deliberate, from the definition of the highest-level functional requirements (FRs) to the choice of the lowest level process variables (PVs). Documenting these decisions ensures that the design task is not carried out in an ad hoc manner. It allows the decision process to be reconstructed if necessary [Krause et al., 1993]. It can also help to plan and perform maintenance [Suh, 1997], to determine "the causes of system failures or [detect] impending failures" [Suh, 1998] and to improve or modify an existing design [Suh, 1997; Lee *et al.*, 2001; Brissaud *et al.*, 2003].

Unfortunately, it is unclear how to document those decisions in the AD framework. As a result, many authors present only their final decompositions with no discussion of their choices beyond the necessity to adhere to the design axioms [Lee *et al.*, 2001; Gu *et al.*, 2001; Peck *et al.*, 2010; Melvin and Suh, 2002; Matt and Rauch, 2013] or with the design rationale included as supplementary information in the text [Cha and Cho, 1999; Kim *et al.*, 2004; Kim *et al.*, 2011; Ouellet and Vadean, 2013]. Examples like Ferreira *et al.* [2013], where multiple design options are developed and compared, are rare.

This work investigates where and how the goals, motivation, values, and design rationale of a design project – the 'why' – are, could, and should be specified within AD. It begins by presenting three options for where to find the goals and motivation (the highest-level 'why') of a design project. Next, it explores the various 'whys' associated with the requirements and mapping and decomposition processes. The design domains are then viewed as a whole and a new model that addresses the relative nature of why-type information is presented. Finally, the documentation process in Axiomatic Design Theory is considered.

2 PROJECT GOAL AND MOTIVATION: DEFINING THE HIGHEST-LEVEL 'WHY'

The goal or motivation is the reason why a design project is undertaken. From a decomposition perspective, it can be thought of as the highest-level 'why'. This section considers three different motivations for the development of an artifact and proposes where to find the highest-level 'why' for each.

2.1 THE HIGHEST-LEVEL 'WHY' IS DEFINED IN THE CUSTOMER DOMAIN OF THE ARTIFACT

The overall goal of a project can be to satisfy the customer needs (CNs) and to bring about customer (client, user, stakeholder, etc.) satisfaction. For example, most design consultancy firms design artifacts either to satisfy their clients or their clients' customers. In these cases, the highest-level 'why' for the design project is not explicitly defined but is implicit in the information contained within the customer domain. This is consistent with Lu and Liu's [2012] claim that the design intent or "highest overall goal to achieve" is "conceptually equivalent" to customer needs in Axiomatic Design Theory.

2.2 THE HIGHEST-LEVEL ‘WHY’ IS DEFINED IN THE HIGHEST-LEVEL FUNCTIONAL REQUIREMENTS OF THE ARTIFACT

In some cases, an artifact’s functionality is its reason to exist. For example, many early flying machines were designed because their designers wanted to fly. In these cases, the highest-level ‘why’ is synonymous with the highest-level ‘what’ and is contained within the highest-level FRs of the artifact. This is consistent with Suh’s statement that the “objective of design is always stated in the functional domain” [Suh, 1990], Alting *et al.’s* [2003] assertion that the “expected benefits of [a] product are expressed in terms of functional requirements”, and Lee *et al.’s* [2001] claim that the highest level FRs serve as the “mission statement” for a design project.

2.3 THE HIGHEST-LEVEL ‘WHY’ IS DEFINED IN THE FUNCTIONAL REQUIREMENTS OF A HIGHER (PARENT) LEVEL SYSTEM

However, many artifacts are a means to an end rather than the end itself. For example, most consumer products are designed to increase a company’s return on investment (i.e. profit). Different artifacts could be chosen to satisfy this FR, each with different customers, customer needs, and functional requirements. In these cases, the highest-level ‘why’ cannot be defined at the artifact level. Instead, the design domains must be viewed as a continuum that extend beyond the boundaries of the artifact (Fig. 1). This allows the designer to see that highest-level ‘why’ is often defined by the FRs of a higher-level (parent) entity. This is consistent with Thompson’s [2013a] assertion that many procedural errors in the definition of functional requirements stem from a conflation of the FRs of the artifact and of related higher-level systems.

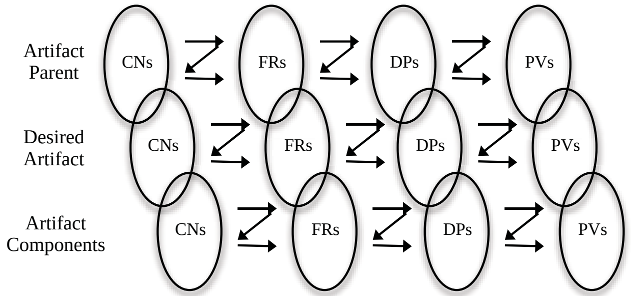

Fig. 1 Design domains of an artifact, its parent system and its components.

3 DEFINING THE REQUIREMENTS

Once the motivation for a project is established and the customer needs have been defined, the CNs are mapped to the highest-level FRs and used to define other types of requirements information. This section addresses how and why those decisions are made.

3.1 WHY THESE HIGHEST-LEVEL FRS?

At the highest-level of a decomposition, FRs are included because they are intrinsic to the artifact and its intended use, because they are needed to satisfy the customer needs, and/or because they are needed to fulfill the requirements of the parent entity. The intrinsic functions are those associated with what Kano *et al*. [1984] describe as basic and performance needs. They are derived directly from the goals and motivation of the project. For example, all mobile phones must send and receive phone calls. These FRs represent many of the project’s ends. Thus, there is no need to document their rationale independently from the project’s goals and motivation.

However, non-essential functions, like those intended to excite or delight users and increase the attractive qualities of an artifact [Kano *et al.,* 1984], are usually a means of accomplishing a higher (parent-level) end. For example, many mobile phones also take photos, access the Internet, and provide navigation instructions in order to increase the competitiveness of the product. Usually, multiple means are available to achieve these ends so there will be multiple highest-level FR options to consider and select from. Unlike their intrinsic counterparts, these FR options and the reasons for their inclusion or exclusion are an important part of the design strategy and should be documented during the design process.

3.2 WHY THESE CONSTRAINTS?

Constraints in Axiomatic Design Theory “represent the bounds on an acceptable solution” [Suh, 1990]. Like the highest-level FRs, some constraints are intrinsic to the artifact and its environment. For example, all artifacts must obey the laws of nature. Similarly, an artifact that is intended to function as a component in a larger system will have physical constraints (size, connection points, etc.) imposed by that system. An artifact that is intended for use by humans must take into account their limitations. And, many artifacts are subject to legal constraints such as building regulations [Albano *et al*., 1993] and emissions standards [Dandy *et al.*, 2008]. The rationale for these constraints is usually obvious and requires no explanation. However, providing some background for each constraint will help to document how it was identified (e.g. what issues were considered) and reduce the chances of missing other constraints during the requirements process.

Constraints are also derived from the customer needs and/or the parent-level requirements. For example, bounds on size, weight, and cost can all be chosen to satisfy the customer and/or to increase an artifact’s competitive advantage. However, unlike the highest-level FRs, these constraints are often comparative and/or contextual. For example, in commercial markets, the features and performance of existing artifacts set the minimum baseline for the development of new artifacts. In order for a new product to be competitive, it must be somehow better (smaller, lighter, cheaper, etc.) than the alternatives. The rationale for these decisions should appear in the documentation of the benchmarking activities performed during the background and stakeholder research phase of the conceptual design process.

3.3 WHY THIS DESIGN RANGE?

In Axiomatic Design Theory, a design range specifies the bounds on the acceptable performance of a function [Suh, 2001]. Some functions are binary; they are either performed or they are not. In these cases, there is no meaningful design range and thus nothing to document. All other design ranges represent a choice by the designer. Like constraints, many design ranges are derived directly from the customer needs and the parent-level requirements. For example, improved performance may be chosen as a means to achieve a parent-level end such as increased sales. And like constraints, the values for many design ranges are comparative or contextual. For example, the improvement of a function will often be defined relative to a previous version of the artifact or to a competitor. As a result, some of the rationale for a design range will appear in the benchmarking documentation. However, it is often necessary to balance stakeholder satisfaction with the techno-socio-economic realities that are reflected in the constraints. The factors that were considered during the definition of a design range, how they were prioritized, and why the final decision was made should be documented as a part of the design process.

3.4 WHY THESE SELECTION / OPTIMIZATION CRITERIA?

Selection criteria (SCs) are used to choose between different design concepts, while optimization criteria (OCs) are used to refine and improve the final artifact [Thompson, 2013a]. They often address the same qualities as constraints (cost, weight, efficiency, etc.) but indicate which to minimize or maximize rather than setting a hard limit on their values. SCs and OCs are derived directly from the customer needs and the parent-level requirements. But because they imply a ranking or a prioritization, they always require choices on the part of the designer. The reason why some criteria were chosen over others and why a given number of criteria were chosen should be documented as part of the design process.

4 MAPPING AND DECOMPOSITION

Once the highest level FRs and the other requirements information have been defined, the mapping and decomposition process can begin.

4.1 WHY THESE DPS?

The process of defining design parameters (DPs) is essentially the same at every level of decomposition. Multiple options for satisfying each FR are generated or are retrieved from knowledge bases [Suh, 2001]. These options are screened [Ulrich and Eppinger, 2008] for feasibility [Kim *et al.*, 2006] and to ensure that they do not violate the constraints [Suh, 2001; Kim *et al.,* 2006]. The remaining concepts are scored or ranked based on performance criteria [Chen and Lin, 2002] and one option is chosen for inclusion in the final decomposition. Although this mirrors the divergent-convergent nature of more general engineering and product design processes, the AD design process differs in two ways: the generation and selection is done for each individual DP instead of for collections of DPs (i.e. design concepts) and both processes are strongly affected by the design axioms.

The generation of design concepts and design parameters depends on the designer's creativity [Suh, 1990], his or her knowledge and experience, and the design tools and methods (brainstorming, morphological charts, analogy, design from first principles, reverse engineering, etc.) used [Suh, 2001]. The generation of DPs is also guided by the need to maintain the independence of the FRs [Suh, 1990]. As a cognitive process, ideation is not well understood. Thus, designers themselves may not be aware of why a given DP option was proposed. However, most of the time a solution is proposed because the designer knows that it has performed well in another form or another context. If this information is available, documenting it may help to inspire the generation of other options and/or to inform the selection process. But this particular 'why' is normally left unaddressed.

The (rational) selection of design concepts and design parameters in engineering and product design usually relies on some kind of weighted decision matrix to rate and rank the design concepts for selection [Slocum, 1992]. In Axiomatic Design Theory, the design axioms should be applied prior to this step and can be thought of as a pre-condition for selection. In an ideal situation, only DPs that lead to designs that satisfy the Independence Axiom and have zero Information Content will be put forward for selection. In these cases, the design rationale is contained in the selection criteria and the weights assigned to them. The design axioms do not answer why a particular DP has been chosen but they can explain why another has not. If the axioms have not been satisfied, then they can be used as selection criteria (i.e. the least coupled design and/or the design with the lowest Information Content should be chosen). In these cases, the design axioms do represent part of the design rationale. However, the 1st Axiom implies that it is better to return to the decomposition and attempt to locate and remove the source of coupling.

4.2 NO 'WHY' FOR SOME UPPER-LEVEL DPS

There are some exceptions to the scenario discussed above. At the highest-level(s) of the decomposition, design parameters often represent "conceptual entities" or the "design intent" rather than specific solutions [Suh, 2001]. As a result, designers sometimes define DPs that perform the desired functions by definition but otherwise have no meaning. For example, if FR1 is to "dry <something>" then DP1 can be defined as a "dryer" or a "drying system". These 'place-holder' DPs are important because they satisfy the 1:1 mapping required by the Independence Axiom and allow the design process to proceed. But they do not require any options to be generated and do not permit any choices to be made. Thus, there is no why-type information associated with theses DPs.

4.3 WHY THESE LOWER LEVEL FRS?

After all of the design parameters for a given level have been defined, the FRs for that level can be decomposed. This process can be viewed in three ways. First, the lower level FRs (FRij) can be viewed as defining the goals or motivation of the object or solution (DPi) that will perform the function required (FRi). From this perspective, the definition of lower level FRs is the same as the definition of the highest-level FRs and the why-type information is found in the same places. While this method may result in a good decomposition, it greatly increases the size of the design space and thus reduces the efficiency of the design process.

Second, the decomposition process can be thought of as an analytical or reverse engineering process that seeks to identify the functions that are commonly performed by the specified DP. For example, many dryers (DP1) heat air (FR11) and then blow the hot air onto a wet medium (FR12). This type of decomposition is often ill advised because it does not allow the FRs to be defined in a solution-neutral environment. This leads to increased opportunities for fixation and bias and thus less potential for innovation. However, it may be useful in cases where the parent DP is well defined and requires decomposition only to specify the interactions between its sub-components and other parts of the artifact.

Finally, the decomposition process can be thought of as a divergent-convergent process in the functional domain that mirrors the one that occurs in the physical domain. In this case, multiple options for each sub-FR are generated (or are retrieved from knowledge bases). These options are then evaluated and one option is chosen for inclusion in the final decomposition. In this case, the design rationale for the lower level FRs is contained within the criteria used to select between the different functional solutions. If the decomposition process is viewed in the third way, the question is not "what functions must the higher-level DP perform?" but rather "how will the higher-level FR be achieved functionally?"

5 THE 'WHY' IS RELATIVE

Thus far, the discussion in this paper has focused on the various stages of the design process. This section considers the 'why' in the design process as a whole.

5.1 THE 'WHY' IS RELATIVE AND REVEALED BY THE BACKWARDS HORIZONTAL MAPPING OF WHAT-TO-HOW

Each design domain in AD represents 'what we want to achieve' relative to the domain on its right and 'how we propose to achieve it' relative to the domain on its left [Suh, 2001]. Thus, the design process can be thought of as a series of what-to-how mappings between each of the four design domains. Lu and Liu [2011a] claim that a backwards mapping of the what-to-how relationship is a how-to-what relationship. However, each PV is present because it is needed to create its associated DP(s). Similarly, each DP exists because it is needed to perform its associated function(s). And, each FR is included to satisfy one or more customer or stakeholder needs. Thus, it might be more accurate to say that a reverse mapping in Axiomatic Design Theory actually represents a what-to-why relationship (Fig. 2). Similar observations have been made in the AD literature [Sohlenius *et al.*, 2002; Moon, 2011; Marques *et al.*, 2013), by Cross [2000] in the context of objective trees, and by Otto and Wood [2001] in association with the FAST method.

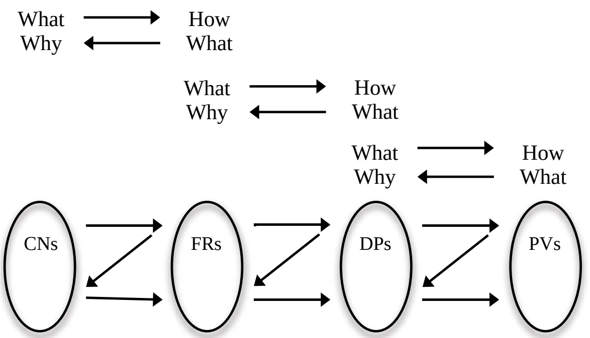

Fig. 2 Forward what-to-how and backwards what-to-why mapping between design domains.

5.2 THE 'WHY' IS RELATIVE AND REVEALED BY THE BACKWARDS VERTICAL DECOMPOSITION OF WHAT-TO-HOW

In their discussion of a logic-based foundation for Axiomatic Design Theory, Lu and Liu [2011b] also claim that the horizontal mapping across domains represents a synthetic "means-of" relationship while the vertical decomposition represents an analytic "part-of" relationship. Each sub-FR, sub-DP, and sub-PV is part of its parent entity from a forward decomposition perspective. Based on this logic, parent entities can be viewed as the reason why each child entity exists. This implies that backwards vertical decomposition can also be thought of as a mapping of what-to-why within each of the design domains (Fig. 3).

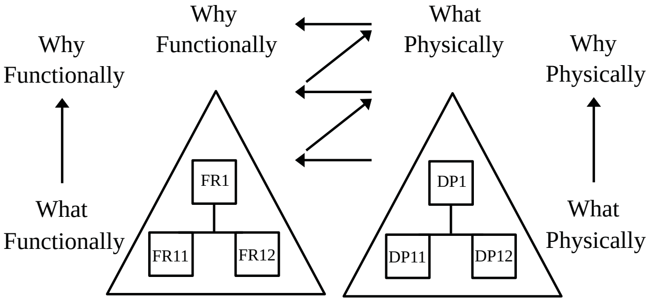

Fig. 3 Backward two-dimensional what-to-why mapping and decomposition.

If the mapping and decomposition process demonstrates a symmetric property of equality, then sections 5.1 and 5.2 indicate that a forward what-to-how mapping also takes place within the design domains (Fig. 4). This is supported by the third view of functional decomposition discussed in section 4.3.

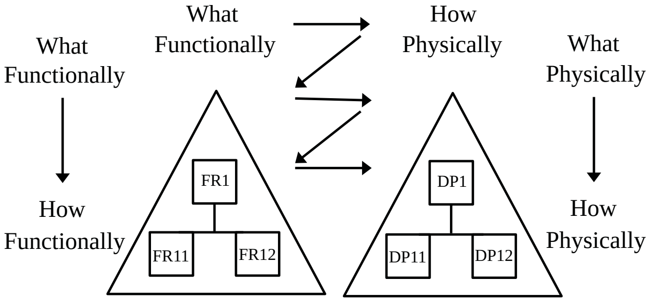

Fig. 4 Forward two-dimensional what-to-how mapping and decomposition.

These views of the relationships within and between the design domains are consistent with the earlier observations that the 'why' appears in the customer domain, the functional domain, and the extended requirements categories [Thompson, 2013b] as well as with observations that it affects all aspects of the design process. This model also explains why the 'why' is so completely integrated into the design process and why it has traditionally been so invisible.

6 WHERE AND HOW TO DOCUMENT THE EXTRINSIC ‘WHY’?

This paper has argued that much of the why-type information in the design process is intrinsic to the artifact and/or contained within the design domains, the extended requirements categories, and the relationships between them. However, it has also argued that some why-type information is not directly incorporated into the Axiomatic Design framework. Traditional engineering and product design captures this information in the form of mission statements, mind maps, concept classification and combination trees, morphological charts, Pugh charts, concept screening matrices, etc. Rather than extending the Axiomatic Design framework to incorporate this information in other ways, the connections between AD and traditional engineering and product design processes and methods could be strengthened so the existing tools can be used more easily with both. Existing Axiomatic Design software [Do and Suh, 1999; Suh and Do, 2000] can also be used and improved to automate the documentation process.

7 SUMMARY AND CONCLUSIONS

This paper has investigated where and how why-type information is specified within the AD framework. It was claimed that the highest-level 'why' can be found in the CNs, the highest-level FRs of the artifact, and/or the FRs of a parent-level entity depending on the design task. Within the requirements process, some why-type information is intrinsic to the artifact while other information must be documented separately. Within the mapping and decomposition process, specific why-type information can either be unknown, contained within the requirements information, or documented outside of the AD framework. Finally, it was claimed that the 'why' is a relative property and represents the relationships between different types of information. Why-type information that is not currently contained within the AD process can be documented using traditional design tools and methods and/or AD software.

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