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Axiomatic Design: Making the Abstract Concrete

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Abstract

Design broadly defined deals with mapping from societal wants or needs to means for satisfying these needs. Axiomatic design is a well-known approach to design that was initially proposed by Nam P. Suh in the late 1970s. Since that time, it has underpinned much academic research in engineering design; it has been taught internationally as part of engineering curricula; and it has been used across many industries. This paper presents a summary of axiomatic design and provides practical suggestions for best practices in implementation and education.

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1. Introduction*

Axiomatic design (AD) was created by N.P. Suh to create an "academic [discipline] for design and manufacturing" and detailed in three books [1-3]. The starting point for axiomatic design is that "there exists a fundamental set of principles that determines good design practice" [1] in contrast to views that good design cannot be taught, but can only be learned through experience. A primary motivation for developing axiomatic design is education. To be effective "the student must be taught to see the big picture and [be taught] the ability to conceptualize a solution, as well as how to optimize an existing product or process" [1]. The keys are "correct principles and [methods] to guide *decision making in design;* otherwise, the ad hoc nature of design cannot be improved" [1].

Since AD theory was first introduced to CIRP in 1978, AD has been drawing significant attention in the CIRP and various engineering communities. 39 papers in CIRP Annals and 5 papers in Journal of Manufacturing Science and Technology directly used AD in their work. Among the articles appeared in the CIRP Annals, there are three keynote papers on Axiomatic Design and there are 28 other keynote papers that cite AD as a major related work. This paper provides two contributions to initiate constructive discussion among the community in CIRP: First it provides a comprehensive, current review and summary of key work that has been done in the field of Axiomatic Design. Second, based on this review, the authors provide their conclusion on whether Axiomatic Design research has achieved Suh's vision of providing a means to teach and practice good design.

2. Concepts

At its most basic, axiomatic design is composed of five concepts. These concepts are domains, hierarchies, zigzagging, and the two design axioms. The theory was later expanded by Suh to include concepts of time-varying large systems, complexity in terms of uncertainty and strategies for reducing complexity [3, 4].

Axiomatic Design Process. A *design process* is a sequence of activities in which engineers or designers develop and/or select the means to satisfy a set of objectives subject to constraints. The way that AD summarizes this is that designers map from "what do they want to do?" to "how do they choose to do this?" [1]. The AD design process consists of at least three activities: "problem formulation," "synthesis" (concept

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generation), and "analysis" (concept evaluation and making a decision) [1, 5].

Domains and mapping. During the design process, the task which is being addressed can be divided into four *domains* [6]. The four domains are generalized as the *customer domain*, the *functional domain*, the *physical domain*, and the *process domain*. Associated with each domain are the design elements it contains. AD terms these *customer attributes* (CAs), *functional requirements* (FRs), *design parameters* (DPs), and *process variables* (PVs). The design axioms are applied as designers map between domains [1, 2]. In addition to these elements, *constraints* on the design task are not restricted to a particular domain, but limit the choice of acceptable solutions [1].

Functional Requirements. *Functional requirements* are "*defined* to be the minimum set of independent requirements that completely characterize the design objectives for a specific need" [1]. A key observation by Suh is that these FRs must be specified in a "solution-neutral environment" in terms of the functions to be achieved, *not in terms of particular solutions*. Related to the solution neutrality requirement is the inherent independence of FRs. That is, when FRs are defined in the functional domain, there is no pre-existing interdependence between the FRs, and in principle it is possible to satisfy the FRs independently.

Design Parameters. *Design parameters* are defined as "the set of elements of the design object that have been chosen to satisfy the FRs" [1]. These can be items used in product design: geometric parameters, material properties, part features, assemblies, and so on. Beyond this, they can consist of intangible items: strategies, methods, software classes, etc.

Process Variables. Process Variables include fabrication methods, resources, and implementation plans to materialize the design parameters. In the axiomatic design process, a directed relationship exists between domains: CAs to FRs, FRs to DPs, and DPs to PVs. This directed relationship is referred to as *design mapping*, in which the objectives (what) are mapped to means to achieve them (how).

Good Practice

The first fundamental principle in the axiomatic design theory is that a design task must begin with carefully defining the goals and objectives of design. Only after they are clearly and explicitly stated, can the designers proceed to conceive appropriate solutions to achieve them. While it sounds simple, our experiences and observations abound with examples where a design project suffers due to poorly and ambiguously defined requirements or requirements that are constantly shifting during the design process. Also, many bad designs come about when designers mix "what" and "how" in the same domain.

Hierarchies. The design process progresses from a system level, or a high level of abstraction, to levels of more detail. The decisions about the design object are represented in three of the domains with *design hierarchies*: an FR hierarchy, a DP hierarchy, and a PV hierarchy.

Zigzagging. The designers go through a process in which they zigzag between domains in decomposing the design problem. At a given level of the design hierarchy, a set of functional requirements exists. Before these FRs can be decomposed, the corresponding design parameters must be selected. Once a functional requirement can be satisfied by a corresponding design parameter, that FR can be decomposed into a set of sub-requirements, and the process is repeated. The designers follow the zigzag approach until they have decomposed the problem to a point where the solutions to the remaining sub-problems are known.

Decision Making in Axiomatic Design. Axiomatic design provides guidelines consisting of axioms, theorems, and corollaries that specify the relationships that should exist between the FRs and the DPs of a design.

The Design Axioms. *Axiomatic design* is defined as the use of axioms to identify good design. The two design axioms are stated as follows [1]:

- *The Independence Axiom (First Axiom):*
  Maintain the independence of functional requirements.
- *The Information Axiom (Second Axiom):*
  Minimize the information content [of the design].

These axioms were generalized from observations of good design decisions. They establish the minimum acceptability for a design solution, and enable the identification of the best among several proposed. In addition to the axioms, AD has many theorems and corollaries that follow from the two axioms.

System Architecture and Modularity. In addition to hierarchies, Suh has proposed definition of system modules according to the design hierarchies combined with the relationships within the design matrices [8, 9]. AD approach to modularity contrasts sharply with other approaches that focus on defining modules based on DPs, rather than based on design matrices.

Measures of Coupling. Some measures of coupling have been tried. These include *reanglularity* and *semangularity* [1, 10]. Lee has proposed methods for understanding the value of removing an off-diagonal term and for identifying an optimal strategy for eliminating coupling terms from DM [11-13].

Common Design Mistakes. Suh provides a list of common design mistakes that the Independence Axiom can catch, as follows [2]:

- **Coupling due to insufficient number of DPs**: When the number of DPs is less than that of FRs, a coupled design always results. To avoid this, the number of FRs should be made equal to the number of DPs.
- **More DPs than FRs**: This results in a *redundant design* and increased variability or decreased robustness. To avoid this, the number of FRs should be equal to the number of DPs.
- **Not recognizing a decoupled design**: One must recognize the design is decoupled and then determine (change) the DPs following the right sequence given by the triangular design matrix. Otherwise, the design will be the same as a coupled design.
- **Functionally coupled design to make a physical integration**: Many designers confuse functional independence with physical independence. Physical integration is desirable as long as the functional requirements remain independent and uncoupled.

Information Content. *Information content* has been defined in AD as the log of the inverse of the probability of success of satisfying a function [1, 14]. This definition of information