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Axiomatic Design: Making the Abstract Concrete

Mats Nordlund^{1*}, Sang-Gook Kim², Derrick Tate³, Taesik Lee⁴, and Hilario (Larry) Oh²

¹Innovation Advisory Partners Scandinavia, Mölndal, Sweden²MIT Park Center for Complex Systems, Cambridge, MA, USA³Department of Industrial Design, Xi'an Jiaotong-Liverpool University, Suzhou, China⁴Dept. of Industrial and Systems Engineering, KAIST, Daejeon, Republic of Korea

* Corresponding author. Tel.: +46-70-398-0837; E-mail address: mats.nordlund@gmail.com

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

* This paper is derived from two papers originally published at the ASME IMECE, “Suh symposium” in November 2015.

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 *reangularity* 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

extends Shannon's definition to physical manufactured designs [15, 16].

$$I = \log_e \frac{1}{P_s}$$

In generating an FR, the designers define a desired target value for the FR. They also specify an appropriate tolerance region about this target value; this region is known as the *design range*. Each available design alternative is able to provide the desired FR within its system range. This *system range* is the region in which the design alternative performs relative to the design range. The intersection of the system range and the design range is called the *common range*.

The *probability of success*, labeled P_s to indicate its basis on the tolerance of the FR is defined as the ratio of the common range to the system range, and the information content, I , is the natural log of this. For uncoupled designs the FRs may be considered independent variables. Thus the total information content for a set of n FRs in an uncoupled design is equal to sum of information contents for each of the n FRs.

Good Practice

The principled nature of axiomatic design differentiates it from many existing design methodologies that study design processes and aim to extract descriptive and prescriptive design rules and guidelines for successful designs. AD teaches a very insightful thinking process, especially useful for the very early stage of design.

Definition of Complexity. Suh looks at large-scale systems that are dynamic [4]. In such systems, the FRs change with time, and traditional ways of synthesizing good solutions are inadequate. Such systems exhibit *complexity* [17], which AD defines as a measure of uncertainty in satisfying the FRs [3] that can take several forms.

Time-Independent Complexity. Time-independent complexity can be either *real* or *imaginary*. *Real complexity* describes uncertainty due to non-zero information content. Part of the system range is outside the design range. *Imaginary complexity* is due to lack of knowledge of the system, for example, a design matrix that is decoupled, but FRs that cannot be met because the sequence of setting the DPs is not known.

Time-Dependent Complexity. Time dependent complexity can be combinatoric, in which the state of the system and the next FRs to be fulfilled are determined by the prior states of the system [3, 17].

Reinitialization and Functional Periodicity. AD introduces guidance to reduce complexity in combinatoric systems through converting them into periodic systems. AD can describe several types functional periodicity: temporal, geometric, biological, manufacturing process, chemical, thermal, information process, electrical, circadian, and material periodicity. AD also provides guidance to reduce combinatoric complexity of systems through reinitializing the system by defining a *functional period*, that is, a repeating set of functions [3].

3. Education

Suh says that "From [his] experience in teaching this subject to many engineers and students, it has become clear that axiomatic design is not an easy subject to learn, much less to master, without some effort—perhaps because of the

conceptual nature of the subject" [2]. Initial interest in the topic of teaching axiomatic design was low in the first two axiomatic design conferences with only one paper in this focus area of "teaching and learning methods" [18]. More recently, the numbers of papers on axiomatic design education have grown [19-23].

Courses on Axiomatic Design

Graduate Level. Axiomatic design was originally taught as a graduate-level course at MIT by Prof. Suh starting in the 1987-88 academic year using a draft of his book *The Principles of Design* [1]. Next it was taught as a summer course at MIT during the 1990s [24]. A more recent iteration of the course from 2005 that incorporates Suh's complexity theory [3] can be found on MIT's Open CourseWare.

Undergraduate Level. The Korea Advanced Institute for Science and Technology (KAIST) conducted a bold initiative for all freshman students to study design [25-28] as part of efforts towards achieving the university's goals and creating a campus-wide culture of design thinking [29]. At KAIST, the goals were to effect a deep change in the students' thinking, view of their role in the world, and mode of working [28]:

Precollege and Community College Level. The axiomatic approach to design has also been applied to community college education in automatic technology [30], and in inspiring a the FRAME design process model for primary through grade 12 (P-12) engineering education [31, 32].

Industrial Workshops. Industrial workshops or short courses have been used to introduce companies to axiomatic design and to work on solutions to particular design tasks. An example of a similar workshop can be found at the website for ICAD2013, see AxiomaticDesign.com.

Good Practice

Many engineers find it challenging to learn axiomatic design. One of the hardest challenges is usually how to establish a minimum set of independent, solution-neutral functional requirements that are all at the same level of abstraction. We believe that the reason that this is perceived to be so difficult is that most engineers are not used to thinking in terms of functions instead of solutions.

We have found that taking a process-oriented approach to establish functional requirements often works well. Establishing the right set of FRs is critical to the success of the design because these will govern the rest of the process.

The next challenge is mapping from the FRs in the functional domain to the design parameters in the physical domain. At this stage of the process, the designer has to propose a solution (in the physical domain) with design parameters that can be selected or adjusted to control the corresponding function in such a way that the independence of the FRs is maintained. Since most engineers are comfortable to think in terms of solutions, this step is generally easier than the first one.

Once the FRs and DPs are established, the analysis of the relationship is relatively straightforward. However, many times there are non-linear relationships, weak relationships, and unknown relationships between the FRs and DPs. At times, the relationships may also change over time (e.g., from wear and tear). In determining the relationships, the designer needs to acknowledge all these non-ideal situations as they do represent the reality the designer must deal with. Understanding the

approach to dealing with decoupled designs through proper sequencing of the DPs can prove critical to proceeding with a successful design when applicable.

Recognizing that the design is coupled, and proposing a new and better design is the only rational way forward when dealing with a coupled design. For advanced students, working with tolerances and constraints also help resolve a number of potentially coupled designs.

Once the design has been analyzed and found to satisfy the design axioms, the FRs are decomposed in the sequence determined by the design matrix, and the next-level independent, solution-neutral functional requirements are established and the process continues until the designer has a full understanding of how to implement the design.

Across the different areas where we have taught axiomatic design, we have found that most people can follow the methods well, but have difficulties to work independently or lead the process.

We have found that for shorter courses for industry (1-2 days), good learning objectives are to develop the designers' abilities to Establish good FRs; Understand the concept of domains and separate "what" from "how"; Map FRs to DPs; and Conduct simple design matrix analyses. Most time should be spent on the first two points and plenty of examples used to get the participants familiar with these steps. For longer courses, more elements and greater complexity can be added.

4. Industry

Axiomatic design has been taught and applied across a wide variety of industries. The areas in which axiomatic design has been applied are numerous: manufacturing process design, product design, organizational design, automotive, semiconductor, software, organizational design, corporate planning, production systems, systems biology, and others [2, 24, 33, 34].

Recent Industrial Examples. A prime example in industrial applications is MuCell Process, commercial name for a widely used manufacturing process for microcellular plastics. The idea of microcellular plastic was originally conceived by Suh when he defined new FRs for light weight high strength plastic products [1]. Microcellular plastics are polymer foams having cell densities much higher than conventional foams. Its small cell size, smaller than the critical flaw size, enables to achieve the desired mechanical properties while reducing significant amount of plastic used in mass produced plastic parts. In the domain of system design, Online Electric Vehicle (OLEV) developed at KAIST is a notable success, which was recognized by TIME magazine as one of the 50 best inventions of 2010. The online electric vehicle (OLEV) is an electric vehicle using electromagnetic induction from the electric power strips buried under the road surface and connected to the national grid. By decoupling the heavy and very inefficient energy storage (battery) from the vehicle, a light-weight, efficient and less CO₂ producing transportation system could be realized. [35].

At the micro- and nano-scale, product realization has been extremely difficult because the make-and-see approach does not work. By decoupling the coupled micro- and nano-systems designs at the early design stage, successful MEMS products and processes have been developed such as thin-film micro

mirror arrays for projection display [36], directed assembly for individual carbon nanotube [37], drop-on-demand process for piezoelectric MEMS devices [38], and high temperature stable nanostructured solar absorbers and selective emitters [39], among others.

AD also has been applied to improve health care systems. By finding a solution to uncouple the patient flow system in hospital emergency departments (ED) [40].

5. Criticism and Future Studies

Axiomatic Design is unarguably one of the highest impact contributions developed by CIRP colleagues in the field of design and manufacturing, influencing theoretical research in academia and design practice in industry. AD teaches insightful thinking process, especially useful for the very early stage of design. As much as the merits of the principles in the Axiomatic Design theory have been evidenced in academic research and applications, validity of design axioms has been questioned and debated over time. On a practical side, there also have been criticisms and questions on difficulty in using AD for real design practices. Some criticize that cases reported in AD literature are obvious and, sometimes, just the retrospective application of AD after finding design solutions

We observe that inexperienced practitioners of the Axiomatic Design theory find it difficult to follow and apply the principles in their design, and this often leads to misunderstanding and skepticism about the theory. Perhaps what underlies this skepticism shed a light on an aspect of the theory that can be strengthened in the future.

One of the hardest challenges is why AD is difficult to learn and complex to use. This is usually associated with the question how to establish a minimum set of independent, solution neutral functional requirements (FRs) that are all at the same level of abstraction. We believe that the reason why this is perceived to be so difficult is that most engineers are not used to think in terms of functions - rather they have been accustomed to think in terms of physical solutions. We have found that taking a process oriented approach to establish functional requirements often work well: the designer should attempt to describe what he/she wants to achieve firstly before any physical solutions. Establishing the right set of functional requirements (FRs) becomes critical to the success of the design since the top level FRs will govern the rest of the design process. Wrong choice of FRs can result in meaningless decomposition and the unsuccessful final design solution. This may frustrate industrial designers who expect AD would provide good solutions only if they keep decomposing their requirements. It should be understood that AD is a thinking framework, not an automated design software.

The next challenge is mapping from the FRs in the functional domain to the design parameters (DPs) in the design domain. At this stage of the design process, the designer has to propose a solution (in the physical solution domain) with design parameters that can be selected or adjusted to control the corresponding function (FR) in such a way that the independence of the FRs is not compromised. This mapping process is also a challenge, but since most engineers are comfortable to think and talk in terms of solutions, this step is generally easier than the previous one.

The above challenges are partly due to the fact that AD is relatively less specific in terms of design process. While AD is well accepted as a design methodology, little emphasis has been given to develop well guided methods in it. A method refers to a systematic procedure or technique, for example, a design matrix analysis. A methodology, on the other hand, is a body of methods, rules, and postulates employed by a discipline. Methods are tools and techniques used in one's research, and a methodology justifies the choice of particular methods. By augmenting the theory with more rich set of standardized methods, it will help potential users of the Axiomatic Design theory to better understand and properly practice the principles in it. The following are the key steps of AD design process, which needs to be incorporated to design processes and specific tools and methods in the future AD studies.

- Establish solution neutral FRs from customer needs
- Map FRs to DPs
- Analyze a design matrix to verify that the design satisfies the independence axiom and the information axiom
- Revise DPs to avoid coupled designs
- Decomposition through a top-down, zig-zag process

Authors view that the greatest benefit of AD really comes from the basic principles – clearly define your problem and then develop a design solution that is free of functional coupling. Across the different areas where we have taught AD, we have found that one successful message to students when they struggle is that “Return to the basic ideas of AD when confused or lost. The key concept of AD is simply to think what you want to achieve before how they can be achieved.”

6. Conclusion

Axiomatic design, since its inception, has underpinned much academic research in engineering design, has been taught as part of engineering curricula, and has been used across many industries.

It is clear, from the surveyed material in this review article and the related progress observed in education and industrial practice, that Axiomatic Design has significantly impacted both design teaching and practice in many places around the world. Thus, we conclude that Axiomatic Design has to a large degree shown that it is possible to achieve Suh's original ambition of establishing a theory on what is a good design which then can be taught and used in practice to improve performance of teaching and industrial activities related to design.

We are looking forward to further contributions in engineering design research from colleagues developing the field of principle-based design theory, methods, and tools.

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