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AXIOMATIC DESIGN: 30 YEARS AFTER

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ABSTRACT

In 1977, Nam P Suh proposed a different approach to design research. Suh's approach was different in that it introduced the notions of domains and layers in a 2-D design thinking and stipulated a set of axioms that describes what is a good design. Following Suh’s 2-D reasoning structure in a zigzagging manner and applying these axioms through the design process should enable the designer to arrive at a good design.

In this paper, we present our own experiences in applying Suh's theories to software design, product design, organizational design, process design, and more in both academic and industrial settings. We also share our experience from teaching the Axiomatic Design theory to students at universities and engineers in industry, and draw conclusions on how best to teach and use this approach, and what results one can expect.

The merits of the design axioms are discussed based on the practical experiences that the authors have had in their application. The process developed around the axioms to derive maximum value (solution neutral environment, design domains, what-how relationship, zig-zag process, decomposition, and design matrices) is also discussed and some updates are proposed.

INTRODUCTION

Systematic research in engineering design began in Germany during the 1850s. Up until around 1990, most research in engineering design focused on developing design methods based on some heuristics and collective experience.

However, there was a lack of a scientific approach to design. One that made it possible for designers to analyze a design early on to determine its merits rather than design the device through a random search process, then build it and finally through a trial an error process (hopefully) arrive at an acceptable design.

In 1977, Nam P Suh proposed a different approach to design research (Suh 1990). He saw a number of analogies between the field of design and the field of thermodynamics. The science of thermodynamics was established as a result of many people trying to generalize how good steam engines work. Before the laws of thermodynamics were established, only experienced designers could design good steam engines, and the performance of two alternative designs could essentially only be compared by experimentation as no analytical framework existed. This was essentially the state of design in 1977: Only experienced designers could be expected to consistently make good designs, and comparison of two alternative designs could often only be made by full scale testing.

Suh analyzed a number of good designs to identify what were common elements present in all these designs. As a result a number of potential axioms were identified. These were then reduced down to two axioms through a logical reasoning process [1]. These axioms are

1. The Independence axiom- “*Maintain the independence of functional requirements*,” and
2. The Information axiom - “*Minimize the information content of the design.*”

These axioms, just like any axioms cannot be proven, but they can be invalidated by a counter example. Since the field of design, like most academic fields, was conservative - many established researchers viewed an emerging axiom-based approach to design with a lot of skepticism. A number of researchers have tried to produce counter examples to invalidate the axioms. The suggested counter examples have so far been shown to be constructed based on a misunderstanding of the design axioms and how to use them. Thus, to this date we are aware of no counter example that invalidates the axioms.

CONCEPTUAL BUILDING BLOCKS OF AXIOMATIC DEISGN THEORY

The Axiomatic Design theory defines design as a mapping between what we want to achieve and how we will achieve it. The theory prescribes normative rules to follow in a design process. In our opinion, the two most fundamental principles that Axiomatic Design theory offers are definition of functional requirements and design axioms. These two principles guide designers to successful outcomes in their design tasks.

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 one proceed to conceive appropriate solutions to achieve them. While it sounds simple and plain, our experiences and observations abound with examples where a design project suffers due to poorly and ambiguously defined requirements. In the classical Axiomatic Design theory, this principle has been formally described based on the concept of design domains and mapping.

Four design domains – namely, *customer* domain, *functional* domain, *physical* domain, and *process* domain – specify a design space where designers iteratively explore to turn customers' needs and wants into a materialized solution. These four domains represent following design processes; customer needs and wants are elaborated (customer domain), functional requirements (FRs) are defined such that the elaborated needs are satisfied (functional domain), solution concepts are generated (physical domain), and means to fabricate or implement the solution are specified (process domain). See

Figure 1 for illustration.

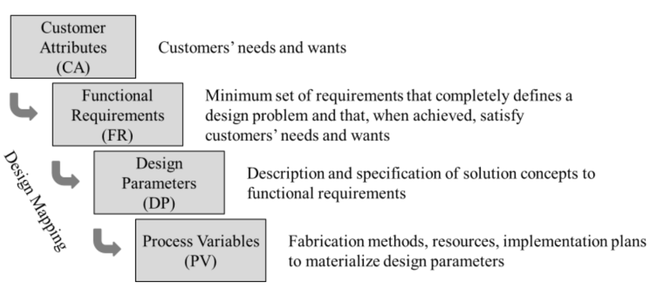

Figure 1. Design domains and mapping

In this design process, a directed relationship exists between domains. Functional requirements FRs are derived from customers' attributes; and solution concepts design parameters, DPs are derived from FRs, and finally means to fabricate them, process variables, PVs are derived from DPs. This directed relationship is referred to as *design mapping*, where the objectives (what) are mapped to means to achieve them (how). Hence, design is an iterative, repeated execution of design mapping with more details incorporated as the process moves on. In many applications of the Axiomatic Design theory, main focus is often on the mapping between FRs and DPs, which is a core process of developing solution concepts.

One important requirement in design mapping is that the objectives (FRs) must be defined in a *solution-neutral* environment. Solution neutrality requires that when defining FR, it shall be stated purely as a requirement and be free of any bias from prospective solution approach such as a specific technical discipline or implementation strategy. When FRs are not solution-neutral, design mapping produces the obvious DPs that have been implied in FRs, making it a mere documentation practice. 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.

While the first principle emphasizes the importance of judiciously identifying and explicitly stating a design problem, the other fundamental principle concerns the goodness of solutions to the given design problem. Two design axioms aid designers to determine the soundness of a solution conceived in design mapping so as to they arrive at a good solution. Independence Axiom dictates that a good design solution must maintain the independence of a set of FRs. Violation of the Independence Axiom is determined by evaluating a design matrix. A design matrix is a matrix representation of the relationship between FRs and DPs. If there exists a cyclic interaction – i.e., DP_i affects FR_j, DP_j affects FR_k, and DP_k affects FR_i –, FRs cannot be satisfied independently, violating the Independent Axiom. Such cyclic interaction is referred to as functional coupling. The second design axiom, Information Axiom, concerns the complexity of a design solution. Information content of a design can be loosely interpreted as the amount of information to achieve FRs by the design. The Information Axiom states that a good design solution must minimize its information contents.

When a design has functional coupling, it can negatively affect the quality and performance in many aspects. Detail design and development can suffer from excessive iterations and rework. A seemingly small change in requirement or solution component may create a ripple-through. Tolerance and specifications need to be tightly controlled, which increase overall cost. Likewise, high information contents imply high complexity of a given solution concept, and more difficulty (less chance of success) in achieving FRs. Thus, designer's objective in the mapping process is to develop a solution concept that yields a design matrix structure free of functional coupling and that has information contents as low as possible.

The principles described above, which are formally codified as design axioms and theorems, help designers avoid mistakes in their design. Common design mistakes Axiomatic Design can catch can be summarized as follows.

- Coupling due to insufficient number of DPs: When the number of DPs is less than that of FRs, a coupled design is resulted always. To avoid this, the number of FRs should be equal to the number of DPs.
- More DPs than FRs: This results in a redundant design. To avoid this, the number of FRs should be equal to the number of DPs.
- Not recognizing a decoupled design: Although a decoupled design satisfies the Independence Axiom, 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 often misunderstand the Independence Axiom by confusing functional independence with physical independence. The physical integration is desirable as long as their functional requirements are independent and uncoupled.

VALUE OF AXIOMATIC DESIGN

Experiences I: Solving Design Problems

Many bad designs result in when designers mix “what” and “how” in the same domain. The concept of domains provides an important foundation of Axiomatic Design by separating “what” and “how” in different design domains. Based on this first principle, Axiomatic Design provides design-thinking framework that ideal design process involves mapping between design domains and evaluating design decisions based on design axioms and theorems to ensure a good design decision at each level of mapping. This step is repeated top to down in a zigzag manner until the solution can be conceived.

The following is a short list of successful AD cases in products, manufacturing processes, large scale engineering systems and socio-economic systems among many reported in the past 30 years.

Basis for DFSS of Large Complex System: One primary task of DFSS is to bring system FRs to their target values. The task is made difficult by functional couplings in the system as evidenced by symptoms and their explanations below. One symptom is that failures emerge only after the system is assembled since only then is couplings triggered. Another is failures are of the whack-a-mole type in which attempts to rid them cause other failures to appear. This is because attempt to fix one FR failure inadvertently triggers other FR failures due to coupling. Still another is failures are not detectable by recursive design/build/test of components since the test does not capture interactions that occur in system assembly.

AD has been used to identify and isolate the couplings described above. First, perform a top-down hierarchical zigzag decomposition of system level functional requirements FRs down to component level physical solutions DPs. This top-down decomposition captures interactions among component physical solutions in a design matrix as shown e.g., in Figure 3a. Next, the design matrix so obtained is condensed to its coupled sub-matrix by sorting out FRs and DPs that are not part of the coupling, Figure 3b. In this way, components DPs responsible for system level couplings are identified and isolated. DFSS efforts are then directed toward these DPs. This approach has been used in several automotive systems, door to body integration involving 28 FRs-DPs being one of them [2].

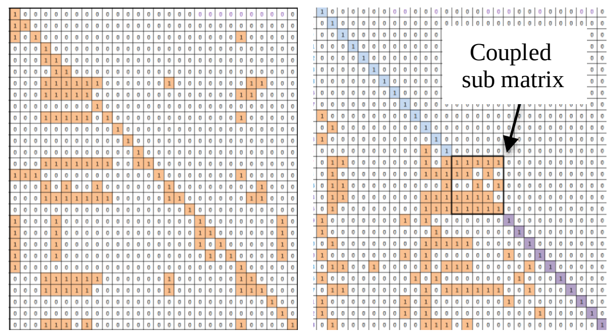

Figure 3 Design Matrix, (a) as obtained, (b) as condensed

New Manufacturing Processes: Microcellular plastics are polymer foams having cell densities in the range of 10^9-10^{15} cells/cm^3 and fully-grown cells on the order of 0.1-10 μm. Unlike conventional foams with ~10^6 cells/cm3 and cell sizes larger than ~100 μm, smaller than the critical flaw size voids in microcellular plastic do not compromise the mechanical properties of the plastic parts while reducing the amount of plastic used in mass produced plastic products. Suh originally conceived the idea of microcellular plastic when he defined new FRs [1]. Then proper process variables to achieve the defined FRs for batch and continuous manufacturing processes for microcellular plastic have been developed though many of his former graduate students’ research work [3]. This technology has been successfully industrialized with the name of **MuCell® Process** which is being widely applied to injection molding, blow molding and extrusion of automotive, medical, packaging and industrial products.

Other notable manufacturing processes developed through AD thinking are: Mixalloy process to make ideal microstructure metals such as high strength, high toughness and high conductivity at high temperatures [4], Vented Compression Molding for thermal protection system of NASA’s space shuttle external tanks (McCree and Erwin [5].

New Products: 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, light weight, efficient and less CO_2 producing transportation system could be realized. The key learning from the AD guided the inventors to develop an efficient wireless power transmission technology with more than 85% transmission efficiency over a ground gap of 20cm (100kW), which became a novel design parameter (DP) to enable the OLEV design uncoupled [6]. City of Gumi in Korea already has the world's first OLEV bus in operation from July 2013, developed by KAIST and TIME magazine chose the OLEV technology as one of 50 Best inventions of 2010.

Other notable products designed with AD are: Coated tungsten carbide tools for more wear resistance without sacrificing toughness [7], Automotive wheel cover which stays well when driving over bumpy road, but easy to remove when needs service [8], and capacitive deionization process with decoupled charging and discharging flow scheme for cost-effective desalination [9].

Micro and nano product design: At micro and nano scale, product realization has been extremely difficult since the make-and-see approach did not work. The design and manufacturing at small scales with newly developed materials such as piezoelectric thin films, photonic crystals or carbon nanotubes (CNTs) has become increasingly complex also. AD can provide product-design-development framework to mitigate the complexity by developing adequate design and manufacturing processes for new materials and by creating new functionalities at the systems level. By decoupling the coupled micro and nano systems design at the early design stage, successful MEMS products and processes have been developed such as thin-film micro mirror array for projection display [10], directed assembly for individual carbon nanotube [11], drop-on-demand process for piezoelectric MEMS devices [12], and high temperature stable nanostructured solar absorbers and selective emitters [13], among others.

Software Design: Many researchers have developed method for computer software development and the back end of the software design has become reasonably successful with automated coding and Structured Design and Structured Analysis methods. However, the software design at the early stage has not been supported by them. AD for software design was demonstrated by defining FRs first and mapping them into DPs in a top-down in zig-zagging manner, resulting in data flow and junction map for individual software modules and routines [14].

Socioeconomic Systems Design: Since AD provides a design-thinking framework, it can be applied to cross-disciplinary systems as well as to engineering systems described above. The FRs and DPs in socioeconomic systems are not well describable or understood often, and the use of AD is not readily applicable. Suh believes the first Axiom (Independence Axiom) is applicable to all systems and applied AD to the organization design of Engineering Directorate of NSF when he was nominated by President Reagan as the head of that Directorate. He established a new academic infrastructure for emerging technologies as well as structures for strengthening the traditional disciplines, which enabled a new field of technology such as Micro-electromechanical Systems (MEMS) [1]. When Suh became the Department Head of Mechanical Engineering (ME) at MIT, he also applied AD to the design of the department in terms of organization, faculty recruitment and curriculum systems. Many believe he transformed the MIT ME department not only strong in mechanical engineering but also in multi-disciplinary engineering and technology by his design and leadership.

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), more than 50% reduction of the patient waiting time-to-see doctors in ED was reported (Peck and Kim 2008).

Understanding Complexity in Design: A relative measure of complexity has been derived from Axiomatic Design as a collective outcome when a design doesn't satisfy the design axioms [16]. The four kinds of complexity can be explained by their causal nature with respect to the design axioms.

- <u>Time-independent real complexity</u>: when a design is coupled. (Independence axiom violation)
- <u>Time-dependent periodic complexity</u>: when the coupled nature of design is capsulated to prevent the propagation across the system
- <u>Time-independent imaginary complexity</u>: when a design is decoupled and not solved in the particular sequence (lack of knowledge).
- <u>Time-dependent combinatory complexity</u>: when a design has many states (FRs, DPs), which are not at equilibrium and change as a function of time (non-equilibrium).

Suh suggested functionally periodic systems could have a smaller scale complexity when the complexity is divided and confined in functionally uncoupled spatial/temporal sub-domains. The above speculation about complexity can be applied to very large or socioeconomic systems design, which has been regarded as extremely complex.

Experiences II: Educating Designers

Axiomatic design has been taught in many countries in a large number of different settings ranging from full semester graduate courses at universities to short courses for experienced designers in industry.

All courses in axiomatic design contain at least the following main elements

- The concept of domains
- The what-how relationship between the domains
- Establishing solution neutral functional requirements
- Mapping between the domains
- Analyzing the relationship between the domains to verify that the design satisfies the independence axiom and the information axiom
- Decomposition through a zig-zag process
- Examples or case studies of both analyzing existing designs and developing new designs.

Most 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 is one of the main challenges. We believe that the reason that 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 talk in terms of solutions only.

We have found that taking a process oriented approach to establish functional requirements often work well: The designer attempts to describe what he/she wants the design to do.

For example when designing a simple water faucet, the Functional Requirements (FRs) can be established from a user perspective as

- FR1: Control the water flow (without affecting water temperature)
- FR2: Control the temperature of the water (without affecting the water flow)

These are independent and describe the ideal function that the user wants to achieve.

Establishing the right set of FRs is critical to the success of the design since these will govern the rest of the design process. Thus, it is very important to ensure that the student of axiomatic design becomes very effective in this step.

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 (the design 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 not compromised. This mapping process can also be a challenge, but since most engineers are comfortable to think and talk in terms of solutions, this step is generally easier than the previous.

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 un-known relationships between the FRs and DPs in the design matrix. At times, the relationships may also change over time (e.g., from wear and tear, or due to external conditions).

In determining the relationships in the design matrix, the designer need to acknowledge all these non-ideal situations as they do represent the reality the designer is dealing with. Understanding the approach to dealing with de-coupled designs through proper sequencing of the DPs can prove critical to proceeding with a successful design when there are off-diagonal elements in the design matrix. 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 full understanding of how to implement the design.

This approach to teaching axiomatic design has been tried not only on designers of engineered systems, but also to design of organizations, corporate strategy, planning, and more.

A cross the different areas where we have taught axiomatic design, we have found that most people can follow the method well, but have difficulties to lead the process or work independently. There are always a few persons in each group (estimate about 30%) who quickly grasp the theory and significantly improve their performance as designers.

Common to all students (university and practicing engineers), we have observed, and received feedback, that they find the following elements of the method alone are most powerful, and generate a lot of value even if the full method is not implemented

- Mapping from what to how (concept of domains)
- Ensuring a one-to-one relationship between FRs and DPs

Developing courses for the future, we have found that for shorter courses for industry (1-2 days), good learning objectives are to develop the designers' ability to

- Establish good FRs,
- Understand the concept of domains and separate "what" from "how"
- Map FRs to DPs
- Conduct simple design matrix analyses.

Most time should be spent on the first two bullet 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.

MOVING FORWARD

Since late 1970's, the Axiomatic Design theory has generated important contributions in the field of engineering design, influencing theoretical research in academia and design practice in industry. The principle nature differentiates AD from many existing design methodologies that studies design processes and aims to extract descriptive and prescriptive design rules and guidelines for successful designs. AD teaches very insightful thinking process, especially useful for the very early stage of design. In the above section, we presented some of the success cases from AD applications in the past.

As much as the merits of the principles in the Axiomatic Design theory have been evidenced in academic research and practical applications, validity of design axioms has been consistently questioned and debated over time. 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. Axiomatic Design theory is well established as a design methodology, but relatively less emphasis has been given to 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.[1]” 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.

CONCLUSION

In this paper, we reviewed the fundamental principles in the Axiomatic Design theory, and the merits of the principles are highlighted with our experiences and observations in the theory’s applications.

What the Axiomatic Design theory emphasizes are threefold; first, instead of relying on a trial-and-error approach by intuition, start by establishing clear and explicit problem definition. Second, when defining your problem, make sure you are not biased and preoccupied with an existing solution concept. Third, when exploring solution concept space, seek a design solution that does not create a functional coupling.

More successful cases in real world product design are expected to come in the next 30 years and AD will be established as a design method as well as a principle.

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