USAGE OF AXIOMATIC DESIGN METHODOLOGY IN THE U.S. INDUSTRIES

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Abstract

Axiomatic Design, originally developed by Nam Suh [1], is a design methodology that attempts to systematize the design practices and to provide a basis on which design can be carried out and optimized. This case-study analysis was conducted to identify the extent to which Axiomatic Design is known to U.S. industries and to identify the factors influencing the use of the methodology. The results indicated that the methodology is not well known in the U.S., in particular in the automotive industries. Also, the methodology should first be applied to relatively small projects in order to realize its strengths and weaknesses. Plus, Axiomatic Design is not, and should not be regarded as, the only design methodology. It provides a framework within which one can use its axioms, as well as other various design methodologies.

Keywords: Axiomatic Design, Design, Design Methodologies

Introduction

Design is one of the fundamental steps in product development. In this process, the designer defines and conceptualizes the purpose of the product, whether it is a component, software, product, or system. History evidences numerous scientific and technological advancements and innovations, yet failures often arise partially due to poor design. Poorly designed products are more difficult to manufacture and maintain [1].

Singh [2] states that several studies have suggested that most of a product's cost becomes fixed in its early life-cycle stage before the original design cycle is completed. A typical characteristic curve that indicates the cost incurred and committed during the product life cycle is shown in Figure 1. As seen in this figure, the majority of the product development cost occurs in the conceptual and detailed design phase. Also, the overall design change is easier in the earlier phases.

The design process can use different methodologies for product development and there are many such methodologies available in the market. One of these is the Axiomatic Design originally developed by Nam Suh [1].

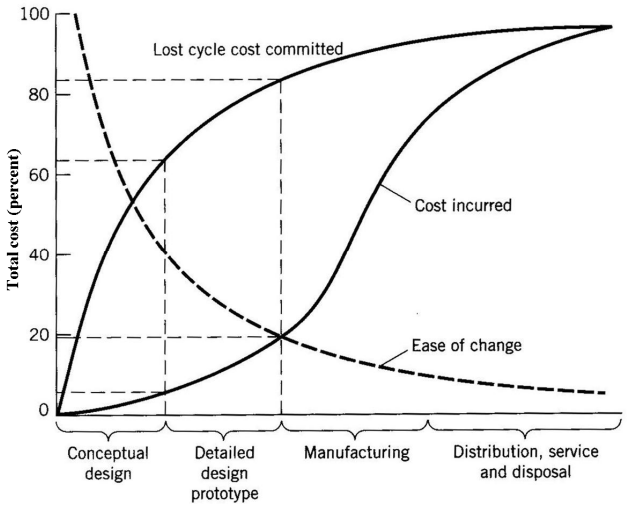

Figure 1. The cost incurred and committed characteristics within the life cycle of a product [2]

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Axiomatic Design

Professor Nam P. Suh at the Department of Mechanical Engineering at Massachusetts Institute of Technology (M.I.T.) developed Axiomatic Design (AD) as a design methodology to systematize the design process and to address the aforementioned weaknesses of traditional design practices. He defines design as an activity that involves the interplay between what the designer would like to achieve and how he/she satisfies this need.

In the Axiomatic Design methodology, there are four domains that drive the process including Customer domain, Functional domain, Physical domain, and Process domain, as shown in Figure 2 [1].

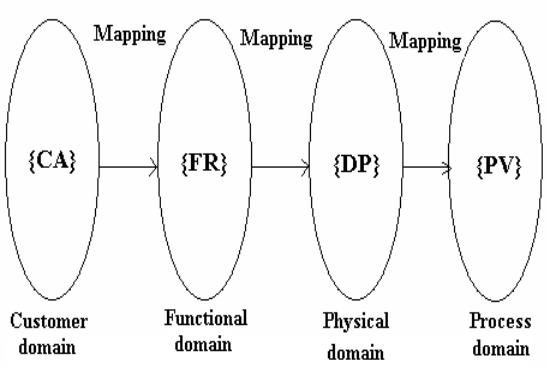

Figure 2. The four domains in AD

Customer's needs, called Customer Attributes (CA), are determined in the customer domain and then in the functional domain; these needs are specified as Functional Requirements (FRs) and Constraints (Cs). To satisfy the FRs, one needs to conceive Design Parameters (DPs) in the physical domain. Finally, Process Variables (PVs), describing the processes needed to fulfill the FRs, are developed in the process domain. Decisions regarding the appropriate design solution are made through a mapping process. These decisions are made on the premise that it should not violate the two fundamental axioms of AD, which are:

- The Independence Axiom: The independence of FRs must be maintained.
- The Information Axiom: The information content of the design must be minimized [1].

The first axiom maintains that the FRs must be set in such a way that each FR can be satisfied without affecting other FRs. The independence of FRs, however, does not necessarily mean physical independence.

The mapping process between the domains can be described mathematically. The functional requirements are considered as components of a vector that define the design goals, hence called a FR vector; similarly, DPs constitute the DP vector. The relationship between FR and DP vectors is shown in Equation 1:

$$\{FR\} = [A]\{DP\} \tag{1}$$

where, Matrix A is called the Design Matrix, whose elements are:

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{2}$$

Therefore, each FR is described in terms of the DPs as:

$$\begin{aligned} FR_1 &= A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3 \\ FR_2 &= A_{21}DP_1 + A_{22}DP_2 + A_{23}DP_3 \\ FR_3 &= A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3 \end{aligned} \tag{3}$$

The first axiom requires independence of the FRs. In order to satisfy this axiom, one should either have a diagonal or triangular design matrix as shown in Equations 4 and 5, respectively.

Diagonal matrix:

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \tag{4}$$

Triangular Matrices:

$$[A] = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \text{ or}$$

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ 0 & A_{22} & A_{23} \\ 0 & 0 & A_{33} \end{bmatrix} \tag{5}$$

If the design matrix is diagonal, the design is called uncoupled; if the design matrix is triangular, it is called decoupled. If the design matrix is none of these types, then the design is said to be coupled. In an ideal design, Suh [1] stated that, the design matrix is uncoupled, which means that each FR is satisfied independently from other FRs.

The information content is defined as the probability of satisfying a given FR; that is, the probability of satisfying FR_i is P_i [1]. Mathematically, this is defined by equations 6 and 7.

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \tag{6}$$

The unit of the information content is a bit. If there are multiple FRs, then the total information content of the system, I_{sys}, is:

$$I_{sys} = -\log_2 P_m \qquad (m = \text{the number of FRs}) \tag{7}$$

where P_m indicates the joint probability that all FRs are satisfied when all of them are statistically independent:

$$P_m = \prod_{i=1}^{m} P_i \quad (8)$$

The second axiom implies that the design with the smallest information content is the best design because it requires the least amount of information to achieve the design goals.

Some scholars within academia have examined the application of AD and have reported its usefulness and impact on the understudied systems and designs in terms of cost and waste reduction [3]-[5]. However, there is a lack of formal study indicating the extent to which this methodology is used and practiced in industry. In addition, the literature review does not indicate existence of any study on what the AD users within the U.S. industry feel about this methodology.

Literature Review

Axiomatic Design (AD) could be an appropriate tool to address the fast-changing nature of lean manufacturing systems [4]. According to Houshmand and Jamshidnezhad [4], identifying the factor(s) influencing implementing decisions of AD in industries would shed more light on the applicability of AD and/or identify technical problems and obstacles to implementing it in a particular industry.

AD has also been applied in the design of manufacturing systems [1], [4], integration of design-method software in Concurrent Engineering [6], developing e-commerce strategies [7], and machine control systems [8]. Moreover, AD has been implemented to provide a design method for lean production [5]. Nordlund, Tate, and Suh [3] stated that companies in Asia, Europe, and the U.S. have successfully trained their engineers in AD and started integrating AD into their product-development efforts. In their studies, they presented several case studies of applying AD in such areas as design process, business plan development, and analysis of reliability in wafer-processing equipment.

In the study conducted by Houshmand and Jamshidnezhad [4], an automotive body assembly was redesigned using AD methodology. Some of the improvements in the redesigned system reported were a 50% reduction in work-in-progress, decreased cycle time of the cell up to 20%, and increased flexibility.

Reynal and Cochran [5] studied assembly lines and machining of two manufacturing companies in order to implement the lean-manufacturing concept through the application of AD. The first company, which was an assembly plant, was completely redesigned; of the results reported, there was more than a 50% reduction in cycle time of parts in the assembly process and space reduction of more than 40%. In the second company, the application of AD resulted in the reduction of the cycle time as well as cost-effective improvement.

Liu and Soderborg [9] presented the application of AD to a Noise, Vibration, and Harshness (NVH) problem in the automotive industry; a major attribute observed in a vehicle's design and analysis involved such quantities as sound pressure (noise), steering wheel vibration (vibration), and discomfort due to rough road conditions (harshness). They developed a design matrix to identify the relationship between FRs and DPs to rearrange the matrix with the aim of decoupling the matrix as much as possible. They concluded that the resulting matrix could provide a clear strategy for tuning the design to meet the intended FRs.

The Study

Although the literature provided individual studies carried out using AD, the extent to which AD is used in industry was not fully evident. Neither was it clear which factors affect its implementation. Hence, the current case study was conducted with the intent of addressing the following questions:

1. To what extent is Axiomatic Design (AD) practiced in U.S. companies involved with engineering design practices?
2. What advantages/disadvantages have been realized through the use of AD?
3. What factors influenced the implementation/non-implementation of AD in these companies?
4. What inferences and recommendations can be identified for the implementation of AD?

This was accomplished by identifying and interviewing appropriate professionals in industry.

Methodology

Initially, the U.S. automotive companies from which the sample would be drawn were chosen as the population, i.e., automotive companies involved with engineering design practices. This list of companies was obtained from the Automotive Engineering International's Worldwide Automotive Supplier Directory available to the members of the Society of Automotive Engineers (SAE) [10].

One of the categories in the directory is engineering design, which has two sub-categories including engineering design and engineering design services. A search in this category revealed a total of 93 companies in the U.S.

All of these companies were contacted to see whether they were familiar with AD. The result indicated that the majority were unaware of AD. Therefore, it was decided to broaden the scope of the study to include non-automotive, yet transportation-related companies, and to conduct the study in those companies that utilized AD in their practices. The method used to identify companies that possibly used AD was to look at the clients of the AD software provider, Axiomatic Design, Inc. This resulted in identifying five companies of which four were willing to participate in the study. Three of these companies were large corporations and one company provided consulting in engineering designs to large companies.

Per contact with these companies, hereafter referred to as companies A, B, C, and D, five individuals, who held either managerial or design supervisory positions in these companies, were identified. The initial contacts with each of the interviewees indicated that they were aware of the current design practices and methodologies performed and used by their engineers in their departments. These individuals are hereafter referred to as *P1*, *P2*, *P3*, *P4*, and *P5*. A questionnaire, shown in Appendix A, was then designed to elicit the desired information. Using this questionnaire, these individuals were interviewed by telephone, the duration of which ranged from 45 minutes to 2 hours. Although the questions on the questionnaire were asked, the interview was conducted in a conversational mode so that additional questions could be asked depending upon the answers given. This was done to gain a deeper understanding of the situation in that company. All conversations were recorded.

Participants P2 and P3 both belonged to Company B. Figure 3 includes the types of the selected companies and the interviewees' job titles.

Results and discussion

An example of the responses to the survey questions is shown, in summary form, in Appendix B. The analysis of the conversations indicated that AD had been introduced and used only partially in the companies under study. It had not been fully used in any of the companies. In most cases, AD had been used just as a tool that was suggested to the designers along with other methodologies.

Company		Interviewee	
Label	Types of Business	Label	Position
A	Aerospace	P1	Program Director
B	Automotive	P2	Reliability Engineer
		P3	Researcher
C	Electronics, Transportation components	P4	Manager
D	Supplier training	P5	Consultant

Figure 3. The backgrounds of the companies and the interviewees

Hence, the designers were free to use any methodology they deemed appropriate. All five participants mentioned that the application of AD had been case-based. They started implementing AD, in the words of one of the respondents, in some 'toy' projects for initial learning and later on, in a few cases, they began using the methodology. Nonetheless, the results show that overall AD is not fully implemented in any of these companies.

The results also show that one of the major advantages of AD is that it provides a theoretical base for design. Therefore, it helps to have the designers think objectively about their designs. Even when not used fully, evidence suggests that AD was recognized as a powerful evaluation tool for existing designs. Designers can diagnose the coupled designs and decouple them. The design-matrix notion was found to be a useful tool in this regard.

It seems that AD is more useful to a company that designs components than to a company that designs systems due to the inherent project complexity. Moreover, if there are products being developed from scratch, their use would be beneficial. Evidence suggests that the major disadvantages of AD are difficulties in its usage, especially for complex systems and its inability to provide examples of solutions, as mentioned by P5 at Company D.

Almost all of the participants agreed that AD is a useful methodology to be used by the designers regardless of the size of the design project. They supported the implementation and/or the introduction of the methodology in design activities. Nonetheless, based on the data obtained from the interviews, the following are among the most referred issues brought up by the interviewees in regard to implementing AD:

- Cultural change in organizations
- Training costs
- Difficulty in implementation of the methodology where there are multi-FR projects

- Size of the design project in terms of the number of FRs and complexity
- The opinions of the customers involved in the projects

One of the main reasons for paucity of use of AD in industry is the sheer difficulty of the methodology. It is a theoretical technique and there is some evidence that it is difficult for most designers to fully comprehend. Also, learning the methodology is very time-consuming and it may not be possible for companies to invest time to train their designers.

The most important obstacle in implementation of any new methodology is the cultural resistance of the organization. The organizations contacted as well as their customers were familiar with and used traditional methodologies such as Design for Manufacturing and Assembly (DFMA), Robust Design, etc. As indicated by some of the interviewees, people who are not used to the new methodology are more likely to resist. This was also found to be true in this case, i.e., resistance to change, especially with AD, which is not widely known in industry. One can speculate that a reason for the unfamiliarity may be due to its absence in colleges' design curricula, as mentioned by one of the interviewees.

The methodology also does not provide examples or mechanisms to find innovative solutions, such those found in the Theory of Inventive Problem Solving (TRIZ) methodology. It is also cumbersome to use, especially for large complex projects. Hence, in the words of one of the interviewees, it does not become a "winner" when competing for its use with other methodologies in the environment, as stated earlier, where designers are free to select any methodology. On the positive side, evidence shows that the methodology being theoretical is useful in design evaluation. Hence, results show that individual designers use it for this purpose.

The organizational factors also influence the lack of acceptance of AD methodology. Contemporary industry uses the culture of collaboration among teams and supply chain members, i.e., the vendors and customers in all phases of design and manufacture. So, as mentioned above, in some cases it becomes difficult to implement new theoretic methodologies such as AD.

The results of the study also showed that Axiomatic Design is a methodology that is recommended to be used along with other methodologies. For example, a combination of AD and Robust Design is useful, as mentioned by one of the interviewees. The application of AD depends on the complexity of the design project or, more specifically, the number of FRs. The company should not mandate or emphasize any one design methodology, AD included.

The first question in implementing the methodology is how and to what degree AD would help the company in its product-design endeavor. There must be a clear understanding of the company's customers, marketplace, and resources available to invest. It is recommended that companies first start implementing AD in simple projects, i.e., with few FRs, to see whether any quality improvement and time and cost reduction would be realized. Then, based on the available budget, they should select the appropriate training to introduce AD. As the results of the study indicate, if there are several design groups and/or too many designers need to be trained, the recommended training method would be in-house workshops. Regardless, the training cost is an important factor and its choice depends on a company's budget and available resources.

The collaboration among various companies and their individual preferences in terms of the methodology can be a problem. In such cases, it is critical to have an agreement on the design methodologies used. Selecting a design methodology that may not be familiar to other companies can cause misunderstanding and miscommunication, which could increase cost, as was mentioned by P1 at Company A.

The role of management in supporting the methodology's implementation is crucial. One needs to obtain their support to introduce the methodology. As one of the interviewees mentioned, "I think you need a management champion who believes strongly in the methodology." Another participant stated that the managers would be interested in seeing what improvements in terms of cost and cycle time one can achieve by implementing any methodology. He believed that the managers would not care what methodology one may use as long as the methodology is cost-effective and beneficial. However, the designers should be interested in trying and/or using the new methodology.

Further Discussion

Often there is commercial software available for implementing different design methodologies. AD is no exception. As stated earlier, Axiomatic Design, Inc. is a provider of the software, called Acclaro. All interviewees were either familiar with this Axiomatic Design software or had used it at some point. Yet, they had used other software such as MS Excel and MATLAB. The interviewees believed that Acclaro was helpful in implementing AD; yet, the version of the software the interviewees were familiar with was not fully capable of handling designs with many FRs. They believed, however, that recent versions of the software would perhaps address this issue. The website of Axiomatic Design claims that one of their software packages, called Acclaro DFSS, is capable of "Implementing Axiomatic Design Quality framework with the DFSS quality processes of VOC, QFD, FMEA, TRIZ, DSM, Pugh concept analysis, and more" [11]. Therefore, it seems that the new version of the software in-

cludes more features and design tools and one can use it to help with design projects. Nonetheless, one still needs to examine this new version to assess its capabilities in handling multi-FR designs as claimed by the software company.

Concluding Remarks

In summary, by definition, Axiomatic Design provides guidelines for designers to ensure that the design contents would meet design requirements. The designer can gauge the design in hopes of meeting the functional requirements using various axioms and corollaries, particularly the Independence and the Information axioms. AD encompasses any design activity in any context such as manufacturing, software development, and so on. Nonetheless, it seems that AD is not known widely in the U.S. Industrial sectors studied here, although the literature review indicated the implementation of the methodology in a few industries.

Some of the interviewees mentioned that the designers did not seem to learn about AD as a part of their educational background. This would result in lack of familiarity with AD and so could be one reason for its limited use in industry. Yet, the impact of the designer's educational background on the expansion of AD in industry seems to be unknown and was not within the scope of the current study. Perhaps a combination of AD and TRIZ might provide a broader framework for design practices; however, one needs to study how these methodologies can be used together to provide such a framework. The other main reason for the lack of widespread use of AD is the organizational and cultural factors.

Appendix A

1. Please explain about your position and the number of years that you have with your company, and your work experience in the current and previous company (ies). What other positions/jobs have you held with current and prior company (ies)?
2. In what context do you use AD? (I.e. product design and development, process design, product/process redesign, mechanical design process, etc.).
3. Do you utilize any other design methodologies?
4. How did you initially learn about AD?
5. Were you involved with the introduction of AD in your workplace(s) (i.e. departments, divisions)?
6. What was the strategy that you used to introduce and implement AD? How long did it take?
7. What is your perception of what the AD users think about utilizing it at your company?
8. Has the number of the AD users in your organization increased/decreased? Why?
9. Was the decision on implementing AD an internal decision (by you or your department) or by the top management? In either case, what do you think about the management support in this regard?
10. In terms of the method of implementation, what methodology and/or strategy do you recommend to introduce AD in an organization?
11. Do you recommend AD to be used?
12. If so, do you recommend to use only AD or in combination with other methodologies?
13. To whom and for what type of design do you recommend AD? What about cost or ROI?
14. Do you implement any AD software? If so, is it commercial?
15. In your opinion, what are the positive and negative aspects of AD, in terms of
    - Methodology?
    - Implementation?
16. Overall, please describe your experience and perspective regarding AD and its implementation, advantages, and disadvantages.

Appendix B

Some example responses from the Interview with P4 of Company C:

Questions and responses regarding the extent to which Axiomatic Design practiced in the U.S.

In what context do you use AD?

It is a part of DFSS curriculum at the company. AD is used in the concept development phase within DFSS. It is used in product design to realize where coupling occurs.

Do you utilize any other design methodologies?

DFSS, Pugh analysis, Taguchi method.

Has the number of the AD users in your organization increased/decreased? Why?

AD is used in the division but not in all others. Nothing specific observed, though there would be a resistance when introducing a new idea/concept but when people see the benefit, they would not object.

Questions related to advantages/disadvantages that have been realized through the usage of AD.

In your opinion, what are the positive and negative aspects of AD, in terms of: Methodology and Implementation?

If one tries to improve design without fundamentally changing the concept, then AD is a difficult tool to use. However, if there is room for innovation and concept modification, then AD is very powerful.

Overall, please describe your experience and perspective regarding Axiomatic Design and its implementation, advantages, and disadvantages.

When developing highest FR, one should not have more than five or six FRs. Sometimes designers confuse FRs with constraints. Also, for the implementation of AD, one needs to have a person with authority.

Questions and responses related to factors influencing the implementation/non-implementation of AD.

What is your perception of what the AD users think about utilizing it at your company?

There were almost no complaints about the methodology at the division. The implementation was successful.

Do you implement any AD software? If so, is it commercial?

Yes, Acclaro is the software used.

How did you initially learn about AD?
Through self-inquiry and workshop.

Were you involved with the introduction of AD in your workplace?

Yes

Questions related to inferences and recommendations for implementation of AD.

What was the strategy that you used to introduce and implement AD?

Nam Suh was invited to give a talk to chief engineers. Then, an in-house workshop was conducted to introduce AD to the engineers.

Was the decision on implementing AD an internal decision (by you or your department) or by the top management?

Yes, it was an internal decision.

What methodology and/or strategy do you recommend to introduce AD in an organization?

In-house workshop.

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