Systematic Review on Applications of Axiomatic Design

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Abstract. Axiomatic Design (AD) is a fundamental methodology in engineering and quality management, offering a structured framework for addressing complex design challenges. Since its inception, Axiomatic Design has been proven to be an effective tool for a systematic and robust design process. this paper discusses the history and development of the Axiomatic Design approach showing the current trends like its applications in sustainable design, autonomous systems, smart manufacturing and applications of Industry 4.0 and Artificial intelligence. This study proposes a systematic methodology to use Scopus database to review the areas where Axiomatic Design approach was applied. The proposed methodology resulted in synthesized set of publications that was used to categorize the applications of the Axiomatic Design approach. Product development and process improvement categories were found to be the most common applications of the axiomatic design approach. Most of process improvement applications focuses on the production process management and improvement which proves that axiomatic design has great potential to be applied in the industrial sector to provide new successful products and decrease the time to market.

1. Introduction

Engineering methodologies, which can provide clear systematic and robust guidelines for designing high quality systems, are widely used in fields like quality management and system engineering. Since Axiomatic Design (AD) was introduced by Nam Pyo Suh in 1990s, it has gained significant recognition in both academia and industry. The framework of axiomatic design is built upon two foundational axioms: the Independence Axiom and the Information Axiom which represent the guiding principles for the decision-making processes during the system design process [1]. The Independence Axiom emphasizes maintaining the independence of functional requirements (FRs) in a design, ensuring that changes in one aspect of the system do not adversely affect others. The Information Axiom, on the other hand, prioritizes minimizing the complexity of designs by reducing their information content. Alternative definition for information axiom states that the optimal design is the design that is functionally unpaired with minimum amount of information [2]. Together, these axioms offer a powerful approach to resolving design challenges, from product development to systems engineering and beyond.

Over the years, axiomatic design has been applied across diverse domains, including mechanical design, manufacturing processes, software engineering, and even non-technical fields such as organizational design, health protection, sports competitions scheduling and decision-making

frameworks[3]. Despite its broad applicability, axiomatic design faces challenges, such as difficulty in defining clear FRs in complex systems and its integration with emerging technologies.
In recent years, axiomatic design has witnessed renewed interest due to its potential integration with emerging technologies such as artificial intelligence, machine learning, and advanced simulation tools [4]. Researchers are exploring how the axioms can be adapted to address the complexities of modern engineering problems, including sustainable design, autonomous systems, and Industry 4.0 initiatives [5]. These advancements have opened new avenues for applying axiomatic principles, making the methodology increasingly relevant in tackling contemporary challenges.
This literature review aims to provide a comprehensive analysis of applications of axiomatic design by reviewing the Scopus data base and find the most effective and applicable publications. By synthesizing these publications, a better understanding for the application of axiomatic design could be formed and the applications could be categorized exploring the applications trends.

2. Literature Review

2.1 Origins and development of Axiomatic Design

The history and development of axiomatic design trace back to the pioneering work of Nam Pyo Suh, who introduced the methodology in the late 20th century as a systematic approach to engineering design. Suh’s foundational contributions were encapsulated in his seminal books, "The Principles of Design" (1990) and "Axiomatic Design: Advances and Applications" (2001). These works laid the groundwork for a framework that emphasizes clear, logical design processes guided by two primary axioms. [1]
Initially, axiomatic design gained attention for its potential to address challenges in mechanical and product design, offering engineers a structured way to map functional requirements (FRs) to design parameters (DPs). Over time, its principles were adopted in broader domains, including software development, manufacturing, and systems engineering. Early adopters recognized its utility in improving design efficiency and minimizing unintended interactions among system components.
In the decades following its inception, the methodology has been refined and expanded through both academic research and industrial practice. Key milestones include the integration of axiomatic principles with computational tools and techniques, enabling more precise and scalable applications. Furthermore, researchers have explored its intersection with other methodologies, such as robust design and lean manufacturing, to enhance its versatility and effectiveness.
Recent advancements have seen axiomatic design applied to complex, multidisciplinary systems, including the design of autonomous systems, medical devices, and sustainable technologies [2]. Its adaptability has been further enhanced through its incorporation into digital environments, leveraging simulation and optimization tools to manage intricate design problems. For example, the methodology has been employed to improve energy efficiency in industrial processes and to streamline the development of renewable energy systems.[5]
Additionally, axiomatic design has evolved to address the challenges posed by Industry 4.0, with applications in smart manufacturing, IoT-enabled systems, and cyber-physical systems. Researchers are also investigating its potential synergy with artificial intelligence and machine learning, enabling automated design processes that align with axiomatic principles. These integrations not only broaden the scope of the methodology but also highlight its relevance in addressing the increasing complexity of modern engineering systems.[5]
A notable area of application is the integration of axiomatic design with Design for Six Sigma (DFSS) [6]. DFSS is a structured methodology aimed at optimizing product and process designs to meet customer needs and achieve high-quality standards. Within this framework, axiomatic design serves as a critical tool for defining and analyzing functional requirements and design parameters. By applying the Independence Axiom, designers can ensure that each customer need is addressed without introducing unintended dependencies, thereby enhancing reliability and performance. The Information

Axiom further complements DFSS by providing a quantitative approach to evaluating and minimizing the complexity of design alternatives. This synergy between axiomatic design and DFSS has proven effective in various industries, particularly in automotive, aerospace, and consumer electronics, where quality and precision are paramount. The goals of axiomatic design were explained as the following:

1. Increase designers' creativity.
2. Reduce random search processes.
3. Reduce the iterative work due to trial-and-error processes.
4. Increase the computational creative power.

2.2 process of application of Axiomatic Design

Axiomatic Design deals with Design process as a mapping process between four different domains as shown in Figure 1. Axiomatic Design process elements were defined as shown in table 1.

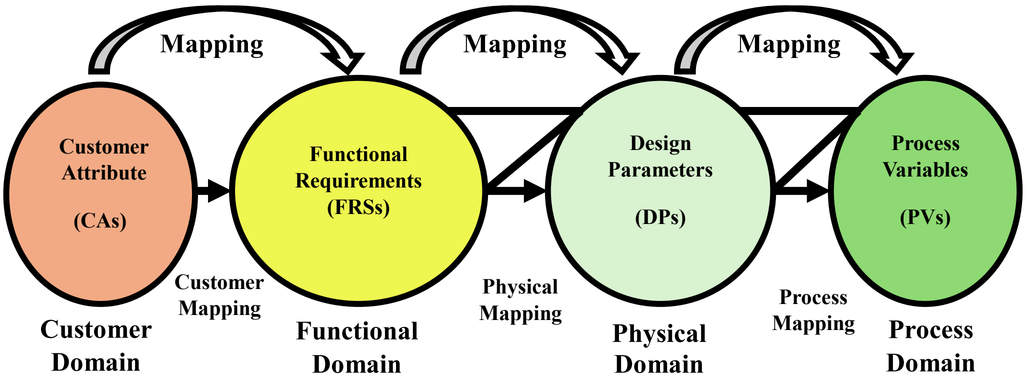


Figure 1. Axiomatic Design Domains

Table 1. Definitions of Axiomatic Design Elements

Element	Definition
CAs	All terms or parameters that the customer uses to describe his expectations and requirements.
FRs	Minimum number of requirements to describe the design objectives
DPs	Physical parameters existing in the Physical domain that are chosen to control the FRS
Constraints	Bounds to specify the acceptable design solutions
PVs	The elements of the process domain that characterizes the process implemented to achieve the DPs targets

The arrow representing customer mapping is referring to the usage of quality function deployment while physical mapping and process mapping are represented by arrows referring to the usage of zigzagging method.

The physical mapping is defined mathematically using the following equation:

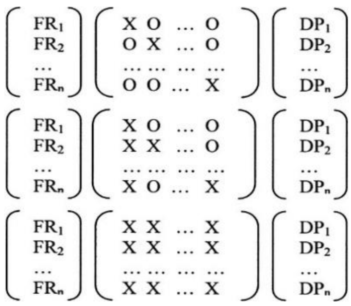
$$\{\boldsymbol{FRs}\}_{\boldsymbol{m\,x\,1}} = [\boldsymbol{A}]_{\boldsymbol{m\,x\,p}}\,\{\boldsymbol{DPs}\}_{\boldsymbol{p\,x\,1}} \quad (1)$$

Where [A] is the design matrix at which the element A_{mp} represented the sensitivity coefficient of the functional requirements FR_m with respect to the design parameter DP_p.

Axiomatic quality aimed to eliminate or reduce conceptual and operational vulnerabilities to design a system right the first time. This target very much matches the targets of several DFSS approaches. AD deals with the two types of vulnerabilities by following 2 axioms that were, by definition, truths with no exceptions. Those axioms were:

- Independence axiom: FRs shall be kept independent.
- Information axiom: information content shall be minimized.

The first axiom stated that the designer shall seek assigning a single DP to control a corresponding FR without affecting other FRs. The first axiom at its best cases will lead to uncoupled design which was a design process where each DP controls a specific FR which was not feasible for real complex systems. The second axiom stated that the design alternatives (Solutions) that minimizes the information content will be better than those with more information content. Violation of independence axiom happened in complex systems development despite all efforts of the design team to avoid it. When the design leads to a coupled FRs, the design team shall decide the status of the design as there exist 3 types of the design matrix [A] shown in Figure 2.



a) Uncoupled Design: Square matrix with all elements off the diagonal equal zeros

b) Decoupled Design: Square diagonal matrix

c) Coupled Design

Figure 2. Types of Design Matrices

3. Methodology of The Research

To conduct this literature review, the primary database used is Scopus database. The reason for choosing Scopus database is its coverage of multiple research areas. This research used the following words: Axiomatic Design, independence axiom, information axiom. Figure 3 shows the applied filters and sequence of applying each of them.

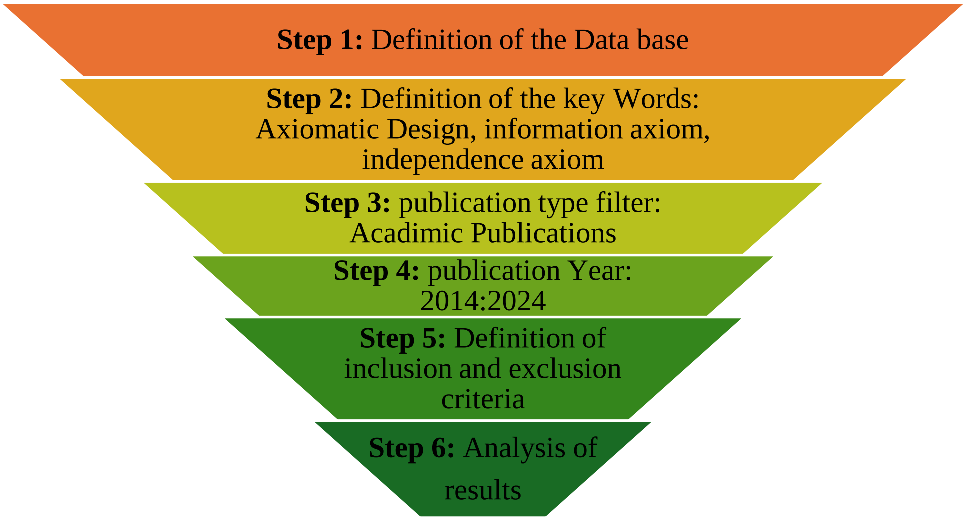


Figure 3. Systematic Review Methodology

Table 2 Shows the inclusion and exclusion criteria to be used to filter the preliminary data set caught by applying the research filters.

Table 2. Inclusion and exclusion criteria

Inclusion	Exclusion
Directly related to applications of axiomatic design	Don't show clear application of the axiomatic design
show relatively high impact	without access to full text
Related to Engineering	Informational and conceptual
written in English	Not aligned with the research theme

4. Results

Application of step 1 to 4 results in 113 publication which represents the raw database for our research. Figure 4 shows the sorting of resulting publications by year of publication.

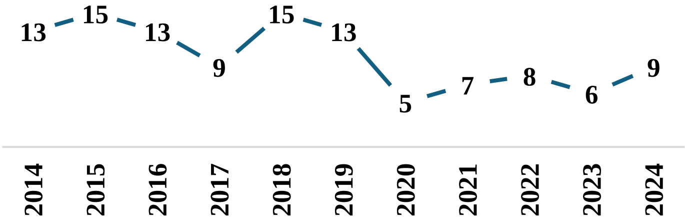


Figure 4. Sorting of Resulting Publications by Year of Publication

By reviewing the fields of the resulting publications, the subject areas of the resulting papers are categorized as shown in Figure 5 which displays the percentage of each subject area contribution.

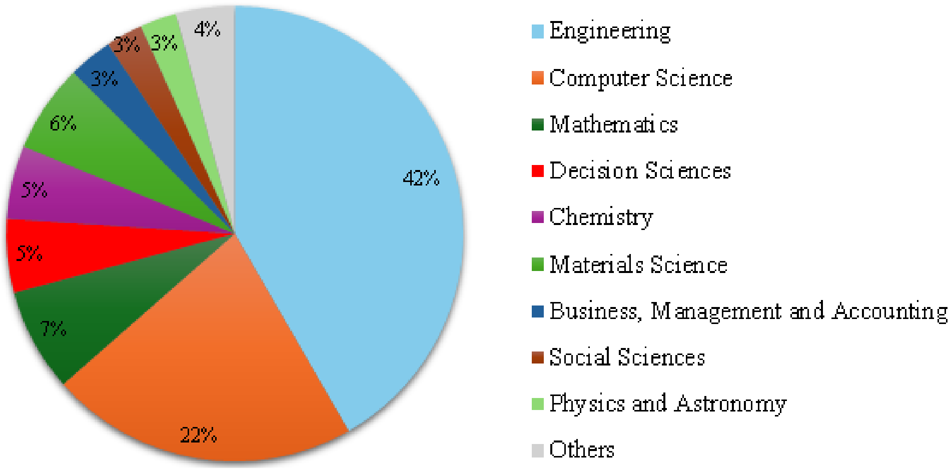


Figure 5. Subject Area Distribution of The Resulting Publications

It's important to discuss the nationality of the publications and relate this with the citation count to investigate the countries in the world where the researchers are interested in studying and applying the axiomatic design. The citation count refers to the probable growth of using axiomatic design. Table 3 shows the distribution of resulting publications over the top contribution countries and the citation count for each country.

Table 3. Top Contribution Countries and Average Citation Count

Country	Publications Count	Citation Count	Average Citation
China	29	320	11
United States	12	50	4.2
Turkey	11	135	12.3
Iran	10	316	31.6
Portugal	9	11	1.2
Italy	6	73	12.2
India	5	100	20.0
Japan	5	5	1

South Korea	5	44	8.8

By applying the inclusion and exclusion criteria to the resulting publications, only 49 publications left for analysis. Table 4 shows the resulting publications with a category describing the application of axiomatic design included at each publication. The papers have been sorted by year of publication first then by title of publications.

Table 4. Resulting Publications After the Application of the Inclusion and Exclusion Criteria

	Reference	Application category	Application Description
1	[7]	System Design	Design of information System
2	[8]	Process Improvement	Development of indexing technique for product usability
3	[9]	Decision Making	Selection of best design from multiple alternatives
4	[10]	System Design	Design of information System
5	[11]	Product Development	AD is used to select from the design parameters to design a manipulation Device
6	[12]	Product Development	A new type of conductive centre pole was innovatively designed using the theory of innovation problem solving (TRIZ) and AD
7	[13]		Using of AD to Select the assembly level design for Additive Manufacturing
8	[14]		A modular design method is proposed to design a modular product based on AD and design structure matrix (DSM). (a cooling system)
9	[15]		Using AD approach in preliminary design of a blended wing body aircraft
10	[16]	Risk Assessment	Fuzzy AD is used to assess the risks and select the best R&D projects
11	[17]	Process Improvement	AD is used to assess the risks and reduce the development cycle
12	[18]	Product Development	AD is used to optimize the design of rehabilitation robot
13	[19]		AD application to design a reciprocating yarn guiding system

14	[20]		AD is used to develop a hair dryer
15	[21]	Decision Making	conceptual prototype design for a loudspeaker is analysed using fuzzy axiomatic design
16	[22]		axiomatic design is used to develop a geometric dimensioning and tolerancing system
17	[23]		AD Application to select tolerance-type of the plane feature
18	[24]	Product Development	AD is used to choose between two types of check valves to use in a chiller: a clap check valve or a ball check valve.
19	[25]	Decision Making	Information axiom is used to determine the best landfill site among the potential alternatives
20	[26]	Process Improvement	risk-based fuzzy evidential approach is proposed by using interval-valued DST and fuzzy axiomatic design (FAD) to assess the risk of failure modes with fuzzy belief structures
21	[27]	Product Development	use of AD in the design of a cork granulation industrial plant
22	[28]	Process Improvement	This research is based on AD theory to explain and confirm the hypothesis of complexity reduction through a near real-time feedback request at the installation site
23	[29]		using AD to develop a service provided by digital factory
24	[30]	Product Development	AD is used to develop an automobile diaphragm spring clutch
25	[31]	Process Improvement	AD is used to enhance project management
26	[32]	Product Development	AD is used to select the optimum design for additive manufacturing produced product
27	[33]	Process Improvement	AD is used to optimize the process of manufacturing and installation of timber modules
28	[34]	Decision Making	AD Application to select dimensional tolerances
29	[35]	Process Improvement	selection of the most suitable nontraditional machining process

30	[36]		Axiomatic Design to design a flexible production System
31	[37]	Product Development	how to use AD to achieve functional requirements with illustrative example of snap-fit
32	[38]	Process Improvement	Fuzzy Axiomatic Design is used to design a reliability based robust manufacturing system
33	[39]	Process Development	application of Axiomatic Design to design Supply Chain Traceability Systems
34	[40]		application of AD principles to optimize the design of manufacturing system
35	[41]		improve produced composite materials properties
36	[42]	Product Development	usage of fuzzy AD approach to select from the design alternatives of an overflow valve.
37	[43]	System Design	Application of Axiomatic Design to design a social system
38	[44]	Decision Making	Axiomatic design is used to select the optimum mobility system for crowded cities and solve the technological barriers facing the system
39	[45]	Process Improvement	AD is used to design an overhead crane
40	[46]	Product Development	Using of AD to Develop a printing process
41	[47]	Decision Making	Fuzzy Axiomatic Design is used to choose between depending on a product or a service to achieve higher sustainability
42	[48]	Product Development	using axiomatic design to reverse engineering of the ceiling type air conditioning system.
43	[49]	Decision Making	help selection of the robot arm to enhance the efficiency of a manufacturing system
44	[50]	Product Development	AD was used to optimize the design of a suspension of torsion beam axle
45	[51]		AD is used to design a robust coating machine
46	[52]		Axiomatic design is used to improve a software to be used to design mechanical products
47	[53]		Modular product design based on relationships between

		functional requirements
48	[54]	How Axiomatic Design is used to reduce design redundancy with examples like crawler crane
49	[55]	Using axiomatic design to develop a limited angle torque motor

By analysing the publications in Table 4 we can categorize the application of axiomatic design as shown in Figure 6 which also shows the percentage of each application.

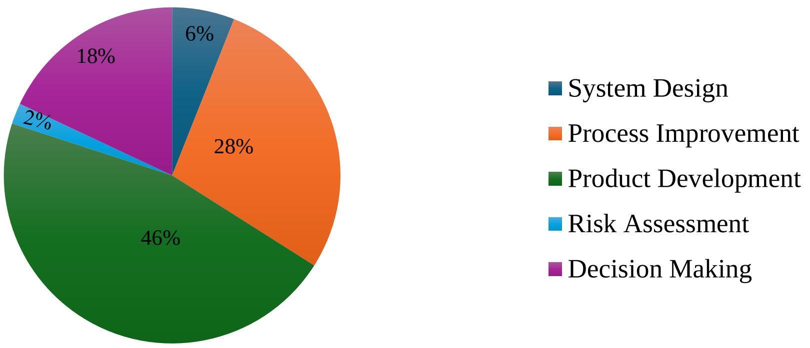


Figure 6. Distribution of Applications of Axiomatic Design

5. Conclusion

This systematic review discussed the history and development of the Axiomatic Design approach. it showed how this approach deals with the Design process as a group of mapping processes between the design domains and the design type is decided by the type of the design matrix. At this study, Scopus database was used to review the application of axiomatic design approach starting from 2014 up to 2024. The study showed that most of the researchers using Axiomatic Design approach apply it for product development which shows the importance of this approach to introduce new successful products to the market. Process improvement was the second largest category in the axiomatic design applications distribution, and it focuses on the improvement of the production processes which shows how AD could be used within the design process for six sigma projects.

Further investigations on the applications of Axiomatic Design could be made on the axioms that were applied at each publication. By investigating the axioms, the progress in application of axiomatic design axioms could be reviewed to show the latest techniques in applying both information and independence axiom. Another gap to review is the integration of Axiomatic Design with other methodologies like Design for Six Sigma.

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