Using the Axiomatic Design in Engineering

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Suh introduced two design axioms to the engineering community about four decades ago. Compared with other theories which presuppose an algorithmic or an iterative approach specific to a field of engineering, Axiomatic Design (AD) can be applied to solve a wide variety of problems. It is possible to apply AD to subjects in humanities and social sciences. Properly using those axioms leads to the best design solution for products, processes, or systems. The work briefly presents the AD approach in its three essential parts: axioms, structure, and process. Thus, this chapter presents a decision-making process using the first axiom. Then it illustrates the second axiom. The AD literature is analyzed, and the published papers were divided into theoretical developments or applications grouped by their field. The advantages and disadvantages of using AD compared with other design processes like QFD, TRIZ, and Taguchi are presented.

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1 Introduction

Engineering is defined as the practical application of pure science or the application of science to the optimum conversion of nature's resources to the uses of humankind. A scientific theory is applied to develop, design, and analyze solutions in all engineering branches. Over the years, there were proposed specific approaches for solving the wide variety of problems that respond to the questions "How to do things better?" and "How to do better things?" which engineers usually have to answer. Due to the practical aspect of the main goal, each solution has to satisfy conflicting requirements and safety requirements for a given cost. The significant functions of engineering are research, development, design, construction, test, modifying, installing, production, inspecting, maintaining, operating, and managing a wide variety of products or systems. Engineers manage to manufacture, supervise design and processes, recommend materials, conduct failure analysis, provide assistance services, etc.

Axiomatic Design (AD) theory was introduced to the engineering community about four decades ago. AD aims to avoid conflicting requirements. The idea is a consequence of students' project activities where they studied design processes and the quality of design solutions at the Massachusetts Institute of Technology conducted by NP Suh. This design theory was a real breakthrough because it can integrate all the main characteristics and ingredients of the design process. Due to its axiomatic approach, AD generalize and establish a common core for important design issues such as efficiency, robustness, simplicity, and probability of success. As Suh says, AD claims to establish a scientific basis for design [1]. Moreover, AD provides a scientific foundation for designers to compare the possible designs and choose the best option. The time and costs associated with the product development are minimized, and the customer needs are detailed.

For the first time, considerations regarding the possibilities of the existence of an axiomatic design methodology were to be published in May 1978 [2] discussing the axiomatic approach to manufacturing problems and manufacturing systems. In that first publication, several hypothetical axioms and some of their corollaries are presented with examples to illustrate the basic concepts. In 1990 Suh published his first book [1]. He explained the principles of design and emphasized that Axiomatic Design (AD) aims to make people more creative, prevent randomly looking for a solution, minimize the iterative process called "trial and error," and choose the best concept from the multitude of proposed concepts. In the early years, the cumulative number of publications was relatively low. After the first decade, the number of papers has significantly risen probably because of the second book published by Suh [3], in which he presented the AD advantages and applications.

The community with AD interest has been developed further, and in 2000 the first edition of the International Conference on Axiomatic Design (ICAD) was held in Cambridge (MA-USA). Since then, Cambridge and Worcester (MA-USA), Seoul and Daejeon (Korea), Lisbon (Portugal), Florence (Italy), Xi'an (China), Iasi (Romania), Reykjavik (Iceland), and Sydney (Australia) have hosted the ICAD conferences.

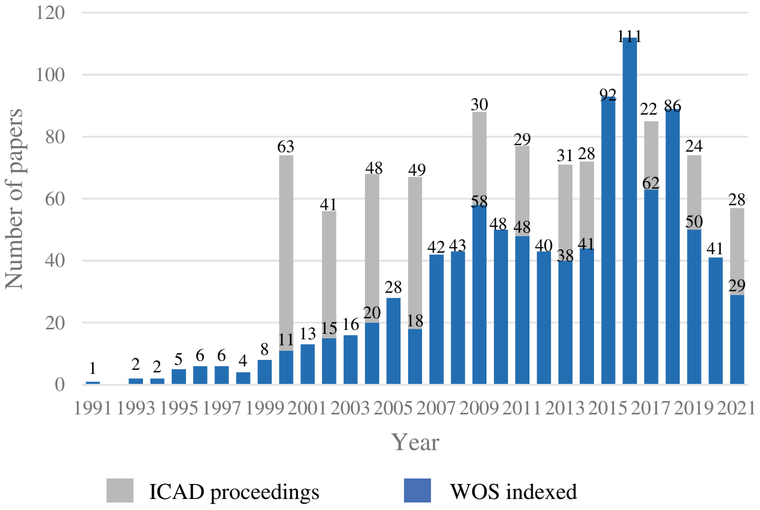


Fig. 1 Number of papers with AD topic, published over time in ICAD proceedings or indexed in Web of Science

Since 2013 the conferences have been held annually except for the pandemic restriction in 2020. Regarding the indexation of volume proceedings, the conference succeeded WOS indexation in 2015, 2016, and 2018. Figure 1 shows the papers published as ICAD conference papers in gray columns for the corresponding years. The blue columns represent the number of papers indexed in the Web of Science (WoS) database with the keyword Axiomatic Design.

To evaluate and classify these publications, few authors publish studies of literature review of AD publications [4–7]. In [4], Kulak et al. considered the papers published from 1990 till 2009. He classifies papers into four main groups, type of axiom used, application area, theoretical consideration on the method, and the type of evaluation. The study emphasized the discrimination concerning the used axioms in favor of the first axiom. The number of papers ranked the following application: Product Design, Decision Making, Software Design, System Design, Manufacturing System Design, and others.

In the form of a literature review, Rauch et al. [5] investigate the number and type of publications between 1996 and 2005 dealing with AD in Manufacturing. The data basis of this analysis is the works indexed in the Scopus. The study shows the preponderance of the first axiom vs. the second one and the application papers compared to the theoretical development.

A nomothetical empirical study of AD application in academic publication between 2013 and 2018 is presented in [7]. The conclusion is that the number of papers concerning system design grew significantly, but the number of papers concerning application for Software design has reduced.

With time, some private companies are involved in the AD community. Many projects have been conducted to promote, provide training, and implement the AD methodology in the design and development processes (www.axiomaticdesign.com). A software named Acclaro was proposed and used for implementing axiomatic designs in the industry with the main advantage of overcoming the barrier of managing many functional requirements of the design and facilitating the application of the axioms.

Recently, Dr. B.J. Park gave the funds to create the AD Research Foundation (www.axiomaticdesign.org). ADRF aims to spread knowledge, provide education and promote axiomatic design methods.

In some universities around the globe, AD is a course in the curricula.

2 AD Approach: Axioms, Structure, and Process

Axiomatic Design theory became a powerful tool for designing new products, systems or processes or analyzing and improving the existing design solutions. Due to its axiomatic approach AD apply to a wide variety of problems [1–6]. According to Merriam-Webster Dictionary, the meaning of the word "axiom" is "an established rule or principle or a self-evident truth," and its synonyms are "postulate" and "maxim." Like any other axioms in science, the validity of Suh's axioms, relies on the lack of observations to the contrary within their domains of applicability. Since 1978, when the first paper was published [2], nobody had come to prove that the axioms are not valid.

Brown presents [8] AD using three pieces: axioms, structure, and process. Each piece can be decomposed into two elements, as it is represented in Fig. 2. The design problems are formulated during the design process, and the design solution is developed, from abstract to detailed, across customer, functional, physical, and process domains structures. The zigzagging decomposition process happens between domains at one level, then proceeding to the next, more detailed level, constantly checking if the axioms are respected.

According to the AD theory, the entire design process of a new product or the improvement of an older design should be consistent with the following two axioms:

Independence Axiom (1.1 in Fig. 2**):** ***"Maintain the independence of functional requirements."*** A product or system design is considered ideal if all functional requirements are independent of the others. The independence avoids any interaction among them, which can have unintended consequences. Without interaction, the functional design requirements are adjustable and controllable, and:

Information Axiom (1.2 in Fig. 2**):** ***"Minimize the information content of the design."*** This Axiom helps choose among multiple possible solutions by favoring those with the greatest possibility of fulfilling the functions, maximizing the probability of success. Therefore the design satisfies the customer's needs.

AD theory proposes four design domains, **Customer Domain**, **Functional Domain**, **Physical Domain,** and **Process Domain**.

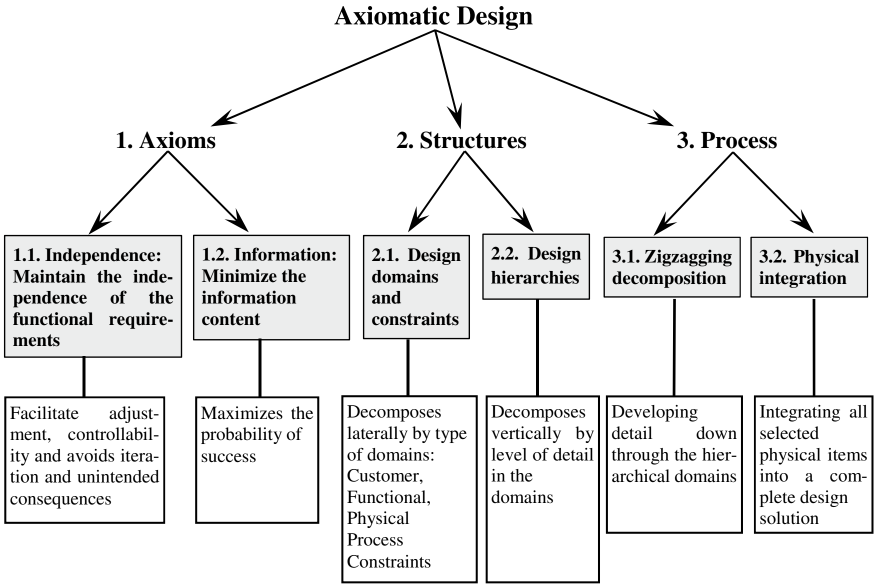


Fig. 2 Parts and elements of Axiomatic Design, after [8]

The Customer Domain consists of all the **Customer Needs (CNs)** or what the customers want or what is needed. A proper requirement gathering process or identification of the customer needs or other stakeholders' needs (manufacturing, transport, salespeople, etc.) is essential for the final design solution [9]. Significant CNs will be missed without recognizing all stakeholders, which probably leads to missed FRs and a less valuable design solution [9]. CNs should describe the fundamental needs, preferences, and constraints like cost, weight, volume, etc.

The Customer Domain maps into the Functional Domain. Its elements are the **Functional Requirements (FRs) that** describe the functions of the design solution. The FRs should state the design objective and should begin with verbs. The selection of good functional requirements (FRs) is essential for design solutions. According to Suh, "a design solution can be no better than its FRs" [1]. In [10] Thompson proposes a helpful classification of other FR-like entities, challenging to differentiate from real FRs. Such entities are the non-FR that describe the qualities or characteristics of the design solution, the *optimization criteria (OCs)* that indicate a maximizing or minimizing function, and the *selection criteria (SCs)* like cheapest, lightest, most robust, etc. The top-level FRs should be the minimum list of functions that satisfy all CNs which means the FRs should be *collectively exhaustive* concerning the CNs. FRs should be *mutually exclusive* concerning each other [8] at any level of decomposition. The top-level FR is FR0, decomposed at the next level into FR1, FR2, FR3, etc. The children of FR1 are FR1.1, FR1.2, FR1.3, etc.

In the Physical Domain the elements, the **Design Parameters (DPs)** describe how to implement the solution physically. The DPs are the physical items that fulfill the FRs. Ideally, the specific DP should influence only the FR that it is intended to satisfy. Moreover, the choice of the DP should meet the FR so that it ensures the highest probability to fulfill a requirement. In other words, the design to choose has the lowest information content.

In the Process Domain, the **Process Variables (PVs)** describe how the DPs are produced. Ideally, the PVs have a one-to-one relation with the DPs.

Developing **the design hierarchies** in all these domains by vertical decomposition at each level of detail and during the zigzagging decomposition process, **System Constraints (Cs)** are also considered. Cs introduces limits or restrictions at any level and can influence all items, e.g., weight and cost limitations [8].

Design hierarchies are established during the design process by mapping/**zigzagging decomposition** process between domains at one level, then proceeding to the next level (Fig. 3). Brown deals with the difficulties of developing good hierarchical decompositions [11]. Decompositions are used to solve problems when the solutions are not immediately obvious because the problems are too large or complex. In AD, the mapping runs the design across the domains. Vertical decompositions decompose the elements of a domain hierarchically and from abstract to detail. The children of a component must be *collectively exhaustive (CE)* with respect to the parents. The children must be *mutually exclusive (ME)* concerning each other at each level. Solving the horizontal and vertical puzzle raises a solution at a level of decomposition. In addition, considering the second axiom, the appropriate decomposition has the minimum information content, symbolized as *CEME-min.*

After the decomposition is complete, the selected items from the physical domain can be **physically integrated** into a complete solution.

The axiom of independence requires that the functions of the design (*functional requirements, FRs*) remain *independent*.

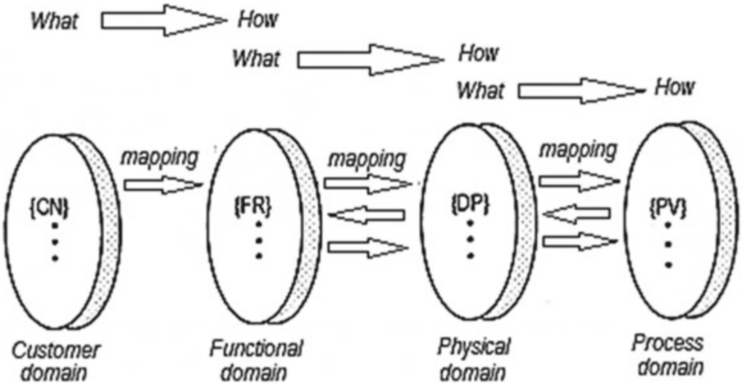


Fig. 3 Design activity approached as a process of "mapping" information, as a result of the transition from one field to another (Adapted from [3] and [12])

Subsequently, at a certain stage of application of the axiomatic design, it is necessary to get a physical issue to materialize each functional requirement. As aforementioned, the solution is the design parameter (DP).

The design matrix depicts the relations between functional requirements and design parameters.

Thus, *the general matrix relation* that connects the FRs functional requirements to the *DP*s design parameters has the form:

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

[A] is the design matrix corresponding to a transfer function between the *FRs* functional requirements and the *DPs* design parameters.

In relation (1), A_{ij} is [1]:

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \tag{2}$$

When there are *n* functional requirements, relationship (1) [1] has the form:

$$\begin{Bmatrix} FR_1 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} A_{11} \ldots A_{1n} \\ \vdots \quad \ddots \quad \vdots \\ A_{11} \ldots A_{1n} \end{bmatrix} \begin{Bmatrix} DP_1 \\ \vdots \\ DP_n \end{Bmatrix} \tag{3}$$

Ideally, fulfilling a specific requirement by a DP_i design parameter does not affect any other functional requirements. It significantly increases the system's flexibility to modifications for improvements [13].

Matrix *A* allows to classify the type of designs:

(a) *A diagonal matrix* corresponding to the so-called *uncoupled design* (concepts). It has $A_{ij} = 0$, for all $i \neq j$:

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

When the matrix [*A*] is diagonal, each of the functional requirements *FRi* is met by a design parameter *DPi*. We will thus be dealing with *an uncoupled design matrix*.

(b) *A triangular matrix*, corresponding to the situation where there are non-zero elements either above the diagonal (*upper triangular matrix*) or below it (*lower triangular matrix*) [1, 14, 15]:

$$[A] = \begin{bmatrix} A_{11} & 0 & . & 0 \\ A_{21} & A_{22} & . & 0 \\ . & . & . & 0 \\ A_{n1} & A_{n2} & . & A_{nn} \end{bmatrix} \tag{5}$$

Such a matrix defines *a decoupled design* (conception). When the design matrix is triangular, the independence of functional requirements is ensured by setting the *DPs* in a certain order. Equation 5 shows a decoupled design. DP_1 is the first to set, followed by DP_2 and so on. If the design matrix cannot be reduced to a triangular matrix, the design is *coupled*.

Therefore, the design should have a diagonal design matrix or a triangular matrix.

The following example shows a decoupled design, where each X is a non-zero element:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & X & X \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{6}$$

(c) *A coupled design matrix* contains non-zero elements above and below the diagonal that columns and row changing cannot solve:

$$[A] = \begin{bmatrix} A_{11} & A_{12} & . & A_{1n} \\ A_{21} & A_{22} & . & A_{2n} \\ . & . & . & . \\ A_{n1} & A_{n2} & . & A_{nn} \end{bmatrix} \tag{7}$$

The number of *FR*s (functional requirements) equals the number of *DPs* (design parameters) necessary to achieve an ideal design. Thus, the design matrix [*A*] is square. The independence axiom is met for uncoupled or decoupled designs. Uncoupled designs ensure *an ideal design.*

However, the number of *FRs* may differ from the number of *DPs*. In this case, the following design categories are:

(1) If the number of *FRs* exceeds the number of *DPs*, the design equation is as in the following example:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \\ A_{31} & A_{32} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{8}$$

It shows a *Coupled design* or some *FRs* cannot be fulfilled. The previous relation shows FR_3 cannot be met if A_{31} and A_{32} are zero. However, if at least one of the two elements has non-zero values, we are dealing with *a coupled design* [15].

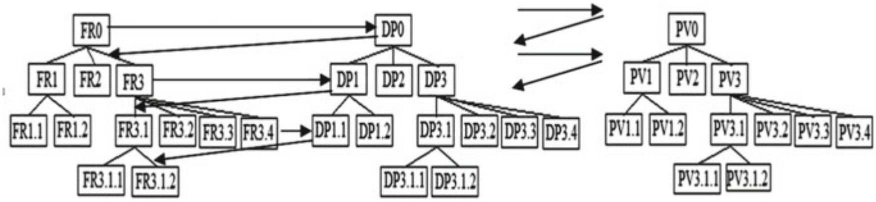


Fig. 4 Hierarchical decomposition of *FRs* functional requirements, design parameters *DPs* and *PVs* process variables by zigzagging

As mentioned before, *if the number of functional requirements is equal to the number of design parameters* (and when we are dealing with a diagonal matrix or a triangular matrix) *the axiom of independence is met*. We deal with an *ideal* or a *decoupled design.*

(2) *A design is a Redundant design* if the number of *FRs* is less than the number of *DPs*. The relation illustrates an example:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & A_{13} & A_{14} \\ 0 & A_{22} & A_{23} & A_{24} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}. \tag{9}$$

The zigzag decomposition takes place between domains and across all domains, as depicted in Fig. 4. From FR_0 the design goes to DP_0 and eventually to PV_0. Thus FR_1, FR_2, and FR_3, are images from DP_0 that exhaustively fulfills FR_0. Each *FR* allows reaching a *DP*, DP_1, DP_2, and DP_3. The process ends at the leaves DPs. A leaf is a single part that can be manufactured or an artifact accessed in the market.

3 Using the First Axiom of Axiomatic Design

The following example briefly presents how to use the first axiom of Axiomatic Design. The first axiom is widely used, while the second has fewer applications due to the challenge of achieving good designs. For this reason, this introductory chapter of AD will only present an application of the first axiom.

The example is the design of a polishing device. The polish device rotates brushes with abrasive blades (Fig. 5) that allows achieving a good adaptation of the blades to the shape of the helical groove. The high-speed rotating brush has a portable device with a shaft to fasten radial abrasive blades made of cardboard or textile. These blades incorporate abrasive grains on one or both of their active surfaces.

Such a device is necessary for polishing the surface of a helical groove located on an outer cylindrical surface. Polishing should ensure a low roughness at the groove surface. The surface to polish is part of the equipment that moves food materials in

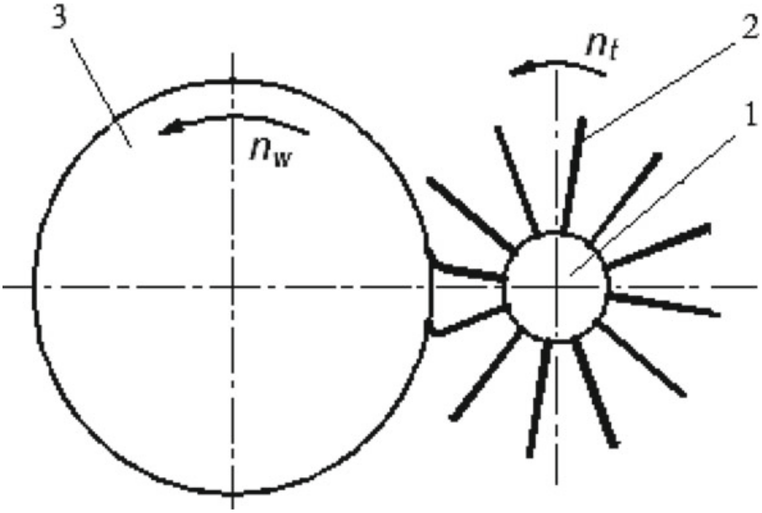


Fig. 5 Schematic representation of the polishing process using rotating brushes with abrasive blades: (1) the shaft of the rotating disk driven in a rotational movement with speed n_t; (2) abrasive blade; and (3) workpiece in rotating motion; n_w—the rotational movement of the workpiece (Adapted from [16])

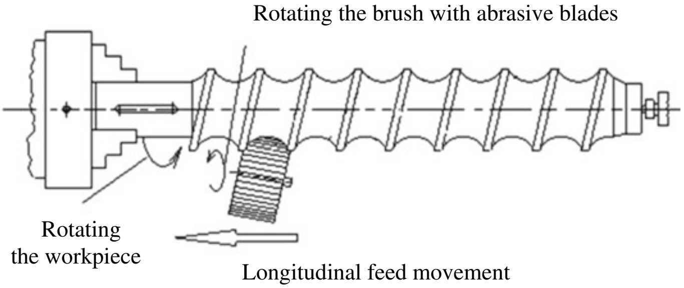


Fig. 6 Machining scheme valid in case of polishing a helical groove using the rotating brush with abrasive blades (Adapted from [17])

a cylinder. Low roughness ensures not to retain food debris on the surface. Figure 6 shows the process, the rotation of the workpiece, and the longitudinal movement of a rotating brush.

The device is part of experimental research activity of the influence exerted by the parameters specific to the polishing process (considered here as input elements in the system related to the polishing process) on the values of parameters of technological interest (process output parameters). The input parameters are the dimension and material of the small abrasive grains, the rotating speed of the brush and workpiece. Finally, it is taken into account the vertical and horizontal angles of the brush axis.

To further develop the experimental research concerning the polishing process, the following customer requirements were formulated:

CN_1: The device must be able to be used on an existing machine tools in a small mechanical workshop;
CN_2: The device must provide conditions for changing polishing parameters.

Notice that the Customer's Needs are about a device, not the polishing process. Therefore, the polishing input parameters regarding the abrasive material are not considered. It makes the main functional requirement (zero-order) to be:

FR_0: Research on the polishing process of a helical groove.
DP_0: Polishing device at a workpiece location.

The zero-level functional requirement may be used to design a simple DP product. However, if the product is not available, it is necessary to decompose the functional requirements into lower levels (levels 1, 2, 3, etc.). In the situation under analysis, the design is decomposed until the second level. The first level decomposition is highlighted in Table 1, showing the (FR_i) and (DP_i).

Figure 7 presents the proposed design for the polishing device. It is found that for polishing the existing helical groove in the workpiece located and clamped in the universal chuck and the live center, a portable drilling machine is used. This portable drilling machine is clamped through a bracelet-type device on the disc, which can be rotated and fixed in a certain angular position using some nuts. The respective nuts are screwed onto threaded rods, which are secured to the fixed disc. The threaded rods pass through a groove in the form of an arc of a circle existing in the disc, which can be rotated and thus immobilized in the desired position.

The detailed description of *FRs* and *DPs* at the second level of decomposition is described in Table 2.

The device can be clamped in one of the four locations of a lathe ordinary tool holder due to its endowment with a part that has a parallelepiped-shaped step. The abrasive blade brush materializes the polishing process. The guide of the tool slide can be rotated and fixed at an angle whose value is determined by taking into account the angle of inclination of the helical groove in the workpiece. The immobilization

Table 1 FRs and DPs on the first level of decomposition

Functional requirements	Design parameters
*FR*1: Rotate the brush with abrasive blades at different rotational speeds	*DP*1: Portable drilling machine
*FR*2: Rotate the workpiece with different rotation speeds	*DP*2: Universal lathe
*FR*3: Adjust the angle of the vertical axis of the brush	*DP*3: Mechanical subsystem for rotating and fixing the brush at a certain vertical angle
*FR*4: Adjust the angle of the horizontal axis of the brush	*DP*4: Mechanical subsystem for rotating and fixing the brush at a certain horizontal position

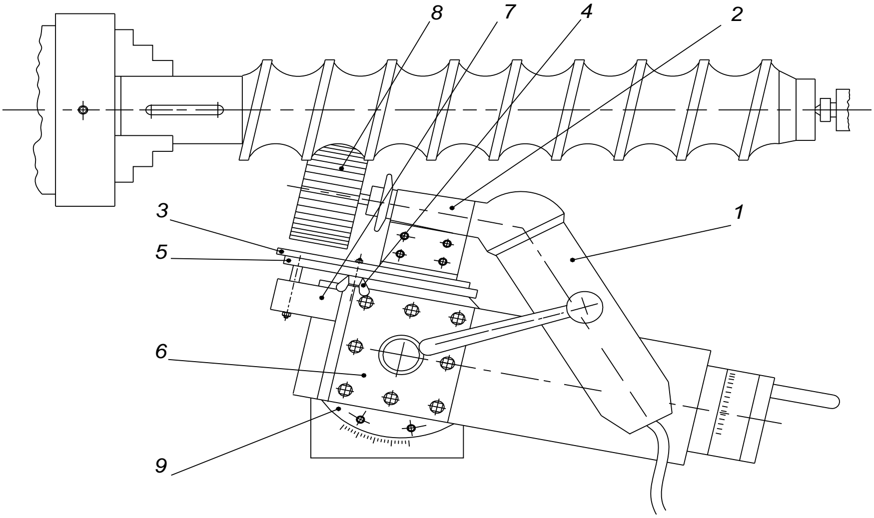


Fig. 7 Device for polishing the surface of a helical groove placed on a cylindrical surface using rotating brushes with abrasive blades: (1) portable drilling machine; (2) bracelet device for clamping; (3) disc; (4) nuts; (5) fixed disc; (6) lathe tool holder; (7) parallelipipedic-shaped part; (8) abrasive blade brush; (9) guide of the tool slide (Adapted from [17])

of the guide in the desired angular position is done using nuts. All these components are parts of the usual equipment of the universal lathe.

The axiomatic design has been used to analyze older projects and identify ways to improve them. Sundar et al. [18] expressed an interesting point of view. They set out to investigate how the human ear meets the specific requirements of axiomatic design.

4 The AD Second Axiom

According to AD, the design is a decomposition process from the highest levels to the sleeve level. At each level of decomposition, the first and Second Axiom applies.

In the previous section, we saw ways to classify the designs. The design to choose might be uncoupled or decoupled. A coupled design is a poor design. From all acceptable designs, the one with the highest probability of success must be the one to choose.

This section presents some of the most common methods to evaluate the probability of success. It shows the definition of information from the probability density function (pdf), the evaluation with fuzzy logic, and the Dempster-Shaper method. Moreover, it gives place to Delphi methods to evaluate information.

Table 2 Matrix comprising *FRs* functional requirements and *DPs* design parameters in the case of a polishing device using rotating brushes with abrasive blades

Line no. 1	Design parameters			Design parameters DP_0: *Polishing device*							
2				*DPs* design parameters of the first order							
3				*DP*1: Portable drilling machine		*DP*2: Lathe		*DP*3: Mechanical subsystem for rotating and fixing the brush at a certain vertical angle		*DP*4: Mechanical subsystem for rotating and fixing the brush at a certain horizontal position	
4				Second order *DPs* design parameters							
5	Functional requirements			*DP*1.1: Electric motor of the portable drilling machine	*DP*1.2: Mechanical subassembly of the portable drilling machine	*DP*2.1: Lathe electric motor	*DP*2.2: Lathe gear box	*DP*3.1: Slide guide of the rotary tool holder that supports a vertical axis	*DP3.2:* Nuts for fixing in the position obtained by rotating around a vertical axis of the slide guide of the tool holder	*DP*4.1: Disc holder that can be rotated relative to a fixed disc	*DP*4.2: Nuts for securing the brush holder disc with the fixed disc
6 Column no. 1	2	3	4	5		6		7	8	9	10
7	Zero order functional requirement	First order *FRi* functional requirements	Second-order functional requirements	Highlighting the *DPi* design parameters corresponding to each *FRi* functional requirement							

(continued)

Table 2 (continued)

8		*FR*1: Rotate the brush with abrasive blades at different rotational speeds	*FR*1.1: Rotate the brush with the abrasive blades	X							
9			*FR*1.2: Change the rotation speed of the brush		X						
10	*FR*0: Research on the polishing process of a helical groove	*FR*2: Rotate the workpiece with different rotation speeds	*FR*2.1: Rotate the workpiece			X					
11			*FR*2.2: Change the rotation speed of the workpiece				X				
12		*FR*3: Adjust the angle of the vertical axis of the brush	*FR*3.1: Put the axis of the brush with abrasive blades relative to a vertical axis					X			

(continued)

Table 2 (continued)

13			*FR*3.2 Fix in the axis of the brush with abrasive blades in a certain position to a vertical axis						X		
14		*FR*4: Adjust the angle of the horizontal axis of the brush	*FR*4.1: Put the axis of the brush with abrasive blades relative to a horizontal axis							X	
15			*FR*4.2: Fix the axis of the brush with abrasive blades in a certain position to a horizontal axis								X

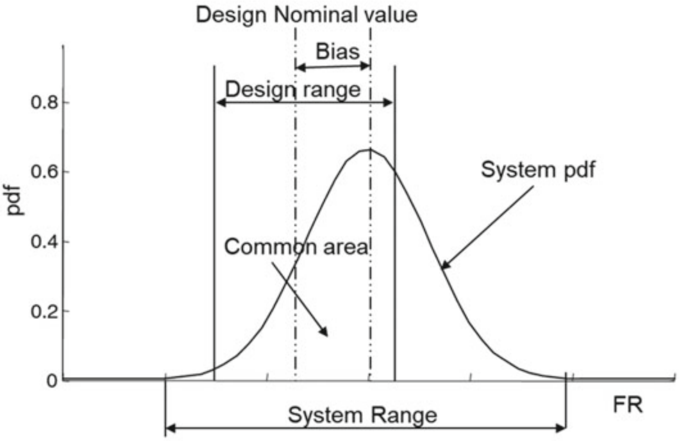


Fig. 8 Probability density function for a design with a single FR

The Second Axiom of AD states: minimize the information content of a design. The information is a measure of the probability of success so that it allows to choose the design with the highest probability of success.

Figure 8 shows the pdf of a single FR, the system pdf, the design range, and the common area. The common area is the intersection between the system area and the design boundaries defined for the FR.

The FR is accomplished if the working system is within the Design range. Figure 8 also shows the nominal value of the design and the bias to the system probability density function (pdf). The more extensive the design range, the higher the probability of success of the design. Notice that the computation occurs in the Functional Domain, not the Physical Domain.

The probability of success is the relation between the common area and the system area (Eq. 10). The system area is unitary when using a pdf.

$$p = \frac{Common\ \ Area}{System\ \ Area} \tag{10}$$

According to the Shannon equation, the information content, I, expressed in bits for a single FR is defined in Eq. 11. The lower the information, the higher the probability of success.

$$I = \log_2(1/p) = -\log_2(p) \tag{11}$$

In many designs, the system pdf is unknown. If the designer achieves a mean and standard deviation, a normal distribution is defined, which allows estimating the probability. For example, the average power of an equipment and its standard deviation can come from the heat needs and schedules.

In other applications, there is no knowledge about the pdf. However, the system range is known, making it possible to compute the information using uniform distributions. Uniform distributions commonly allow the evaluation of the pdf for mechanical tolerances. It can be used to calculate the information of two or three FRs for any design, uncoupled, decoupled, or coupled.

Fuzzy logic has been used to evaluate the system pdf by using the system membership. The System membership function can be a triangular, trapezoidal, sigmoid function, or any user-defined or computed. The system range is usually known, and the function shape can be selected from the designer's experience. Moreover, FR may arise from fuzzy algebra if a mathematic expression defines the FR. Each parameter of the mathematic expression has a membership function.

Figure 9 shows an example of a system membership computed from a mathematic expression.

The Figure 9 depicts a system membership function computed from the product of fuzzy numbers. The design membership is a trapezoidal function in the example, other than a crisp design range.

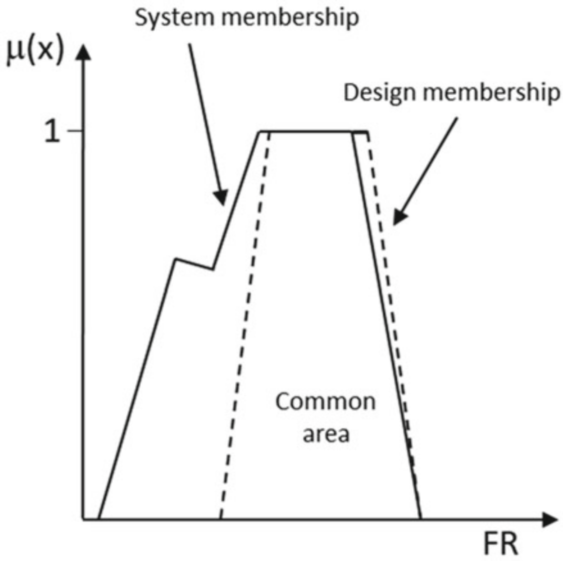
The system membership area is not necessarily unitary in the fuzzy sets theory. Therefore, Eq. 11 applies to pdf applications as well as fuzzy applications.

As the reader already read, a design with more than one FR system can be uncoupled, decoupled, or coupled. As already mentioned, from the available designs, the one with the minor information content must be the design to choose.

The matrix shape is essential to define the information content of the design.

If the design is uncoupled, all FRs adjust independently. The join probability P of all independent events is the product of all probabilities. Therefore, the information content is the sum of the information of the FRs, as depicted in Eq. 12.

Fig. 9 Membership function for a single FR



$$I = -\log_2(P) = -\log(\prod_i p_i) = \sum_i (-\log_2(p_i)) = \sum_i I_i \tag{12}$$

Each probability p_i is achieved by knowing the system pdf of a system membership function.

If the design is decoupled, there is a sequence to tune the FRs. Referring to Eq. 6, FR_1 is the first FR to adjust, then FR_2, and finally FR_3. In other words, FR_2 is subjected to FR_1, and FR_3 to the occurrence of FR_2 and FR_1. The probability problem turns into a Bayesian probability. For decoupled designs, the probability is according to Eq. 13:

$$P = p(FR_1) \cdot p(FR_2|FR_1) \cdot p(FR_3|FR_1, FR_2) \tag{13}$$

In sequential applications, the probability of fulfilling an FR is in the context of all former FRs. In a failure evaluation, an FR_2 is a function affected by a former letdown of FR_1.

In many engineering situations, the picture is well described by fuzzy logic. Experts can estimate ranges of values of an event subject to the occurrence of previous events. Moreover, they can define a type of fuzzy function from their knowledge of the problem. Triangular functions are the most used ones. As a result, the probability of the design is the product of all fuzzy events in a sequence.

Similar reasoning applies using the Dempster-Shafer Theory (DST) to estimate the information of a decoupled design.

DST uses belief, a measure of what we know, and plausibility, the measure of what we can know about the event or scenario. The design can be defined in different uncertain scenarios at the same time. Therefore, DST is most attractive for the higher decomposition levels of any design when knowledge about the complete system is scarce.

In DST, the events have a frame of discernment Θ with n mutually exclusive and exhaustive singletons. Suppose the frame of discernment has three singletons $\Theta = \{f_1, f_2, f_3\}$. It can correspond to a known scenario f_1, improved scenario f_2, and unknown scenario f_3. The set of all subsets Θ is the power set P with 2^n sets.

For three singletons,

$P = \{\emptyset, \{f_1\}, \{f_2\}, \{f_3\}, \{f_1, f_2\}, \{f_1, f_3\}, \{f_2, f_3\}, \{f_1, f_2, f_3\}\}$.

Let A be any set of sets of P. It represents a proposition $A \in P$. The example can be f_1, f_2, f_1, and f_2, and none of them.

The mass probability $m(A_i)$ is the basic probability assignment (*bpa*). The focal elements are the sets with non-zero mass. The *bpa* can be used to compute the information content. Likewise, the *pdf*, *bpa* has the properties shown by Eq. 14:

$$m(\emptyset) = 0, \qquad \sum\nolimits_{A_i \in P} m(A_i) = 1 \tag{14}$$

Mass probability maps the values of a power set, not from the x values of a universe of discourse. The belief in a set A_i, is the sum of mass evidence in the subsets B such that $B \subseteq A_i$ (Eq. 15):

$$bel(A_i) = \sum_{B \subseteq A} m(B) \tag{15}$$

Equation 16 shows the plausibility *pl(A_i)*. It is the evidence in all subsets of A_i that intersect B.

$$pl(A_i) = \sum_{B \cap A \neq \emptyset} m(B) \tag{16}$$

Bl(A) and *pl(A)* allow computing the information content. Therefore, it makes *bl(A)* and *pl(A)* the lower and upper bounds of the probability of fulfilling an FR.

Finally, despite the lack of scientific foundation of the Delfi models, it is worth presenting it because of their broad application. Delphi models are an iterative process of Estimate-Talk-Estimate. A panel of experts compares the probability of success of different designs. Then they discuss the results and compare them again. The process is supposed to converge to a decision. The group must have all the necessary skills to make a proper decision. Delphi methods can be applied to evaluate the probability of success of different designs. Moreover, a panel of experts can decide between two coupled designs, case no uncoupled design is available.

5 Comparison with Other Design Methods

This section analyzes common concepts, values, practices, and assumptions between AD and other design methodologies. It explores different methods to create a design framework together with AD. We will call framing how to merge concepts, values, and practices from several design methods to create frameworks that ensure a greater capability to create value.

5.1 Context of Comparison with Other Design Methods

Design Theory and Methodology (DTM) is a field of design research that deals with the study of design principles, knowledge, procedures, and practices. We could say that the objective of the DTM is instead focused on the way it is designed (principles, practices, activities) than on what is designed (products or services).

The ways in which scientific knowledge evolves are complex and different. The early stages are based on observations, experiments, events, intuition, imagination, and the gain is a collection of facts. The facts are validated by testing strategies in the context of hypotheses. Not infrequently this road encounters many difficulties.

We could consider that scientific knowledge starts from facts interpreted in a field of hypotheses to reach laws.

This is also the case with DTM which begins with a collection of individual design cases and evolves into more abstract and general forms intending to become a general (universal) or abstract theory about design.

There is a wide variety of DTMs. The elaboration of a list of DTM may risk not including all methodologies. A comprehensive list of twenty-three DTMs is summarized in [19].

Over time, several classifications of DTMs have been attempted. Tomiyama proposed one of the classifications that seemed appropriate to this approach based on GDM (General Design Theory) founded by Yoshikawa [19].

According to GDP, knowledge can be mathematically formalized, and for this three axioms are proposed:

- The first axiom ("axiom of recognition") according to which any entity can be identified and modeled by attributes;
- The second axiom ("axiom of correspondence") establishes a one-to-one cardinality between the set of entities and the set of entity concepts;
- The third axiom ("axiom of operation") is according to which the set of entity concepts and the set of abstract concepts form a topological space.

Mathematically, theorems may be derived from these axioms to explain the design process.

From a GDT perspective, the design process is a mapping of the functional space to the attribute space, defined on the set of conceptual entities, as exemplified in the GDT proposed by Tomiyama [19]. Three different categories of using DTMs in design activity have been identified, such as [19]:

- *Using DTM to generate a new design solution* (based on creativity, modification, adaptation, combination, systematic approach, etc.);
- *Using DTM for the development of adjacent functionalities* (QFD, AD, DfX, Taguchi, etc.);
- *Use of DTM for design knowledge management* (design knowledge management, concurrent engineering, etc.)

These categories are not mutually exclusive, and some design methodology overlaps two or more areas.

However, Axiomatic Design appears in categories together with Taguchi method, QFD, DfX, FMEA, analysis technique, optimization technique, and genetic algorithm. Therefore, the Axiomatic Design can relate to other methods in the same category (compare what is comparable).

In the following subsections, we will analyze/present comparisons of the Axiomatic Design methodology with the Taguchi, QFD, and TRIZ methodologies.

5.2 Comparison AD and Taguchi Method

The literature in the field [19–22] states that the method was first proposed by Genichi Taguchi in the 1950s in Japan at NTT (Nippon Telephone and Telegram Coop.). It was also stated that the Japanese industry accepted it well. In the 1980s the method was introduced in the US and then in Europe.

Robust parameter design is a method of systematic application of DoE (Design of Experiments) to optimize projects by improving their transfer functions.

The central concept of the method is the sensitivity of a design to the uncontrolled factors encountered in production as well as in use.

According to the method, the loss of quality during the life cycle is assimilated with the deviation from the desired performance, and a good design minimizes the loss of quality. Such a model is considered as robust as it is less sensitive to noise.

The concepts of Taguchi theory could be summarized as follows:

1. The primordiality of quality in the design phase and not of inspection;
2. Immunity of the product to uncontrolled environmental factors;
3. Evaluate the quality costs of the entire system by measuring the deviation from the standard.

In order to achieve the desired quality of the product through design, the methodology recommends a three-phase approach:

1. Systems design—identifying appropriate work levels for design factors.
2. Parameter design—determination of factor levels based on the condition that the influence of uncontrolled factors (noise factors) produces minimal variation in system performance.
3. Tolerance design—focusing attention on the tolerance of the factors determined in the previous stage, factors that have a significant influence on the product.

The Taguchi method uses the concept of the loss function to define the evaluation of product quality, a function that expresses the loss in use of a product due to variations in product function and other losses (secondary costs). Losses are estimated by mean square deviation from the target value and the smaller they are the more robust the design is.

The use of Taguchi methods for the application of design axioms is an approach in which the author argues that the engineering analysis methods developed by Taguchi are consistent with the two axioms of axiomatic design set forth by Suh [23]. The proposed framework, especially when the number of requirements is very high, starts with AD by organizing the problem in terms of functional requirements. Each functional requirement requires a controlling factor that can be determined using the Taguchi method and the experimental design. The author concludes that AD's language is different from that of Taguchi methods, although the principles are the same: independence of functional requirements and minimization of design information content. There are examples where AD is combined with several tools (the seven quality control tools) and the design of experiments [24]. The link between the complexity and robustness of a system is a topic debated in the literature. AD and Taguchi methods are inevitably taken into account when discussing this topic. Gohler presents a quantitative approach to relate robustness and complexity using a model-based probabilistic [25]. Authors define complexity through the degree of coupling (directly related to axiom 1 of AD) and the level of contradiction between functional requirements. The problem that the authors set out to clarify is whether there is an association between the degree of coupling and the level of contradiction of a design on the one hand and its robustness on the other.

There are many and varied approaches to developing frameworks for design. An example is a framework for robust design and Variation Management Framework (VMF) by combining central models to Robust Design, and the Domains of Axiomatic Design [26]. The authors concluded that VMF has proven to be a valuable framework to communicate robust design and variation to engineering and senior management levels.

An example of sustainable product development by integrating Robust Design criteria and Axiomatic Design principles is presented by [27]. The authors propose a design framework in four steps. Once the customer requirements are selected, the axiomatic design process proceeds.

Product design frameworks ensure quality in the conceptual stages instead of quality inspection, where the quality of a product remains undetermined until the product is built and tested [28]. The author proposes a methodology for integrating design for quality in modular product design by considering the underlying principles of axiomatic design and robust design along with the product's perceived quality. For evaluating the modular architecture, metrics are defined. Each module (Membership functions) is evaluated based on robustness and compliance with the axiomatic design principles.

Oh [29] equates the relationship between functional requirements (FRs) and design parameters (DPs) as a transfer function. Suppose a specific value of a DP determines that the corresponding FR reaches a particular target. In that case, the variation of this design parameter will determine a variation of the corresponding functional requirement around a value. A Taylor series expansion can approximate this variation of the functional requirement. The transfer function is developed using two matrices in the relationship between functional requirements and design parameters: one that reflects independence (Axiom 1), called the matrix [A], and a second that reflects the informational content (Axiom 2) named matrix [B]. Through this approach, the mathematical treatment between Axiomatic Design and Robust Design was extended.

In a mixed approach for robust design integrating the Taguchi method in Axiomatic Design [30], the authors consider that the main difficulty in checking the second axiom of AD theory is the identification of relations among FRs and DPs. In the case of an uncoupled problem, each DP regards only one FR. The most robust solution is the one with the lower "information" or higher probability of success. For uncoupled designs, information is the sum of the effects from each relationship. The problem is complicated in the case when it is modeled as coupled, where more DPs influence the same FR. The authors consider that the relationship law between

FRs and DPs can be identified by working on a physical prototype of the product. During concept design and early embodiment, the second axiom cannot be applied. Taguchi method can supply this kind of information since the preliminary phase of an embodiment when first product architectures appear, and suggestions about dimensioning and material choice for each component can guide the designer toward a deeper knowledge of the solution he/she is pursuing. The first phase of the design process take place in two steps:

- check by means of the first Axiom of Axiomatic Design if the solution is good;
- measure by means of Taguchi Method the level of robustness of the solution.

Several design methodologies such as axiomatic design, robust design, and the theory of inventive problem-solving have been integrated with the functional prioritization framework provided by reliability-centered maintenance to develop a new conceptual design methodology [31]. To propose a framework that encompasses the four methodologies, the authors compared their features.

Yihai [32] propose a design framework that combines AD, TRIZ, and Taguchi. AD provides an analysis function to find latent contradictions, and TRIZ is used to solve specific contradictions by contradiction matrix and solving principles. The Taguchi method is used for parameter optimization—parameter design and tolerance design.

5.3 Comparisons Axiomatic Design and TRIZ

The name of the method “TRIZ” comes from the Russian title of the book “Theory of Inventive Problem Solving”:—Theory Resheniya Izobretatel’skih Zadach (TRIZ), being an acronym [33, 34]. TRIZ is the work of Genrich Altshuller and consists of the formulation of a number of generally applicable inventive principles that resulted from the analysis of forty thousand patents.

TRIZ is an engineering problem-solving toolkit that systematically uses known solutions to solve future problems. TRIZ is used for each stage of problem-solving by preparation for problem-solving, problem-solving, and solution selection and development [34]. The TRIZ methodology is oriented toward an ideal end result (Ideality) and leads the user to inventive solutions, rejecting compromises as a possible result. Identifying contradictions and applying the principles of solving them involves a systematic direction of solving problems.

There are many ways AD and TRIZ are combined in design methodologies.

Targeting industry best practices, Borgianni and Matt developed a study that looked at the application of AD and TRIZ methods and developed a classification of AD and TRIZ applications in different industries [35]. The study was based on articles published in 2014 and 2015 on the application of TRIZ, and Axiomatic Design reported in Scopus-indexed. From the trends revealed by applying AD and TRIZ methods, we can deduce the decrease of their mutual/synergistic implementation. The authors also consider that the sequential use of the two methods, AD (to analyze the problem) and TRIZ (to resolve circumstantial contradictions), is ineffective and suggest ways to exploit the opportunity to build a new framework capable of addressing issues related to complex systems.

Understanding TRIZ through the review of top-cited publications [36] is a paper reviewing the literature, including the top 102 indexed publications concerning TRIZ, according to the number of citations received. The description of the TRIZ application fields and their use in different work frameworks are organized in clusters. Clusters 5–6 refer to TRIZ for ideation and conceptual design used as a stand-alone methodology and combined with other techniques (Case-Based Reasoning, Axiomatic Design, etc.).

Regarding the relationship between AD and TRIZ, the authors opine that there are two distinctive features of the AD paradigm that can be seen as complementary aspects of the TRIZ application domain:

- The first distinctive feature is that AD focuses on functional requirements and relates them to physical requirements.
- The second distinctive feature consists of the existence of the two axioms that help distinguish good from bad designs. The design classification allows the hypothesis of a framework integrating AD and TRIZ: AD is firstly used to formulate technical requirements (problem setup), then TRIZ is entrusted to the invention, and solutions are evaluated from axioms perspective.

A methodology to conceptually design firmware that will help bridge the gap between software and hardware conceptual design is presented in [37]. The proposed framework integrates UML (Unified Modeling Language), AD, and TRIZ. A conversion method between the axiomatic design matrix and the widely used UML sequence diagram was developed. DPs of the design matrix are defined as the objects in the UML sequence diagram, and FRs of the design matrix are generated by merging FMs depending on their flow of information in the sequence diagram. According to the authors, the methodology developed helps bridge the gap between axiomatic design theory and software design and creates the possibility of improving the full integrated system (hardware and software) simultaneously.

A framework for solving problems using synergistically TRIZ and AD is proposed in [38]. The authors consider that by applying AD and TRIZ in a framework, the strengths of both methodologies are capitalized. First, AD is applied to analyze the problem and break down the main problem into a hierarchy of problems, and then TRIZ is applied to generate innovative solutions to the problems in the previous hierarchy. In this way, the framework formed by AD and TRIZ uses synergistically the capacity of detailed analysis of AD with the innovative process of generating ideas of TRIZ.

There are conceptual design approaches in which AD is used in a TRIZ framework [39]. According to the authors, the strengths of the methods are:

For TRIZ—problem identification (contradiction) and concept generation.
For AD—problem identification (coupling) and formulation steps.

The authors consider that the axiom of independence of AD can be used to narrow down the list of possible standard solutions generated by the existence of a physical contradiction (according to the TRIZ principles).

In [40], the authors summarize the possible relations between Axiomatic Design rules and TRIZ problem-solving tools. Seven corollaries that serve as the design rules are directly derived from two axioms, so comparing these "lower level design rules" with TRIZ tools is useful for understanding these two methodologies.

5.4 Comparisons Axiomatic Design and QFD

Quality Function Deployment, or QFD, is a method and a set of tools for product development. QFD is used to effectively define customer requirements and convert them into detailed engineering specifications and plans to produce the products that fulfill those requirements. QFD was founded in the 1960s by Mizuno and Akao in Japan [19].

QFD process may be different, depending on the types of products, such as improvements of existing products, innovative new products, mass production products, order-made products, etc. QFD is implemented iteratively, and each iteration consists of mapping some quality elements into other quality elements by using a matrix formulation (called the House of Quality). Iterations of QFD implementation are presented as follows:

- Product planning: identify customer requirements; translate VOC (voice of customers) into design specifications; prioritize requirements; evaluate the competition.
- Product design: generate design ideas or concepts; translate the outputs of the product planning phase into individual part details, identify product risks, define the product specifications.
- Process planning: defines the product development process; establishes process controls; creates a manufacturing process flowchart and process parameters.
- Process control (production planning): define the production requirements for each component/operation; establish inspection and test methods; define performance indicators to monitor the production process.

The basic design tool of quality function deployment is the house of quality. This tool allows the identification and clarification of the client's requirements (What's), identifies the importance of these requirements, identifies the engineering characteristics relevant to these requirements (How's), and the correlation of the two allows the assignment of objectives and priorities. House of quality summarizes customer requirements, weights, and correlation matrix of customer requirements and technical specifications using a matrix form.

There are a variety of attempts to create frameworks by identifying concepts, best practices, common values between AD and QFD (even with other methods). Some of these attempts are presented below.

A literature review study on comparing and integrating AD with QFD as a design method is presented in [41]. The authors developed a comparative analysis between the two methods based on this study. The authors conclude that the QFD method is used to identify the problem that occurs early in the design, and Axiomatic Design is more suitable for product development with high quality. By integrating both methods, the axiomatic design is used to analyze the systematic changes of customer requirements into design parameters, functional requirements, and process variables from the house of quality.

Attempts to develop frameworks for design sometimes extend to combining several methods organized into different flows [42]. The authors present a method of integrating QFD, AD, and benchmarking methods (BM) to conduct the searching process of design solutions.

The proposed method consists of three processes: applying QFD to map customer requirements (CRs) into function requirements (FRs); mapping FRs into design parameters (DPs) by using AD; and applying the benchmarking method (BM) to search for optimal design specifications by the comparative analysis and concept combination from benchmark products.

5.5 Discussion

All above-analyzed design methods are part of DTMs and could be used to choose or optimize products or processes and solve problems in general. Various literature review articles signal the organization of design methods in different frameworks. Each framework proposal is accompanied by case studies, arguments that support the organization in the proposed way. However, there are rare proposals to validate different methods or frameworks.

This subchapter considers four design methods and philosophies that are used nowadays in the industry.

Some considerations about comparison criteria, differences, and similarities are synthesized in Table 3. Table 4 highlights the main issue. Notable differences can be identified between methods but also common or similar things.

AD is the only method that concentrates on obtaining an ideal design. It is possible to propose a new design or to analyze an old design, and the axioms are the scientific bases used for this goal. The concept of mapping or zigzagging process belongs only to AD, and it allows to avoid the relations between the function of the product, processes, or systems.

TRIZ's concept of solving contradictions is similar to the idea of independence from the first axiom of AD. Only AD and TRIZ handling with the problem of functional coupling.

QFD concentrates on satisfying the customer needs, and the importance is given to the VOC is similar to the importance of choosing the FRs in AD because a design solution cannot be better than its FRs. However, QFD creates coupled designs in the

Table 3 Comparison between AD, Taguchi Method, TRIZ, QFD

	AD	Taguchi Method	TRIZ	QFD
Main objective	• Ideal design	• Minimize variability • Quality loss function	• Solve technical problems	• Set targets for the technical attributes of a product • Understand the importance of each/hierarchization
Main output	• New design that satisfy all customer needs • Improving of an existing design	• Robustness of the quality characteristics	• Elimination of contradictions • Technical improvement	• Satisfaction of customer needs
How to improve the design	• Trying to eliminate the relationship between functions • All functions need to be fulfilled, so there are no function weights	• Optimize/minimize the quality loss function • Take into consideration the cost	• Incorporate quality and reliability in the design stage	• Increasing the parameters that have a most important impact in some perspective
Ease of use/application	• Medium difficulty • Not widely spread	• Medium difficulty	• Relatively widely spread	• Relatively easy • widely spread
Main strength/ advantages	• Identify the best design easily • Suitable for the decision making of product development with high quality	• Transform the variation from nominal value taking into consideration with financial depiction	• Focus its studies on inventive problem-solving • Generating creative design solutions	• It is a customer driven process
Disadvantages	• The creative process comes from applying the two axioms but is not straightforward	• Define tolerances of a design instead of changing the design to allow higher tolerances	• Lack of formalization	• Sometimes, it does not use meaningful information • Creates a coupled design • Prioritize functions

Table 4 Main issues regarding the comparison between AD and Taguchi method, TRIZ, QFD

Differences/similarities	Taguchi method	TRIZ	QFD
AD	• Taguchi takes into consideration some components of the cost • Taguchi method does not implie a zig-zagging process • Concentrate on tolerance specification, rather than design change to allow higher tolerance	• TRIZ contradiction concept is similar to the functional coupling in AD. Overcoming contradiction means the removal of functional coupling • TRIZ has no method to identify couplings • AD theory states the general rules of engineering design to help innovation; TRIZ methodology concentrates on inventive problem-solving techniques for coupling problems	• Produce a coupled design • VOC $\approx$ CNs • prioritize functions rather than using the minimum number of functions with no weights

vast majority of applications. Moreover, QFD prioritizes functions, and AD aim to define the minimum number of functions necessary to fulfill the Customer Needs.

The Taguchi method can be used efficaciously in combination with AD. After obtaining a good design, the level of its robustness could be measured. Taguchi's main objective is to minimize the quality loss function. This is similar to the AD second axiom, which states minimizing the information content of a design that represents choosing the design with the highest probability of success. However, the approach is different—Taguchi method aims to reduce the deviation from a target by reducing tolerances; AD aims to define tolerances as large as possible and thus define a system within the range.

Taguchi is the only method discussed in this chapter that explicitly considers the cost to improve the design. Cost can be a constrain in AD or defined as a function.

6 AD Application

As can be seen from the above, the first applications of axiomatic design aimed at developing the design of manufacturing technologies. Axiomatic design can be used efficiently in the case of constructive design activities, and so far, quite a lot of applications have been identified in this area.

However, there are many other areas without apparent connections with manufacturing technologies' design or constructive design. Efficient results have been obtained by applying axiomatic design to them.

There are various ways of identifying sectors of human activity in which design or analysis activities have so far been undertaken based on axiomatic design principles. Economic and social life fields have applied AD and are briefly presented below, taking into account the classification of the sectors of activity proposed by Borgianni and Matt in 1996 [35].

Design of vehicles and vehicle components. Naddeo addressed the issue of designing a car platform usable in the case of an electric rear-wheel-drive vehicle. He also used a fuzzy approach to this problem, reaching optimized solutions for battery placement and car platform crossbars as chassis components [43].

Tate et al. used AD to develop competitive cars in the Texas Tech University Eco-CAR program [44]. The AD use led to the decision to use a two-mode hybrid architecture. The correctness of the selected solution was verified by simulation.

Materials processing. Kazmer used axiomatic design principles to improve the control of the injection molding process [45]. Thus, he found that multi-cavity pressure control contributes to a spatial decoupling that increases the number of degrees of freedom that define the quality characteristics. Also, the dynamic temperature control ensures a temporary decoupling of the injection and solidification stages, which facilitates the identification of ways to increase the performance of the injection molding process. Esther Richards used the axiomatic design to design and materialize an apparatus usable in evaluating the gas solubility in polymers [46].

Civil engineering. A proposal to use axiomatic design and Product Platform Design to design a temporary shelter was formulated by Gilbert et al. [13]. It was appreciated that this example demonstrates the extent to which the combination of the two design methodologies can be used for an optimal solution to the problems raised by the realization of a complex civil engineering project. Puik et al. addressed the possibilities of combining the advantages offered by agile development and axiomatic design, respectively, aiming at harmonizing approximately contradictory design rules specific to the two methods of developing new products [47]. They appreciated that an attenuation of the agile design rules in the first phase and the axiomatic design rules in the subsequent phase would improve the design process.

Manufacturing tools and systems. The problem of using axiomatic design in the case of manufacturing tools and systems has been relatively often addressed by researchers. The first applications of axiomatic design aimed at improving manufacturing processes probably contributed to this situation. It can thus be seen that the principles of axiomatic design have been used to balance assembly lines [48], to develop total productive maintenance applied in manufacturing organizations [49], to develop manufacturing systems [50], etc.

Extensive and distinct approaches to manufacturing systems through the principles of axiomatic design have been described in several papers by Cochran et al. [51–53]. The problem of developing computer integrated manufacturing systems was addressed by Delaram and Valilai [54]. A point of view on axiomatic design in manufacturing systems was carried out by Rauch et al. in 2016 [5].

Energy. The heat ventilation and air-conditioning (HVAC) systems in commercial buildings could be improved, taking into account comfort and energy consumption using axiomatic design. Cavique and Conçalves-Coelho proposed practical solutions starting from the requirement corresponding to the first axiom, which implies the existence of independent or coupled systems [55].

Mechanical components. Probably a wide application of axiomatic design took place in mechanical structures and components. There are thus a wide variety of such structures or components in the design of axiomatic design principles.

Hydraulics and fluid mechanics. In principle, the components of hydraulic systems are also mechanical components, so they could be included in the topic addressed in the previous paragraph. Some specific problems of a hydrostatic spindle subsystem appeal to the use of the first axiom of AD [56]. The authors highlighted the importance of integrating the multisource information for the use of axiomatic design.

Electronics and electrical components. The conceptual design of mechatronic systems was the topic of research conducted by Chen and Jayram [57]. They developed an improved design methodology, starting from the principles of other methodologies, among them being axiomatic design.

The field of health. Optimization of patient flows in hospitals applying lean management principles, but applying a theoretical framework developed using axiomatic design was proposed by Arcidiacono et al. [58]. They considered that a group of patients with similar characteristics would contribute to better development of hospital activities.

Devices for older and disabled people. In a certain connection with the use of axiomatic design to solve health problems, it can be mentioned the identification of devices for elderly people or people with disabilities by applying axiomatic design principles. Thus, Mark et al. have invested efforts in designing worker assistance systems that can be used in the workplace by older people and respectively by workers with certain disabilities [59]. It is worth noting the use of one-on-one interviews to define the client's needs in this case clearly.

Agriculture and forestry. Sadeghi et al. found many work accidents in agricultural works deriving from the use of different solutions for power take-off of agricultural tractors [60]. They analyzed the existing alternatives of the power take-off subsystems and used axiomatic design to define functional requirements to reduce the risk of injury.

Jiang proposed a correlation of the axiomatic design process with the ontology information representation in the case of the development of small agricultural machinery products [61]. A reconfigurable product design system was considered.

Management in industry. Brown and Rauch analyzed the importance of functional requirements for promoting product creativity and sustainability when using axiomatic design [62]. The paper written by Brown and Rauch shows that "no design solution can be better than its FRs." They further considered that it is possible to select the most convenient design parameters by using axioms of axiomatic design. The integrated development of a product and its manufacturing process was the subject addressed by Vallhagen in his doctoral thesis [63].

The educational system. The systemic approach of the educational process, so the acceptance of the idea that there is an educational system, urged researchers to consider axiomatic design principles in the analysis and design of this system.

Thus, Mirzi and Liego-Betasolo evaluated the courses of materials engineering and fluid mechanics through an axiomatic design model [64]. In the case of his doctoral thesis, Towner has developed an interesting set of considerations according to which engineering education can be treated as a manufacturing system, and its problems can be solved efficiently using axiomatic design [65]. In a course at the University of Tokyo, Iino and Nakao used Design Record Graph and axiomatic design to identify and use students' creative resources [66].

Object handling and conveyors. Some problems regarding the handling and transport of products made from forest residues have been solved using the axiom of independence by Rodrigues et al. [67]. In this way, it became possible to equip better and organize the wooden pellets production line. Nadeo has proposed combining axiomatic design principles with a fuzzy logic approach to design an alternative propelled rear-wheel-drive vehicle chassis of car platform [68]. Khandekar and Chakraborty used fuzzy axiomatic design principles to select material handling equipment [69].

Services. The use of axiomatic design principles for developing knowledge management implementation services was proposed by Hao et al. [70]. They appreciated that in this way, a better collaboration of knowledge producers and receivers is possible and proposed the use of tools designed for this purpose. The possibility of using axiomatic design in financial services was noted by Banciu and Drăghici [71].

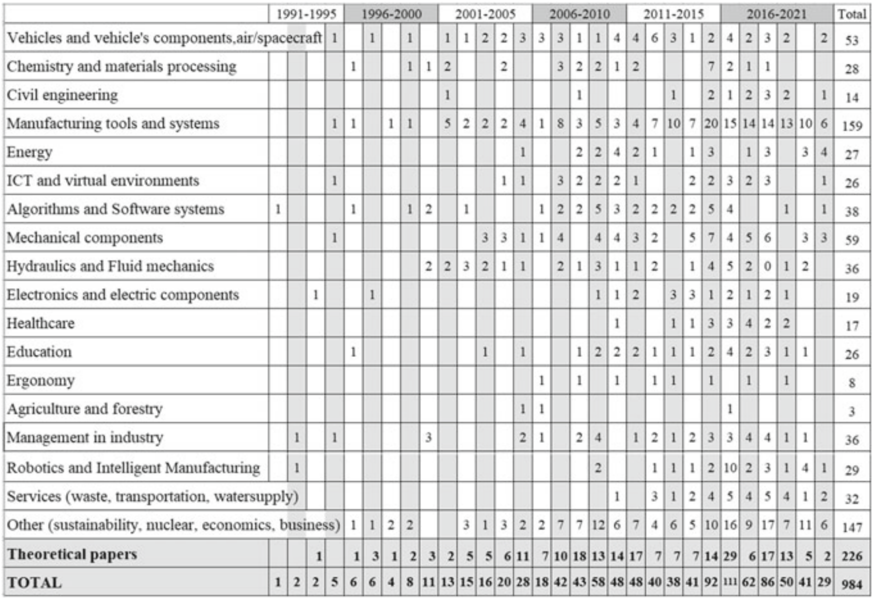
Mining and extraction. Zeng et al. considered the use of extended axiomatic design theory to the global mining supply chains, the latter appreciated as complex systems [72]. They considered that solving the problems specific to the global mining supply chains is difficult in the absence of methods capable of reducing the structural complexity of supply networks.

Illumination. The axiomatic design was used by Guls et al. to improve observation conditions around an autonomous underwater vehicle [73]. Based on the experience gained through previous research, a lighting module was proposed to be used to capture still images and video. An agile ergonomic monitor stand also involving a light source was proposed using the axiomatic design by Spalding et al. [74]

Breeding and fish farming. Vilbergsson mentioned axiomatic design as a solution to identify several possibilities to improve the specific functions of an intensive aquaculture system [75]. Using the axiomatic design theory, optimization of the solution of transfer bins for whole salmon grading has become possible [76].

Food and beverages. It is not surprising that axiomatic design principles are used in addressing food and beverage issues. Thus, an analysis of complexity in the kitchen was performed by Foley et al. [77], revealing the possibilities of using axiomatic design principles. Various issues specific to space life support systems, including food production, have been addressed through axiomatic design by Jones [78].

One can observe the large share of using axiomatic design to solve problems in the fields of industrial engineering and manufacturing engineering. A highlighting of the application of axiomatic design principles in different sectors of activity is possible, for example, by identifying papers published in these fields and indexed



	1991-1995				1996-2000					2001-2005					2006-2010					2011-2015					2016-2021						Total
Vehicles and vehicle's components,air/spacecraft				1		1		1		1	1	2	2	3	3	3	1	1	4	4	6	3	1	2	4	2	3	2		2	53
Chemistry and materials processing					1			1	1	2			2			3	2	2	1	2				7	2	1	1				28
Civil engineering										1							1					1		2	1	2	3	2		1	14
Manufacturing tools and systems				1	1		1	1		5	2	2	2	4	1	8	3	5	3	4	7	10	7	20	15	14	14	13	10	6	159
Energy														1			2	2	4	2	1		1	3		1	3		3	4	27
ICT and virtual environments				1									1	1		3	2	2	2	1			2	2	3	2	3			1	26
Algorithms and Software systems	1				1			1	2		1				1	2	2	5	3	2	2	2	2	5	4			1		1	38
Mechanical components				1								3	3	1	1	4		4	4	3	2		5	7	4	5	6		3	3	59
Hydraulics and Fluid mechanics									2	2	3	2	1	1		2	1	3	1	1	2		1	4	5	2	0	1	2		36
Electronics and electric components			1			1												1	1	2		3	3	1	2	1	2	1			19
Healthcare																			1			1	1	3	3	4	2	2			17
Education					1							1		1			1	2	2	2	1	1	1	2	4	2	3	1	1		26
Ergonomy															1		1		1		1	1		1		1		1			8
Agriculture and forestry														1	1										1						3
Management in industry		1		1					3					2	1		2	4		1	2	1	2	3	3	4	4	1	1		36
Robotics and Intelligent Manufacturing		1																2			1	1	1	2	10	2	3	1	4	1	29
Services (waste, transportation, watersupply)																			1		3	1	2	4	5	4	5	4	1	2	32
Other (sustainability, nuclear, economics, business)					1	1	2	2			3	1	3	2	2	7	7	12	6	7	4	6	5	10	16	9	17	7	11	6	147
Theoretical papers			**1**		**1**	**3**	**1**	**2**	**3**	**2**	**5**	**5**	**6**	**11**	**7**	**10**	**18**	**13**	**14**	**17**	**7**	**7**	**7**	**14**	**29**	**6**	**17**	**13**	**5**	**2**	**226**
TOTAL	**1**	**2**	**2**	**5**	**6**	**6**	**4**	**8**	**11**	**13**	**15**	**16**	**20**	**28**	**18**	**42**	**43**	**58**	**48**	**48**	**40**	**38**	**41**	**92**	**111**	**62**	**86**	**50**	**41**	**29**	**984**

Fig. 10 Use of axiomatic design in different fields, from papers published over time in Web of Science database

in the Web of Knowledge database. By considering some ideas from a previously mentioned paper [35] including other areas of activity in which axiomatic design was used, it was possible to develop the graphical representation in Fig. 10.

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