Axiomatic Design

Design methods all aim to lead a designer to one or more good solutions to a design problem. The design method's developer expresses his or her own beliefs about the best tactics for identifying good designs in the method's principles or major strategies. Axiomatic Design was developed by Nam P. Suh, a mechanical engineering professor at MIT. Suh's intention was to identify a set of fundamental laws or principles for engineering design and use them as the basis for a rigorous theory of design. A design theory would make it possible to answer such questions as: Is this a good design? Why is this design better than others? How many features of the design must satisfy the needs expressed by the customers? When is a candidate design complete? What can be done to improve a particular design? When is it appropriate to abandon a design idea or modify the concept?

Professor Nam Suh and his colleagues at MIT have developed a basis for design that is focused around two design axioms. This section will introduce Suh's axioms and how they are used to structure design creation and the improvement of existing designs.

Axiomatic Design Introduction

Axiomatic Design operates with a model of the design process that uses state spaces to describe different steps in generating design concepts.

- Consumer Attributes (CAs)—Variables that characterize the design in the consumer domain. CAs are the customer needs and wants that the completed design must fulfill. These are similar to the customer requirements defined in Chap. 3.
- Functional Requirements (FRs)—Variables that characterize the design in the functional space. These are the variables that describe the intended behavior of the device. The FRs are much like the function block titles defined for functional decomposition in Sec. 6.5. However, there is no standard set of FRs from which a designer must choose.
- Design Parameters (DPs)—Variables that describe the design in the physical solution space. DPs are the physical characteristics of a particular design that has been specified through the design process.
- Process Variables (PVs)—Variables that characterize the design in the process (manufacturing) domain. PVs are the variables of the processes that will result in the physical design described by the set of DPs.

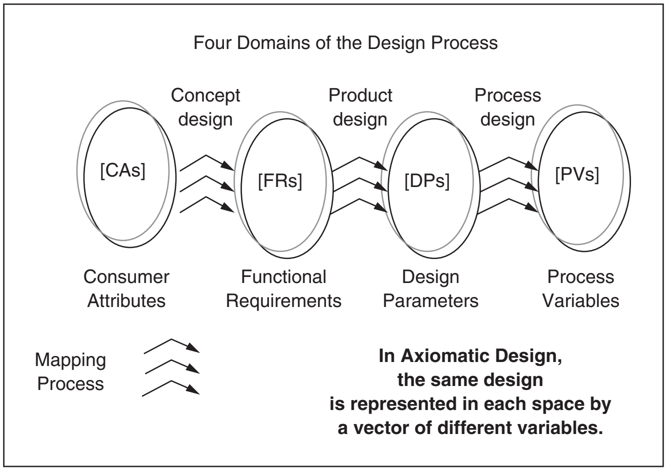

FIGURE 1
The design process from an Axiomatic Design perspective.

Figure 1 depicts the relationships among these different variables throughout the Axiomatic Design process. Suh's naming of phases in the design process is a little different from the usage in this text. He called the generation of a feasible design described by DPs selected to satisfy a set of FRs product design. In this text, that is generation of a conceptual design with some embodiment detail.

Suh[51] views the engineering design process as a constant interplay between what we want to achieve and how we want to achieve it. The former objectives are always stated in the functional domain, while the latter (the physical solution) is always generated in the physical domain.

The Axioms

In mathematics, an axiom is a proposition that is assumed to be true without proof for the sake of studying the consequences that follow from it. Theorists working in mathematically based fields declare a set of axioms to describe the ideal conditions that are presumed to exist and must exist to support their theories. Many economic theories rest on presumptions that corporations act with perfect knowledge of their markets and without exchanging information with their competitors.

More generally, an axiom is an accurate observation of the world but is not provable. An axiom must be a general truth for which no exceptions or counterexamples can be found. Axioms stand accepted, based on the weight of evidence, until otherwise shown to be faulty. Suh has proposed two conceptually simple design axioms in Axiomatic Design. Axiom 1 is named the *independence axiom*. It can be stated in a number of ways.

51. N. P. Suh, *The Principles of Design,* Oxford University Press, New York, 1990; N. P. Suh, *Axiomatic Design: Advances and Applications,* Oxford University Press, New York, 2001.

- An optimal design always maintains the independence of the functional requirements of the design.
- In an acceptable design the design parameters (DPs) and functional requirements (FRs) are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements.

Axiom 2 is the *Information axio:* The best design is a functionally uncoupled design that has the minimum information content. Axiom 2 is considered as a second rule for selecting designs. If there is more than one design alternative that meets Axiom 1 and has equivalent performance, then the design with the lesser amount of information should be selected.

Many users of Axiomatic Design focus on value and the implementation of the independence axiom. The function focus of Axiom 1 is more fundamental to mechanical designers and the relationships between functional requirements and physical design parameters is also clear. Axiom 2 has been adopted more slowly and is still the subject of interpretation. The treatment here will focus on Axiom 1. The reader is encouraged to refer to Suh's texts (referenced previously) for interpretation of Axiom 2.

Using Axiomatic Design to Generate a Concept

The Axiomatic Design procedure is a mapping of one set of variables to another. A type of design specification is obtained by examining the customer's needs and expressing them as a list of attributes. These attributes are mapped into a set of functional requirements. This process is labeled concept design in Suh's design process schematic shown in Fig. 1 . In this text we have considered the mapping of customer needs into functional requirements to be a prerequisite step that takes place prior to the generation of feasible concepts.

The design parameters (DPs) depict a physical embodiment of a feasible design that will fulfill the FRs. As Fig. 1 illustrates, the design process consists of mapping the FRs of the functional domain to the DPs of the physical domain to create a product, process, system, or organization that satisfies the perceived societal need. Note that this mapping process is not unique. Therefore, more than one design may result from the generation of the DPs that satisfy the FRs. Thus, the outcome still depends on the designer's creativity. However, the design axioms provide the principles that the mapping techniques must satisfy to produce a good design, and they offer a basis for comparing and selecting designs.

In the design process of any device of meaningful complexity, there will be a hierarchical ordering to the functional requirements (FRs). Figure 2 displays the functional hierarchy for a metal cutting lathe. The most general functional description appears at the top of the hierarchy and is labeled "Metal removal device." At the next lower level in the hierarchy, the functions are broken up into six separate functions: "Power supply" (read this as the function "supply power") is the leftmost function at the second level of the hierarchy. Figure 2 breaks down the functional requirement details of "Workpiece support and toolholder" to the third level. Clearly, Suh was employing a strategy of functional decomposition.

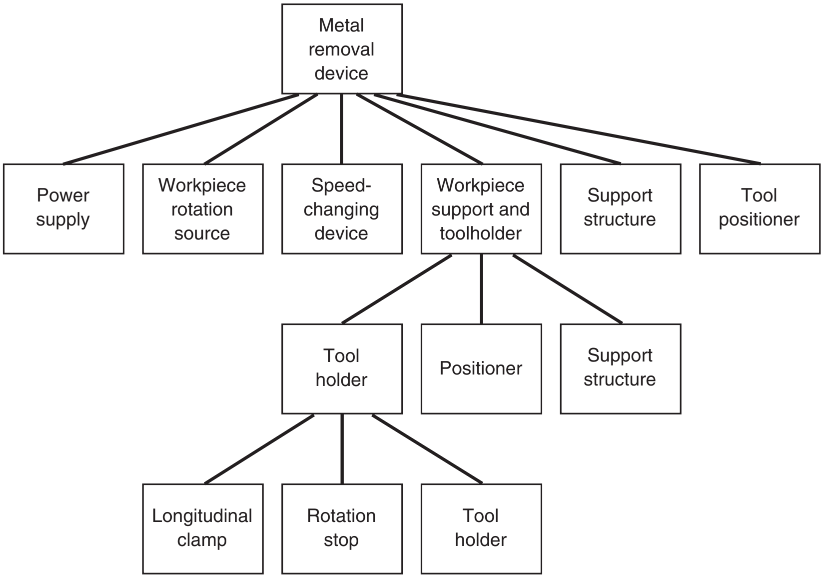

FIGURE 2
Hierarchical display of functional requirements for a metal cutting lathe. *(From N. P. Suh,* The Principles of Design*, copyright 1990 by Oxford University Press. Used by permission.)*

The hierarchical embodiment of the metal removal device is shown by a hierarchy of design parameters in Fig. 3 . Each FR from Fig. 2 is mapped to one or more DPs in the physical domain. FRs at the i^{th} level of the hierarchy cannot be decomposed into the next level without first going over to the physical domain and developing a solution that supplies all the requisite DPs. For example, the FR of "Workpiece support and tool holder" (Fig. 2) cannot be decomposed into the three FRs at the next lower level until it is decided in the physical domain that a tailstock will be the DP used to satisfy it. The design generation process becomes an interplay of mapping from FRs to DPs.

An experienced designer will take advantage of the hierarchical structure of FRs and DPs. By identifying the most important FRs at each level of the tree and ignoring the secondary factors, the designer manages to keep the work and information within bounds. Otherwise, the design process becomes too complex to manage. Remember that Axiom 1 prescribes that each FR must be independent. This may be difficult to achieve on the first try; it is not unusual to expect that several iterations are required to get an independent set of FRs.

Correspondingly, there can be many design solutions that satisfy a set of FRs. Also, when the set of FRs is changed, a new design solution must be found. This new set of DPs must not be simply a modification of the DPs that were acceptable for the original FRs. Rather, a completely new solution should be sought.

Note that the DP hierarchy is much like a physical decomposition of a device. The difference is that the DP hierarchy was created from the functional requirements.

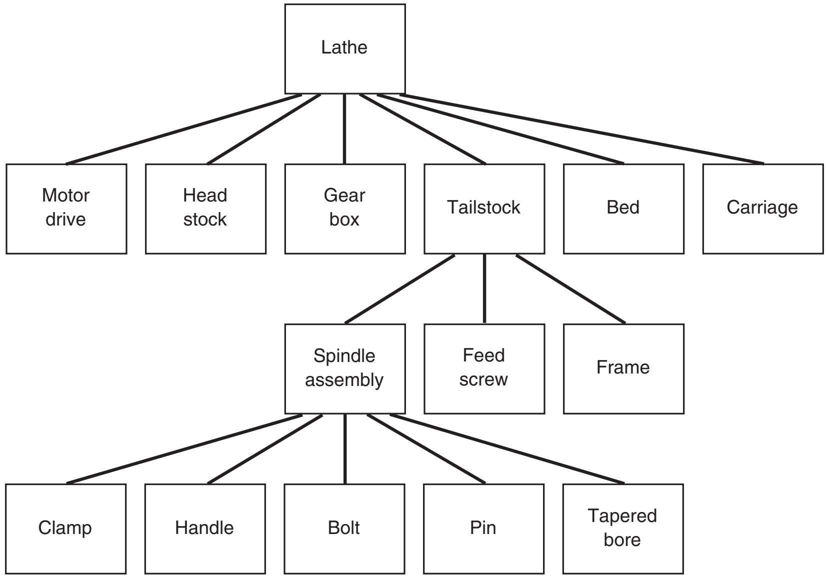

FIGURE 3
Hierarchical display of design parameters for a metal cutting lathe. *(From N. P. Suh,* "The Principles of Design," *copyright 1990 by Oxford University Press. Used by permission.)*

There may not be any physical device in existence yet. A physical decomposition diagram is a representation that begins with the completed design.

Using Axiomatic Design to Improve an Existing Concept

Thus far, we have seen how Axiomatic Design provides a framework for generating one design concept from a set of functional requirements. The designer is supposed to be aware of the axioms during this process, but the axioms may be overlooked. In this section we discuss how Axiomatic Design's formulation of the design process mapping steps using matrix algebra allows designers to develop insight about their design concepts and determine how to improve them.

Nam Suh used mathematics to formalize his work in Axiomatic Design. The following equation articulates any solution to a given design problem.

$$\{\mathbf{FR}\} = [\mathbf{A}]\{\mathbf{DP}\} \qquad (1)$$

In Eq. 1, the vector of function requirements, **FR**, consists of m rows and 1 column (i.e., size m × 1) and the vector of the design parameters, **DP**, is of size (n × 1). The *design matrix*, **A**, is of size ($m \times n$) and holds the relationships between members of the two vectors as defined in the next equation.

$$[\boldsymbol{A}] = \begin{bmatrix} A_{11} & A_{12} & A_{13} & \cdots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \cdots & A_{2n} \\ A_{31} & A_{32} & A_{33} & \cdots & A_{3n} \\ A_{41} & A_{42} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & A_{(m-1)n} \\ A_{m1} & A_{m2} & \cdots & A_{m(n-1)} & A_{mn} \end{bmatrix}_{\text{with}} \quad A_{ij} = \frac{\partial FR_i}{\partial DP_j}. \qquad (2)$$

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Each element in the design matrix (A_{ij}) represents the change in the i^{th} functional requirement due to the value of the j^{th} design parameter. Note: this is the theoretical formulation of a design matrix under ideal conditions. There is no expectation that a specific value exists for any (A_{ij}) term. The formulation is powerful because of the insight it brings to the design problem even when it is analyzed with symbols and not numerical values. Axiomatic Design does not require that the equation can be solved for values of any of the terms.

The equation format for a design solution given in Eq. 1 allows users to define the relationship of any FR to the set of DPs. This is shown in Eq. 3.

$$\begin{aligned} FR_i &= \sum\nolimits_{j=1}^{n} A_{ij} DP_j, \text{ so that} \\ FR_j &= A_{i1}DP_1 + A_{i2}DP_2 + \ldots + A_{i(n-1)}DP_{n-1} + A_{in}DP_n. \end{aligned} \qquad (3)$$

Like some other design methods, Axiomatic Design decomposes the design problem. From Eq. 3 it is clear that the design team must set the values of all relevant design parameters (DPs) at levels that will achieve the desired value of the functional requirement FR_i. The fact that some of the A_{ij} values are zero gives a design team insight into their design problem. For example, if only one term is nonzero in Eq. 3, then only one design parameter must be set to satisfy FR_i.

Axiomatic Design's representation of a solution concept provides another way to describe the design axioms. The independence axiom states that acceptable designs maintain independence among the functional requirements. That means, to uphold the functional requirements' independence, each design parameter (DP) can be set to satisfy its corresponding FR without affecting other functional requirements. That means no design parameter should contribute to satisfying more than one functional requirement. Any concept that satisfies Axiom 1 will have a diagonal design matrix like the one in Fig. 4a. This also implies that an "ideal" design for satisfying Axiom 1 is one that provides one and only one DP for the satisfaction of each FR. This type of design is uncoupled, but it is rare to find in mechanical engineering where the behavior of each component is leveraged to serve as many aspects of required functionality as possible. In some designs, the components are so integrated that every DP materially contributes to each FR. Such a design is *coupled,* and its matrix would be like the one in Fig. 4c. Most designs fall into a middle category of being not fully coupled (i.e., some elements of [**A**] are equal to zero), but the design matrix is not diagonal.

Some of the coupled designs belong in a third category, *decoupled* designs. There are designs with some dependence among their functional requirements, but the de-

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{23} \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{aligned} FR_1 &= A_{11}DP_1 \\ FR_2 &= A_{22}DP_2 \\ FR_3 &= A_{33}DP_3 \end{aligned}$$

(a) Uncoupled design: Each design parameter can be set directly to achieve the desired level of performance required by one functional requirement.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ 0 & A_{22} & A_{23} \\ 0 & 0 & A_{33} \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{aligned} FR_1 &= A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3 \\ FR_2 &= A_{22}DP_2 + A_{23}DP_3 \\ FR_3 &= A_{33}DP_3 \end{aligned}$$

(b) Decoupled design: It is possible to order the process of setting values for design parameters to allow seperate consideration of each FR. However, any change in one DP requires a review of the entire design.

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

(c) Coupled design: No DP value can be set without considering how it affects all the FRs of the design.

FIGURE 4
Three different types of design matrices that indicate the level of adherence of the design concept to Axiom 1.

pendencies are such that there is an order of decision making for the design parameters that minimized the dependence. A decoupled design is one that has a triangular design matrix as shown in Fig. 4b. The equations beside the triangular matrix highlight that that the DPs can be set in the order of DP_3, DP_2, then DP_1 to achieve a lesser degree of dependence among the FRs. Decoupled designs require reconsideration of all DP values when any one must change. Yet it is easier to create a decoupled design than an uncoupled design.

EXAMPLE

We return to the mechanical pencil example used to describe function structures in Sec. 6.5 to illustrate the use of Axiomatic Design to gain insight about a design concept. The designer has already developed the functional requirements for the pencil, and they are as shown in the vector {**FR**} at the right.

$$\begin{Bmatrix} FR_1 = \text{Erase lead} \\ FR_2 = \text{Import \& store eraser} \\ FR_3 = \text{Import \& store lead} \\ FR_4 = \text{Advance lead} \\ FR_5 = \text{Support lead in use} \\ FR_6 = \text{Position lead in use} \end{Bmatrix}$$

To determine design concepts, the design team must know the functional requirements. Engineering expertise supplies information about the design matrix elements. It is the size, type, and values of the design vector {**DP**} that are determined during conceptual design. The axioms of this method cannot be applied until a

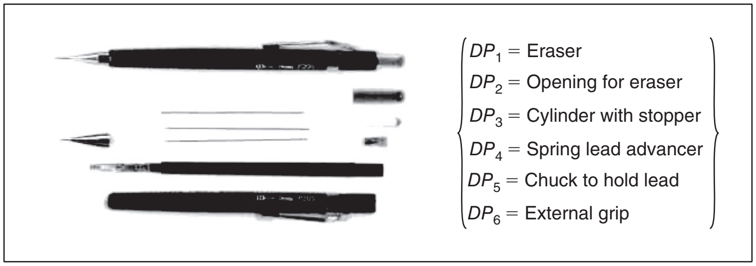

FIGURE 5
Mechanical pencil with all relevant design parameters listed in the vector.

design concept has been described in enough detail so that the {**FR**} and {**DP**} vectors can be written.

For this example, a typical mechanical pencil is used as the current design concept. A picture is shown in Fig. 5 with all relevant design parameters listed in the vector {**DP**}.

Analysis of the design concept continues with the creation of the design matrix [**A**] for the given set of functional requirements and the concepts design parameters. Recall that the elements of [**A**] are symbolic of the existence of a relationship, not specific parameters or values. Each nonzero A_{ij} is depicted in the matrix as an X. The X signifies that there is a relationship between the corresponding FR and DP. The design matrix for the mechanical pencil follows.

$$\begin{Bmatrix} FR_1 = \text{Erase lead} \\ FR_2 = \text{Import \& store eraser} \\ FR_3 = \text{Import \& store lead} \\ FR_4 = \text{Advance lead} \\ FR_5 = \text{Support lead in use} \\ FR_6 = \text{Position lead in use} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 \\ X & X & X & X & 0 & 0 \\ 0 & 0 & 0 & X & X & X \\ 0 & 0 & 0 & X & X & X \\ 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{Bmatrix}$$

The matrix form indicates that the design is not uncoupled, nor is it decoupled (review possible matrix forms in Fig. 4). The current design does not fulfill the independence axiom; each individual functional requirement is not satisfied by fully independent physical components or subsystems. A decoupled or uncoupled design for the mechanical pencil is essentially difficult to achieve, as many of the design parameters are reused for multiple functions. An inexpensive (nearly disposable) mechanical pencil was chosen for this exercise, with a lead advancement mechanism controlled by a push button at the back end of the pencil. For this specific mechanical pencil design, the eraser (DP_1) serves both as an erasing element and a stopper for the lead storage compartment. Additionally, the clutch system to hold the lead in place (DP_5) is integrated with the lead advancement mechanism.

The mechanical pencil example illustrates that even simple devices are not always going to satisfy the independence axiom. The design matrix, [**A**], is a graphical representation that is useful in evaluating information about various designs. First of all, they can be examined to see if they satisfy the independence axiom. Secondly, a coupled design matrix may be partitioned into independent submatrices. This means that the DPs can be partitioned into independent subsets. Identification of any DPs that can be set without impacting all the FRs is useful in structuring the design process.

The previous discussion was an interpretation of the mathematical implications of the matrix [**A**] for a particular design problem solution. This is one way to capitalize on the formalism of Axiomatic Design. Suh also developed corollaries from the axioms that suggest ways to improve the independence of functional requirements. Here are a few corollaries with short descriptions.

- *Corollary 1:* Decouple or separate parts or aspects of a solution if FRs are coupled in the proposed design. Decoupling does not imply that a part has to be broken into two or more separate physical parts, or that a new element has to be added to the existing design.
- *Corollary 3:* Integrate design features in a single physical part if FRs can be independently satisfied in the proposed solution.
- *Corollary 4:* Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and constraints.
- *Corollary 5:* Use symmetric shapes and/or arrangements if they are consistent with the FRs and constraints. Symmetrical parts require less information to manufacture and to orient in assembly.

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We can view these statements as design rules for making design decisions, especially when our goal is to improve an existing design. The guidelines expressed as corollaries are similar to some design guidelines for improving assembly.

In the larger context, Suh has proposed 26 theorems of Axiomatic Design that must be examined by all serious students of the method. For example:

> *Theorem 2:* A high-level coupled design may be treated as a decoupled design if the full system matrix may be re-sequenced to form a triangular matrix.

The reader is referred to Suh's texts (referenced earlier) for more details of how to determine the independence of FRs, how to measure information content, and for a number of detailed examples of how to apply these techniques in design.

Strengths and Weaknesses of Axiomatic Design

Axiomatic Design is useful in focusing the designer or design team on the core functionality required in a new product. The method provides tools for classifying existing designs once they are represented in the key design equation that uses the design matrix to relate functional requirements to design parameters. Axiomatic Design is also one of the most widely recognized design methodologies, especially within the academic community (where it originated).

As with the other design methods in this chapter, there are strengths and weaknesses in Axiomatic Design. The strengths are rooted in the mathematical representation chosen by Suh. They are, in brief:

- Mathematically based—Axiomatic Design is built with a mathematical model of axioms, theories, and corollaries. This meets the need of the design theory and methodology community to incorporate rigor in the field.

- Vehicle to relate FRs and DPs—The representation of designs using FRs, DPs, and the design matrix [**A**] opens up their interpretation in mathematical ways more common to students of linear algebra.
- Powerful if the relationship is linear—the design matrix [**A**] is a powerful conceptual tool and is also a reminder that there may be some realtionships of FRs and DPs that are understood to the point of mathematical expression. If others aren't, it's still a goal.
- Provides a procedure for decomposing decision process—Reviewing the design matrix [**A**] can reveal natural partitions in the setting of FRs that will aid in ordering the efforts of the design team.
- Basis for comparing alternative designs—Axiomatic Design provides a metric (degree of independence of functional requirements) that can be used to differentiate between competing design concepts.

Weaknesses of Axiomatic Design lie first in the fact that the axioms must be true in order to accept the methodology. There is no proof that the independence axiom is false, but there are examples of designs that are strongly coupled and are still good designs in the eyes of the user community. Other weaknesses are as follows:

- The design method describes a way to create new designs from FR trees to DPs. Yet the methodology is not as prescribed as others (e.g., systematic design). This can lead to a problem with repeatability.
- Designs are usually coupled—This echoes some concern for the strength of Axiom 1 and also means that it will be difficult to decouple existing designs to create improvements.
- Axiom 2: Minimize Information Content is difficult to understand and apply. There are many approaches to interpreting Axiom 2. Some designers use it to mean complexity of parts, others use it to mean reliability of parts, still others have considered it to refer to the ability to maintain the tolerances on parts. Axiom 2 has not been used by the design community as much as Axiom 1, leading to questions about its usefulness, or about the axiomatic approach in general.

Regardless of the open questions of Axiomatic Design, the overall message holds true: The best design of all equivalent designs is a functionally uncoupled design having the minimum information content. This chapter has also shown how to use the method to diagnose and prescribe improvements to candidate designs.