# 41

# Enhancing Robust Design with the Aid of TRIZ and Axiomatic Design

## 41.1. Introduction

The importance and benefits of performing robust parameter design advocated by G. Taguchi are well known [1,2]. Many people are familiar with Taguchi's robust parameter design with such terminologies as orthogonal array, signal-to-noise ratio, and control and noise factors. However, a generally ignored but most important task for a successful robust parameter design project is to select an appropriate system output characteristic.

The identification of a proper output characteristic is a key step to having a higher success rate for robust design projects. To identify a proper output characteristic, Taguchi suggests the following guidelines [2,3]:

- ❏ Identify the ideal function or ideal input/output relationship for the product or process. The quality characteristic should be related directly to the energy transfer associated with the basic mechanism of the product or process.
- ❏ Select quality characteristics that are continuous variables, as far as possible.
- ❏ Select additive quality characteristics.

- ❑ Quality characteristics should be complete. They should cover all dimensions of the ideal function or input/output relationship.
- ❑ Quality characteristics should be easy to measure.

According to Taguchi, it is important to avoid using quality symptoms such as reliability data, warranty information, scrap, and percent defective in the late product development cycle and manufacturing environment as the output characteristic. But improving a symptom may not be helpful in improving the robustness of a system's ability to deliver its functions, which is really the key objective of a robust design project. Understanding a system function, especially the basic function, is the key for robust technology development [1]. Defining the ideal state of the basic function, called the *ideal function,* is the centerpiece for identifying output characteristics.

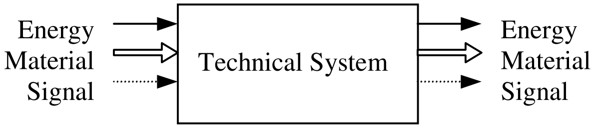
The reason for using an energy-related system output response, according to the discussion of Pahl and Beitz [8] and Hubka and Eder [9], is due to the fact that an engineering system is always designed for delivering its basic function. To deliver its basic function, at least one of the three types of transformation must be used (Figure 41.1).

1. *Energy:* mechanical, thermal, electrical, chemical; also force, current, heat, and so on
2. *Material:* liquid, gas; also raw material, end product, component
3. *Signal:* information, data, display, magnitude

For example, in a machining process as an engineering system, the ideal relationship between output and input should be that the output dimensions are exactly the same as the dimension intended. This type of transformation system is the material transformation, since energy transformation is a very important type of transformation and there are many similarities in using these three types of transformation to identify the appropriate output characteristic. Without loss of generality, energy transformations are used as examples throughout this chapter.

Some of the published literature and articles point out that an energy-related characteristic is very helpful to identify proper quality characteristic and should be considered. Nair and Vigayan [4] cite Phadke's discussion, finding system output response that meets all of these guidelines is sometimes difficult or simply not possible with the technical know-how of the engineers involved. In general, it will be quite challenging to identify system output responses that will meet all of these criteria. Taguchi acknowledges this fact and states that the use of Taguchi methods will be inefficient to the certain extent if these guidelines are not satisfied. Revelle et al. [5] cite Shin Taguchi, Verdun, and Wu's work and points out that the selection of system output response that properly reflects the engineering function of a product or process is the most important and perhaps the most difficult task of the quality engineer. The choice of an energy-related system output response is

**Figure 41.1**
Technical system: conversion of energy, material, and signals



vital to ensure that the system output response is monotonic. According to Box and Draper [6], the monotonicity property requires that effects of control factor be both linear and additive. Based on Box and Draper's study, Wasserman [7] concludes that from a response surface methodology perspective, the requirement of the monotonicity property is equivalent to an assumption that the true functional response is purely additive and linear. The reconciliation of Taguchi's viewpoint is possible based on the assumption that energy-related characteristics are used to ensure that interactions are minimal.

Therefore, identification of the key transformation process is very important to understanding and identifying the ideal functions of the engineering system. By the choice of a good functional output, there is a good chance of avoiding interactions [2,3]. Without interactions, there is additivity or consistency or reproducibility. Laboratory experiments will be reproduced and research efficiency improved.

However, the foregoing guidelines for selecting an appropriate output characteristic are still very conceptual, and their implementation is highly dependent on the project leader's personal experience. There is very little literature that shows how a system output response can be designed and selected in a systematic fashion.

In this chapter we address these shortcomings. With an emphasis on robustness at the early stages of the product development, the proposed methodology will integrate the concept of Taguchi methods with the aid of TRIZ and axiomatic design principles. The proposed methodology has the following three mechanisms: (1) definition and identification of different system architectures, inputs/outputs, and the ideal function for each of the system/subsystem elements; (2) systematic attempts to facilitate a design that is insensitive to various variations caused by inherent functional interactions or user conditions; and (3) bridging the gap between robust conceptual design and robust parameter design through proper identification and selection of a system/subsystem output response.

## 41.2. Review of the Taguchi Method, TRIZ, and Axiomatic Design

### Taguchi Method

Robust design using the Taguchi method is an efficient and systematic methodology that applies statistical experimental design for improving product and manufacturing process design. Genichi Taguchi's development of robust design is a great engineering achievement [10]. By 1990, concurrent engineering was becoming widespread in U.S. industry. It brought great improvements. However, pioneers such as Ford and Xerox realized that more was needed. Robust design, especially, needed to be practiced widely throughout the development of new products and processes.

Taguchi essentially uses the conventional statistical tools, but he simplifies them by identifying a set of stringent guidelines with an energy transformation model–focused engineering system for experimental layout and analysis of results. Taguchi used and promoted statistical techniques for quality from an engineer's perspective rather than that of a statistician.

As Taguchi's ideas have become more widespread, more and more design engineers use Taguchi's methodology in their everyday lives. Due to the growing popularity of robust design methods, more and more quality and engineering professionals have shifted their quality paradigm from defect inspecting and problem solving to designing quality and reliability into products or processes.

Taguchi's approach to design emphasizes continuous improvement and encompasses different aspects of the design process grouped into three main stages:

1. *System design.* This corresponds broadly to conceptual design in the generalized model of the design process. System design is the conceptual design stage in which scientific and engineering expertise is applied to develop new and original technologies. Robust design using the Taguchi method does not focus on the system design stage.
2. *Parameter design.* Parameter design is the stage at which a selected concept is optimized. Many variables can affect a system's function. The variables need to be characterized from an engineering viewpoint. The goals of parameter design are to (a) find that combination of control factors settings that allow the system to achieve its ideal function, and (b) remain insensitive to those variables that cannot be controlled. Parameter design provides opportunities to reduce the product and manufacturing costs.
3. *Tolerance design.* Although generally considered to be part of the detailed design stage, Taguchi views this as a distinct stage to be used when sufficiently small variability cannot be achieved within a parameter design. Initially, tolerances are usually taken to be fairly wide because tight tolerances often incur high supplier or manufacturing costs. Tolerance design can be used to identify those tolerances that, when tightened, produce the most substantial improvement in performance.

Taguchi offers more than techniques of experimental design and analysis. He has a complete and integrated system to develop specifications, engineer the design to specifications, and manufacture the product to specifications. The essence of Taguchi's approach to quality by design is this simple principle: Instead of trying to eliminate or reduce the causes for product performance variability, adjust the design of the product so that it can be insensitive to the effects of uncontrolled (noise) variation. The losses incurred to society by the poor product design are quantified using what Taguchi calls a *loss function,* which is assumed to be quadratic in nature. The five principles of Taguchi's methods are:

1. Select the proper system output response.
2. Measure the function using the SN ratio.
3. Take advantage of interactions between control and noise factors.
4. Use orthogonal arrays.
5. Apply two-step optimization.

## TRIZ

TRIZ is a Russian acronym that stands for the *theory of inventive problem solving,* originated by Genrikn Altshuller [18]. How can the time required to invent be reduced? How can a process be structured to enhance breakthrough thinking? It was Altshuller's quest to facilitate the resolution of difficult inventive problems and pass the process for this facilitation on to other people. In trying to answer these questions, Altshuller realized how difficult it is for scientists to think outside their fields of reference, because that involves thinking with a different technology or "language." In the course of the study of some 400,000 inventions as depicted in patent descriptions, Altshuller noticed a consistent approach used by the best inventors to solve problems. At the heart of the best solutions, as described by the patents, existed an engineering conflict or contradiction. The best inventions consistently solved conflicts without compromise. Upon closer examination and classification of innovative solutions, natural patterns of solutions started to emerge. Altshuller discovered that when an engineering system was reduced to reveal the essential system contradictions, inventive solutions eliminated the contradictions completely. Furthermore, Altshuller noticed that the same inventive solutions appeared repeatedly at different points in time and in different places.

### SUBSTANCE-FIELD ANALYSIS

Substance-field (S-F) analysis is a TRIZ analytical tool for modeling problems related to existing technological system. *Substance field* is a model of a minimal, functioning and controllable technical system [11]. Every system is created to perform some functions. The desired function is the output from an object or substance ($S_1$), caused by another object ($S_2$) with the help of some means (types of energy, $F$). The general term *substance* has been used in the classical TRIZ literature to refer to some object. Substances are objects of any level of complexity. They can be single items or complex systems. The action or means of accomplishing the action is called a *field*. Within the database of patents, there are 76 standard substance-field solutions that permit the quick modeling of simple structures for analysis. If there is a problem with an existing system and any of the three elements is missing, substance-field analysis indicates where the model requires completion and offers directions for innovative thinking. In short, S-F analysis is a technique used to model an engineering problem. S-F analysis looks at the interaction between substances and fields (energy) to describe the situation in a common language. In cases where the engineering system is not performing adequately, the S-F model leads the problem solver to standard solutions to help converge on an improvement. There are four steps to follow in making the substance-field model [12]:

1. Identify the elements.
2. Construct the model.
3. Consider solutions from the 76 standard solutions.
4. Develop a concept to support the solution.

### OTHER TRIZ TOOLS, STRATEGIES, AND METHODS

The TRIZ innovative process consists of two parts: the *analytical stage* and the *synthesis stage*. A basic description of some of the instruments/tools is as follows:

1. *Ideality concept*. Every system performs functions that generate useful and harmful effects. *Useful effects* are the desirable functions of the system; *harmful effects* are the undesirable effects of the system. When solving problems, one of the goals is to maximize the useful functions of a system. The ideality concept has two main purposes. First, it is a law that all engineering systems evolve to increasing degrees of ideality. Second, it tries to get the problem solver to conceptualize perfection and helps him or her to break out of psychological inertia or paradigms.
2. *ARIZ*. This algorithm of inventive problem solving is a noncomputational algorithm that helps the problem solver take a situation that does not have

obvious contradictions and answer a series of questions to reveal the contradictions to make it suitable for TRIZ. There are four main steps in ARIZ.

3. *Contradiction table.* This is one of Altshuller's earliest TRIZ tools to aid inventors. It shows how to deal with 1263 common engineering contradictions (e.g., when improving one parameter, another is degraded).
4. *Inventive principles.* These are the principles in the contradiction table. There are 40 main principles and approximately 50 subprinciples. These are proposed solution pathways or methods of dealing with or eliminating engineering contradictions between parameters.
5. *Separation principles.* This technique has been used with great success to deal with physical contradictions. The most common separation principles can take place in space, time, or scale.
6. *Laws of evolution of engineering systems.* Altshuller found through his study of patents that engineering systems evolve according to patterns. When we understand these patterns or laws and compare them to our engineering system, we can predict and accelerate the advancement of our products.
7. *Functional analysis and trimming.* This technique is helpful in defining the problem and improving ideality or value of the system. The functions of a system are identified and analyzed with the intent of increasing the value of the product by eliminating parts while keeping the functions. Functionality is maximized and cost is minimized.

## Axiomatic Design

Design is attained by the interactions between the goal of the designer and the method used to achieve the goal. The goal of the design is always proposed in the functional domain, and the method of achieving the goal is proposed in the physical domain. Design process is the mapping or assigning relationship between the domains for all the levels of design.

Axiomatic design is a principle-based design method focused on the concept of domains. The primary goal of axiomatic design is to establish a systematic foundation for design activity by two fundamental axioms and a set of implementation methods [13]. The two axioms are:

- ❏ *Axiom 1: Independence Axiom.* Maintain the independence of functional requirements.
- ❏ *Axiom 2: Information Axiom.* Minimize the information content in design.

In the axiomatic approach, design is modeled as a mapping process between a set of functional requirements (FRs) in the functional domain and a set of design parameters (DPs) in the physical domain. This mapping process is represented by the design equation:

$$\mathrm{FR} = [A]\mathrm{DP} \tag{41.1}$$

where

$$A_{ij} = \frac{\partial \mathrm{FR}_i}{\partial \mathrm{DP}_j} \tag{41.2}$$

Suh defines an *uncoupled design* as a design whose $A$ matrix can be arranged as a diagonal matrix by an appropriate ordering of the FRs and DPs. He defines a *decoupled design* as a design whose $A$ matrix can be arranged as a triangular matrix by an appropriate ordering of FRs and DPs. He defines a *coupled design* as a design whose $A$ matrix cannot be arranged as a triangular or diagonal matrix by an appropriate ordering of the FRs and DPs. The categories of design based on the structure of the design matrix are shown is Figure 41.2.

The first axiom advocates that for a good design, the DPs should be chosen so that only one DP satisfies each FR. Thus, the number of FRs and DPs is equal. The best design has a strict one-to-one relationship between FRs and DPs. This is uncoupled design. If DP influences the FR, this element is nonzero; otherwise, it is zero. The independence axiom is satisfied for uncoupled design matrix $[A]$ having all nonzero elements on its diagonal, indicating that the FRs are completely independent. However, complete uncoupling may not be easy to accomplish in a complex world, where interactions of factors are common. Designs where FRs are satisfied by more than one DP are acceptable, as long as the design matrix $[A]$ is a triangle; that is, the nonzero elements occur in a triangular pattern either above or below the diagonal. This is decoupled design. A decoupled design also satisfies the independence axiom provided that the DPs are specified in sequence such that each FR is ultimately controlled by a unique DP. Any other formation of the design matrix that cannot be transformed into a triangular formations represents a coupled design, indicating the dependence of the FRs. Therefore, the design is unacceptable, according to axiomatic design.

The information axiom provides a means of evaluating the quality of designs, thus facilitating selection among available design alternatives. This is accomplished by comparing the information content of the several designs in terms of their respective probabilities of satisfying the FRs sucessfully. Information content is defined in terms of *entropy*, which is expressed as the logarithm of the inverse of the probability of success, $p$:

$$I = \log_2 \frac{1}{p} \tag{41.3}$$

In the simple case of uniform probability distribution, equation (3) can be written as

$$I = \log_2 \frac{\text{system range}}{\text{common range}} \tag{41.4}$$

where *system range* is the capability of the current system, given in terms of tolerances; *common range* refers to the amount of overlap between the design range and the system capability; and *design range* is the acceptable range associated with the DP specified by the designer. If a set of events is statistically independent, the

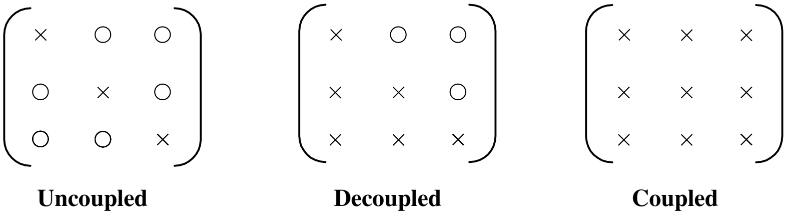


**Figure 41.2**
Structure of the design matrix

probability of the union of the events is the product of the probabilities of the individual events.

**Comparison of Disciplines**

The purpose of such a comparison is to point out the strength and focuses of different contemporary disciplines, such as axiomatic design (Suh), robust design (Taguchi), and TRIZ (Altshuller).

A product can be divided into functionally oriented operating systems. Function is a key word and the basic need for describing our product, behavior. Regardless of what method is to be used to facilitate a design, they all have to start with an understanding of functions. However, what is the definition of function? How is the function defined in these disciplines? Understanding the specific meanings of function (or the definition of function) within each of these disciplines could help us to take advantage of tools to improve design efficiency and effectiveness.

According to *Webster's* dictionary, function has three basic explanations: (1) the acts or operations expected of a person or thing, (2) the action for which a person or thing is specially fitted or used, or (3) to operate in the proper or expected manner. Generally, people would agree that a function describes what a thing does and that it can be expressed as the combination of noun and verb: for example, creating a seal or sending an e-mail.

In axiomatic design, function is defined as desired output that is the same as the original definition. However, the importance of functional requirements is not identified in the axiomatic design framework. There are no guidelines or termination criteria for functional requirement decomposition. Functional requirements are treated as equally important, which is not necessary practical and feasible.

In robust design, the definition of function has the same general meaning but with more meaning in terms of ideal function, which is concerned about what fundamental things a system is supposed to do so that the energy can be transferred smoothly. For example, how can a seal be formed effectively? What is the basic function of an engineered seal system? Therefore, the definition of function in robust design using the Taguchi method may best be defined as energy transformation.

In TRIZ methodology, the definition of function also has the same general meaning, with negative thinking in terms of physical contradictions. Altshuller sought to deliver all system functions simultaneously with maximization of existing resources.

Table 41.1 shows a comparison of axiomatic design, TRIZ, and Robust Design; Table 41.2 shows the comparison using design axioms. Based on the comparisons, we can see that these three disciplines have their own focuses. They complement each other. The strengths and weakness are summarized in Table 41.3.

## 41.3. Design Response Structural Analysis: Identification of System Output Response

Any system output response is in one of the forms of energy, material, or signal. If the energy-related system output response can help to reduce the interactive effects of design parameter to minimal for the purpose of design optimization, we can better find a way of converting non-energy-related system output response

**Table 41.1**
Comparison of axiomatic design, TRIZ, and robust design

| Approach | Function Focus | Best to Be Applied | Thought Process | Emphasis |
|---|---|---|---|---|
| Axiomatic design | Desired output | System structure and foundation in conceptual design | Positive thinking; how a design can be created perfectly; how a design is immune | Mapping from functional requirements to design requirement |
| TRIZ | Basic function | System structure and foundation in conceptual design | Negative thinking; start with conflicts or contradictions; how a contradiction can be resolved | Attacking on contradictions; start with design parameter, then back to functional requirements |
| Robust design | Energy transformation | Given specific technology optimization or a given structure or concept design optimization | Within a given structure or design, how an engineered system can be optimized to desensitize the side effects of uncontrollable conditions | Effective application of engineering strategies; identify ideal function (ideal relationship); start with a proper system output response, then maximize the system's useful function |

**Table 41.2**
Comparison using design axioms

| Approach | Independence Axiom | Information Axiom |
|---|---|---|
| Axiomatic design | Maintain the independence of the functional requirements. | Minimize the information. |
| TRIZ | Eliminate technical or physical contractions (maintaining independence of parameters). | Apply the concept of ideality. |
| Robust design | Identify ideal function; select proper system output characteristic and control factors to promote the additivity of effects of parameters. | Maximize the signal-to-noise (SN) ratio. |

**Table 41.3**
Summary of strengths and weaknesses of axiomatic design, TRIZ, and robust design

| Approach | Strengths | Weaknesses |
|---|---|---|
| Axiomatic design | It provides a good structural foundation for system (concept design.<br>Design axioms are a strong referent.<br>Domains are well defined.<br>Quantitative models exist for coupled, uncoupled, and decoupled design. | Customer attributes are vague.<br>“Zigzagging” between domains is lengthy.<br>Information content is difficult to apply. |
| TRIZ | Conflict domain, physical contradiction, and its elimination target functional requirements and design parameters more precisely. | It is difficult to work on large, complicated systems.<br>There is no customer attributes process. |
| Robust design using Taguchi methods | It improves the robustness of basic technology.<br>It provides more depth of understanding of a given technology or a system’s functional behavior.<br>Within the domain of given design parameters, the side effects of uncontrollable (noise) factors can be desensitized through the optimization of levels of control factors. | There is no process for system (concept) design.<br>It is limited to a given concept design.<br>It is a black-box approach. |

to an energy-related system output response. Instead of searching blindly for an energy-related system output response based on an empirical approach or experience, it is necessary to develop an energy-related system output response. With respect to a technical system, any technical system consists of three minimal numbers of elements: two substances (objects) and a field (energy) [11]. A substance can be modified as a result of direct action performed by another substance. Having the same thought process, a system output response can also be modified as a result of direct action performed by another substance, which can be used as an input signal from the perspective of Taguchi methods. The substance field analysis concept furnishes a clue to the direction of developing a system output response.

Consider as an example a product improvement task in which the plastic molding strength has to be improved to withstand a certain force. The objective function in this case is to improve the strength. What is the output response in this case? Many people would agree that the characteristic (output response) of push force (force to break the molding) could be the one (Figure 41.3). The concern about using push force as the output characteristic may be summarized as follows:

- ☐ It is difficult to understand the structure of material such as bubbles or voids.
- ☐ It is a destructive test.
- ☐ It is hard to take the advantage of a signal factor in a robust design experiment. In other words, it is difficult to understand the input and output relationship in this engineered system.

In an evaluation of the functional behavior of a system, failure modes are only symptoms. The evaluation of that will not provide insight on how to improve the system. Therefore, the push force characteristic is not a good system output response in this case. How can we have a proper characteristic instead of using push force to evaluate the strength?

Let us analyze the problem and its solution in detail. First, as the conditions of the problem suggest, nothing else can be selected to evaluate the strength: the direct response of the engineered system is out of consideration. Therefore, a new system output response should be created.

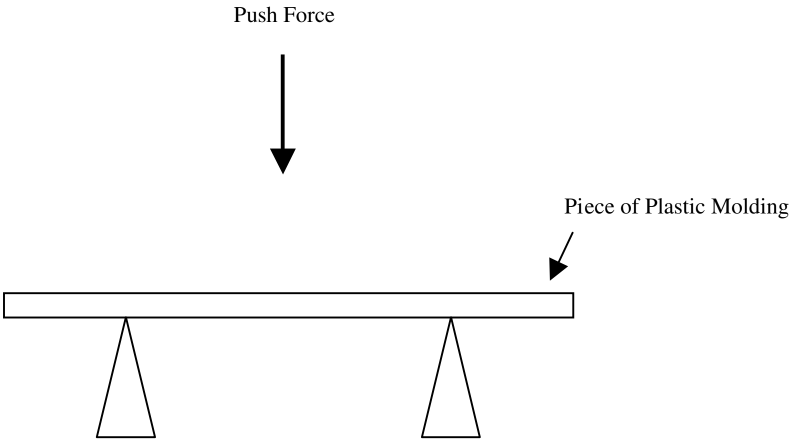


**Figure 41.3**
Plastic moldings strength test

In Figure 41.4, there is one substance (a piece of plastic molding) at the beginning; in the end there are two substances (a piece of plastic molding and a push bar) and a force field and the bent (not broken) piece plastic molding. We use the following symbols to represent the initial situation:

$S_1$: straight piece of plastic molding

$S_2$: bent piece of plastic molding

$S_3$: push bar

The result is represented by

$F$: push force

Let us now look at how the system works. Mechanical field ($F_{\text{push force}}$) acts on push bar $S_2$, which, in turn, acts on the piece of plastic molding ($S_1$). As a result, $S_1$ is deformed (bent) to $S_1'$. Graphically, the operation can be represented as in Figure 41.4.

Until now, can we see the alternative system output characteristic? Can the $S_1$ be used to evaluate system behavior instead of push force? Let's validate this idea: Can the evaluation system work if we take off any of the substance? No, the system will fall apart and cease to apply the force to the piece of plastic molding. Does this mean that the evaluation system's operation is secured by the presence of all of its three elements? Yes. This follows from the main principle of materialism: Substance can be modified only by material factors [i.e., by matter or energy (field)]. With respect to technical systems, substance can be modified only as a result of direct action performed by another substance (e.g., impact-mechanical field) or by another substance. $S_1'$ is modified from $S_1$ and is the output due to system input force of $F_{\text{push force}}$. The characteristic $S_1'$ is closer to the structure of plastic molding than the push force.

According to Hubka and Eder [9], to obtain a certain result (i.e., an intended function); various phenomena are linked together into an action chain in such a way that an input quantity is converted into an output quantity. This chain describes the mode of action of a technical system. The mode of action describes

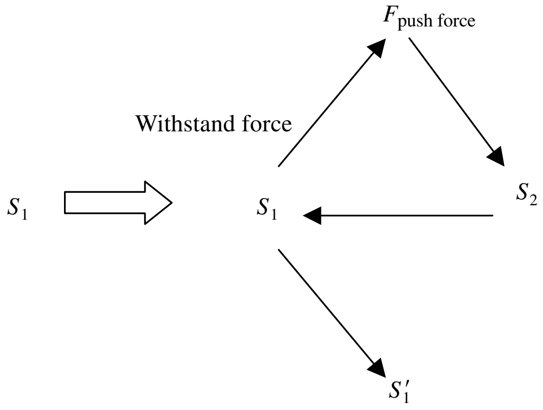


**Figure 41.4**
System diagram

the way in which the inputs to a technical system are converted into its output effects. The mode of action is characterized by the technical system internal conversion of inputs of material, energy, and information. The output effect is achieved as the output of an action process (through an action chain) internal to the technical system in which the input measures are converted into the effects (output measures) of that technical system. The action process is a direct consequence of the structure of the technical system. Every technical system has a purpose, which is intended to exert some desired effects on the objects being changed in a transformation process. The behavior of any technical system is closely related to its structure.

As a consequence, the $S_1'$ (the bent $S_1$) in terms of displacement (bent distance) is a better system output response (Figure 41.5). As a matter of fact, the displacement of $S_1'$ is proportional to the push force, which enhances effectiveness of the efforts of robust parameter design. A robust parameter design case study has been developed successfully using the output characteristic of displacement in an automotive company [14,15].

In a robust design approach using the Taguchi method, the displacement, $M$, can also be used as an input signal. The spring force, $Y$, within the elastic limit, can be used as system output response. The displacement is an input signal, $M$. The ideal function will be given by

$$Y = \beta M \tag{41.5}$$

$Y$ will be measured over the range of displacement (Figure 41.6). The signal-to-noise (SN) ratio will be optimized in the space of noise factors such as environment and aging.

Identification of system output response using $S$-field models sheds light on the essence of transformation of engineered systems and allows one to use universal technical or engineering terminology rather than customer perceptions, such as percent of failures, good or bad, to evaluate the system's behavior. The key idea is how the material, information, and energy are formed or transferred.

Searching for system output response based on $S$-field model analysis presents a general formula that shows the direction of identifying the possible system output characteristic. This direction depends heavily on the design intent of the system.

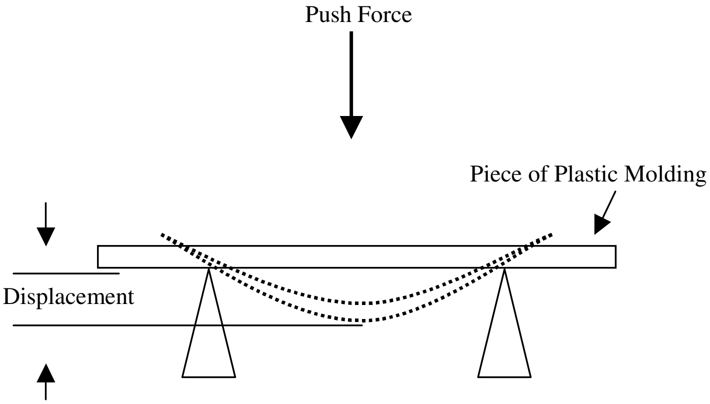


**Figure 41.5**
Better system output response

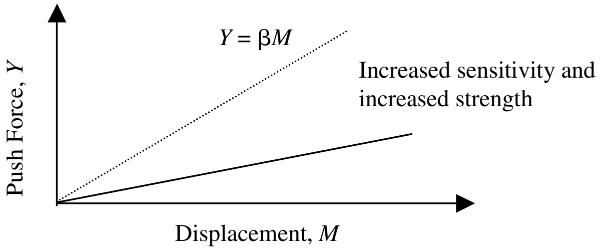


**Figure 41.6**
Range of displacement

Consider the example above: Introducing a substance or a field will profoundly change the process of identifying the system output response.

Gathering expert knowledge about the engineered system and various components in the product and how they affect one another is of the most importance if the identification of system output response is going to be more effective.

There are several rules for identifying system output response using *S*-field synthesis. Since we are interested in identifying proper system output characteristics in this chapter, our goal is to develop some principles for identification of system output response using *S*-field analysis.

- *Rule 1: Substance-Field Model Development for System Output Response.* If there is an output characteristic that is not easy to measure or not proper to reflect the system design intent, and the conditions do not contain any limitations on the introduction of substances and fields, the output characteristic can be identified through synthesizing a system output response–based *S*-field: The output characteristic is subjected to the action of a physical field that produces the necessary corresponding physical effects in the engineered system.
- *Rule 2: Change in Scope or Boundary of a Technical System.* If the conditions contain limitations on the existing system output response, the alternative output response has to be identified by synthesizing an *S*-field using external environment as the system output response. Changing the scope or the boundary of the technical system can help to identify a proper system response.

## 41.4. Examples

To illustrate this, let's use as an example a case study on a temperature-rising problem in a printer light-generating system [16]. During the development stage of a printer, it was noticed that the temperature in the light source area was much higher than expected. To solve this problem, there are some possible countermeasures, such as upgrading the resin material to retard flammability or adding a certain heat-resisting device. Since these countermeasures would result in a cost increase, it was decided to lower temperature. However, trying to lower temperature creates the need to measure temperature. Such an approach is not recommended, for two reasons. First, the environmental temperature must be controlled during experimentation. Second, the selection of material must consider all three aspects of heat transfer: conduction, radiation, and convection. It would take a long time to do.

In the system in this example, there are two subsystems: $S_1$ lamp (light-generating system) and $S_2$, fan (cooling system). The heat (field) in this system must be reduced. Since the heat energy is created by $S_1$ (lamp) and the cooling energy by $S_2$ (fan), the *S*-field system diagram may be drawn as in Figure 41.7.

The constraints for problem solving in this example are that (1) $S_1$ cannot be changed, (2) temperature is not preferred to measure the heat accumulated around the system, and (3) an rpm meter gauge is not available. What else can be measured to evaluate the status of temperature? Obviously, the rotation of the fan to remove the air surrounding the heat source could be another way of improving temperature condition. To improve the rotation of the fan, the rpm value has to be measured. The ideal situation is: "The air speed surrounding the heat source changes proportionally to the fan rotation. The sensitivity must also high." The modified *S*-field is shown is Figure 41.8.

However, as stated in the constraints, measuring rpm is not possible at that time, unfortunately. What can we do now? According to rule 2, we may have to change the scope or the boundary of the technical system. Can we find something that is not related to temperature directly? Of course, our goal is still to find a way of measuring heat for the purpose of achieving lower temperature if possible. Can we use motor voltage to measure the temperature indirectly? Let's validate this idea. Voltage is the input energy to drive a motor. The rpm of a fan, as the result of motor rotation, is probably proportional to motor voltage. Therefore, the ideal situation can be redefined as "the air speed surrounding the heat source is proportional to motor voltage with high sensitivity." The further-modified *S*-field is shown in Figure 41.9. Based on robust design, the ideal relationship between motor voltage and air speed may be shown in Figure 41.10.

Technical systems display numerous internal and external connections, both with subsystems (components of each technical system), systems of a higher rank, and the environment. Each technical system can be represented as a sum of *S*-field. The tendency is to increase the number of *S*-fields in a technical system with consideration of the chain of action mode as necessary.

- ☐ *Rule 3.* Efficiency of system output response–based *S*-field analysis can be improved by transforming one of the parts of the system output response–based S-field into an independently controllable system output response–based S-field, thus forming a chain of system output–based *S*-field analysis.

The graphical view of the chain of the system output response–based *S*-field is shown in Figure 41.11.

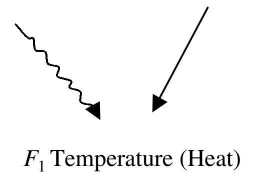


**Figure 41.7**
Harmful side effect

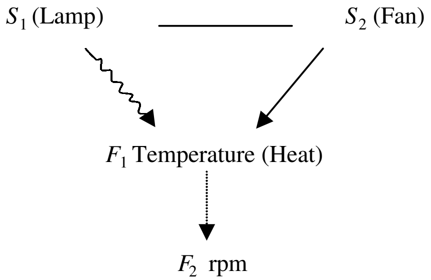


**Figure 41.8**
Rotated *S*-field

- ❑ *Rule 4: Chain of Action and Effect for System Output Response.* If an output characteristic is conflicting with another output characteristic in terms of the same design parameters, it is necessary to improve the efficiency by introducing a substance or a sub *S*-field and consider the chain of action in a technical system.

Rules 3 and 4 are often used together to identify a proper system output characteristic. For example, in a mechanical crimped product case study [17], pull strength force and voltage drop have to be optimized simultaneously (Figure 41.12). But the optimized design parameters are not the same with respect to the two different system output responses. Obviously, something may have to be compromised, unfortunately.

The reliability of complex electrical distribution systems can be dramatically affected through problems in the connecting elements of wires to the terminal in this case study. Minimum voltage drop is the design intent, and maximum pull strength is required for the long-term reliability concerns.

In this example, the pull strength is created by crimping force ($F_1$) acting on wire ($S_1$) and terminal ($S_2$). The *S*-field system diagram may be expressed as shown in Figure 41.13.

The pull strength, $F_2$, is not a good system output response for two reasons: first, pull strength has to be compromised by voltage drop. Second, the pull strength does not take the long-term reliability into consideration in terms of gas holes, void, and so on. According to rule 4, we could introduce an output response and consider the chain of action modes and the chain of effects. What effect can

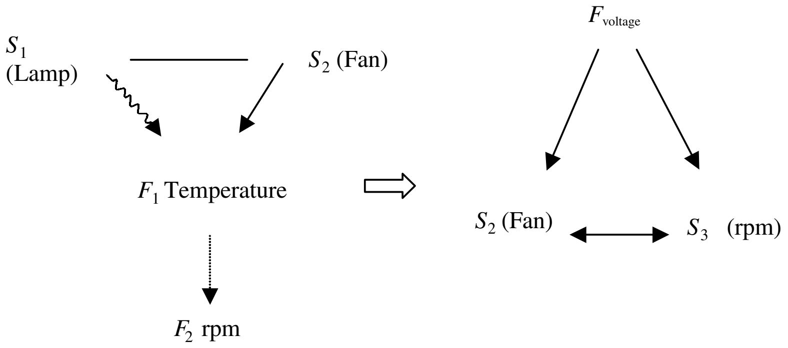


**Figure 41.9**
Changed boundary of the technical system

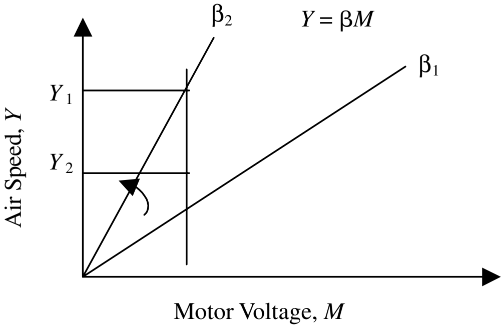


**Figure 41.10**
Relationship between voltage and speed

we find before the effect of pull strength is formed? When we crimp the wires and terminal, the wires and terminal are compressed into a certain form. Such a form can be measured by compactness. Can the compactness be used as a system output response? Let's validate this idea. The compactness is formed before the pull strength, and the compactness takes the gas holes and voids into consideration. What is the relationship between the compactness and the pull strength? The data show that the compactness is strongly related to the pull strength and the voltage drop. Therefore, the compactness could be used as a system output characteristic. The *S*-field diagram can be modified as shown in Figure 41.14.

The identification system output response using substance-field analysis is based on the law of energy transformation and the law of energy conductivity. Selecting a proper system output response using *S*-field analysis is one of the approaches based on the energy transformation thought process. Any technical system consists of three elements: two substances and a field. The identification system output response using substance-field analysis furnishes a clue to the direction of identifying a system output response for the purpose of conducting robust parameter design through a dynamic approach. This approach is very helpful when it is not clear how an object or a system, especially in the process of identifying a system output response, is related to the energy transformation for the purpose of design optimization.

## 41.5 Limitations of the Proposed Approach

Searching for a proper system output characteristic through the system output response based–*S*-field model, we often look at the technical system at only one

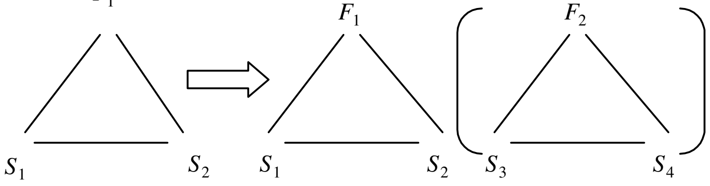


**Figure 41.11**
System output response

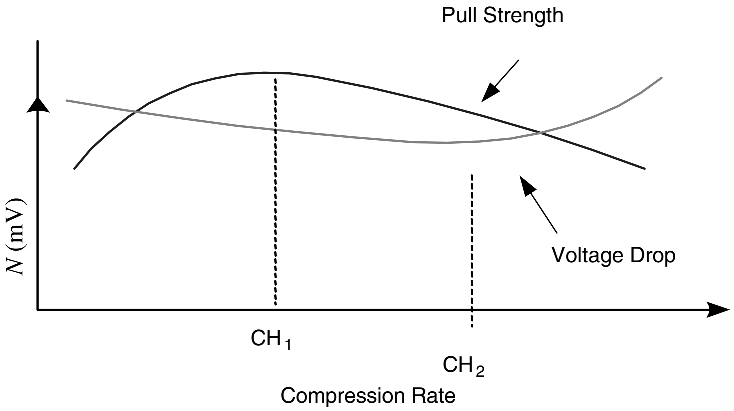


**Figure 41.12**
Pull strength and voltage drop

level. In a more complex system, it is difficult to identify a proper system output response without looking into the structure of the system design. A thorough understanding of the design intent is essential for finding a way to identify a truly engineering-related output response.

## 41.6. Further Research

One interesting topic might be to investigate how the framework of axiomatic design could be used to improve the limitations of identifying system output response using substance-field analysis. Of course, we would like to investigate a way of bridging the gap between the conceptual design and parameter design so that the up-front robustness thinking and testability can be emphasized. Design through an axiomatic approach is attained by interactions between the goal of the designer and the method used to achieve the goal. The goal of the design is always proposed in the functional domain, and the method of achieving the goal is proposed in the physical domain. The design process is the mapping or assigning relationship between the domains for all levels of design.

As the functional requirements become diverse, satisfying the requirements becomes more difficult. Therefore, concentrating on the functional requirements for the given stage or level of the design process is necessary. A design or a problem

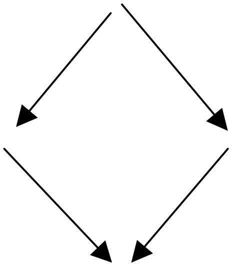


**Figure 41.13**
*S*-field diagram

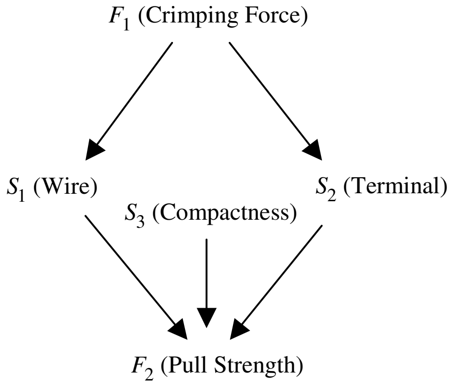


**Figure 41.14**
Modified *S*-field diagram

with many variables is very complicated. To prioritize the tasks and the proper focus, it is necessary to sort the primary and secondary functional requirements and handle each functional requirement according to its importance. For the purpose of design evaluation and optimization, it is essential to select a proper system output response to evaluate and understand an engineered system or a product's functional behavior. Such system output characteristics (responses) should be related to basic functions. A *basic function* is a function to transfer material, energy, and information from the input of the system to the output of the system. Obviously, the basic function of a product or process technology is related to its capability (highest probability) to transform input to output in terms of material, information, and energy.

Functional requirements are included in the functional domain. The designer should thoroughly understand problems in the functional domain and should not limit possible selections without a special reason. Clearly defining the problem is closely related to defining the functional requirements. On the other hand, the designer should select the design elements in the physical domain by specifying the functional requirements. Selecting a system output response characteristic is closely related to the physical domain to reflect how material, information, and energy are transferred smoothly from input to output in the technical system.

According axiomatic design principles, the essence of the design process lies in the hierarchies. The designer begins with functional requirements (top-down approach); and because of the different priorities of all the functional requirements, the designer can categorize all the functional requirements into different hierarchies. The important point in this process is that the functional requirements must be satisfied with specific design parameters. As it goes to the lower level, more details should be considered. This can be a very effective way of considering all details of the design. The functional requirements of the higher level must be satisfied through the appropriate design parameters in order for the lower-level functional requirements to be satisfied.

By using an axiomatic approach, the ideas in the initial stages of the design can be brought to bear in a scientific way once the design zigzagging mappings have been completed according to the design axiom. To evaluate the system's functional behavior, of course, a key system output response has to be identified. The lower level of functional requirement in the axiomatic design framework is not necessarily the best system output response for the purpose of system evaluation. But the lower level of functional requirement is certainly the proper starting point to identify or develop a proper system output characteristic. Additional creativity in the design can be induced when going through this task. The bottom-up approach is necessary to identify a system output response based on a result of zigzagging mapping.

## 41.7. Conclusions

In this chapter we suggest an approach for identifying a proper system output response using substance-field analysis along with analysis of the chain of action mode. The approach presented consists of four elements: (1) system output response–focused substance-field model development, (2) change in the scope or boundary of a technical system, (3) efficiency of system output response–focused substance-field model, and, (4) chain of action and effect for system output response.

The law of energy transformation and the law of energy conductivity guide the identification of system output response using substance-field analysis. One of the biggest advantages of using this approach is that the signal factor will come with the system output response identified. With the proper identification of signal factor and system output response, the chance of using dynamic robust design will be increased. Of course, the effectiveness of the robust parameter design will be improved.

Compared with other approaches to the identification of system output response, the approach presented in this chapter provides specific and detailed directions not only to search for but also to create an energy-related system output response. The approach has been applied successfully to several challenging case studies at some automotive companies. The findings from the case studies motivated the researchers to bridge the gap between the robust conceptual design and the robust parameter design.

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