Proceedings of DETC'98
1998 ASME Design Engineering Technical conferences
September 13-16, 1998 — Atlanta, Georgia

DETC98/DTM-5653

AN ENHANCED AXIOMATIC DESIGN PROCESS

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ABSTRACT

This paper describes an Axiomatic Design process enhanced by the House of Quality that combines the advantages of these two methods: 1) the House of Quality is used to translate customer needs into engineering specifications; 2) decomposition by theme is used to determine the Basic Functional Requirements; 3) engineering specifications are categorized into strategies, constraints, Quality Functional Requirements and possible Basic Functional Requirements; 4) Quality Functional Requirements are assigned to different Basic Functional Requirements; 5) Basic Design Matrix, Single Quality Design Matrix and Cross Quality Design Matrix are generated to study and evaluate design concepts from different aspects. By using this approach, it is possible that an improved understanding and higher efficiency of the design process may be achieved.

INTRODUCTION

The Committee on Engineering Design Theory and Methodology of the National Research Council (1991) stated that an estimated 70% of the life cycle cost of a product is determined during design. In product development, the design process has a great effect on the cost of a product but the design process itself may cost little. Dixon and Poli (1995) describe the design process as an iterative progression through the following stages: conceptual design, configuration (embodiment) design, parametric design and detail design. Conceptual design, as the front end of the entire design process, has the greatest leverage on product cost and performance. The Axiomatic Design method, developed by Suh (1990), is applied mainly during the conceptual design stage. However, some difficulties arise in using this approach, especially during the generation of appropriate FRs (Functional Requirements) and DPs (Design Parameters). In this paper, an Axiomatic Design process enhanced by the incorporation of the House of Quality, decomposition by theme, and the assignment of the Quality FRs to Basic FRs is described. The approach presented in this paper aims to improve the clarity and ease of applying Axiomatic Design.

BACKGROUND

The first phase of conceptual design is to analyze the perceived needs from customers and develop functional requirements. Due to the increasing complexity of design, this phase is usually accompanied by or followed by system decomposition that brings insight into the overall structure of product design.

Decomposition

Ullman (1997) talks about decomposition from two perspectives. He first looks at the decomposition of a product from the functions performed. This process is called functional decomposition. Then he looks at a product as an assembly of physical components. This can be called physical decomposition. Ulrich and Eppinger (1995) mainly discuss functional decomposition, while decomposition by the sequence of user actions and decomposition by key customer needs are also introduced.

Dixon and Poli (1995) point out that there are two approaches to conceptual decomposition in mechanical design, direct decomposition and function-first decomposition. Direct decomposition is to decompose the product or subassembly directly into its subsidiary sub-assembly and component embodiments. Function-first decomposition has two steps: 1) first a functional decomposition is performed in which required sub-functions are identified; 2) then embodiments are identified to fulfill each of the sub-functions. Direct decomposition is actually physical decomposition, while function-first decomposition is mainly functional decomposition.

Kusiak and Larson (1995) recognize three areas where decomposition is applied: product decomposition, problem decomposition and process decomposition. Product decomposition is used to describe the physical elements of a product, using two approaches, product modularity and structural decomposition. Problem decomposition is performed to capture design requirements and define the functionality of a product. These two types of decomposition can also be called physical and functional decomposition, respectively. Different from the above two types of decomposition, process decomposition is not used for a product, but for the design process. It breaks down the design process into concurrent or sequential design activities and optimizes the organization of the activities. It helps to increase the cooperation of multidisciplinary design teams in a concurrent design environment.

Allan and Mistree (1993) have a different view on decomposition. They categorize decomposition as hierarchical or heterarchical (non-hierarchical). Hierarchical decomposition breaks a system down into different levels of interactive subsystems. However, for some problems, it is impossible to identify a hierarchy. In this case, the system is non-hierarchical, or heterarchical.

From the above discussion, we can see that there are basically two ways to look at decomposition: functional or physical, versus hierarchical or non-hierarchical. In most cases, functional and physical decomposition of a mechanical system is hierarchical. Since form follows function in design, functional decomposition should be conducted before physical decomposition in most design cases. However, many designers perform physical decomposition by studying existing products without performing functional decomposition explicitly. This inevitably brings bias into design. The trend away from conducting functional decomposition may be because functional decomposition is more abstract and thus more difficult than physical decomposition. Therefore, functional decomposition is of great interest to design researchers.

Functional Decomposition

In functional decomposition, different approaches are taken. Pahl and Beitz (1996) produce a function structure to represent the functional interrelationship of a system. They specify the overall function first. Then the overall function is divided into subfunctions by following the flow of material, energy or signal through the system. Ullman (1997) and Ulrich and Eppinger (1995) basically use the same decomposition technique to develop the function model of the required design. This type of decomposition can be called decomposition by theme. The theme can be material flow, energy flow or signal flow, whichever is the main flow of a certain system. In general, a system could be decomposed according to different themes. In this way, designers can look at the system from different points of view. The different decomposition results of different themes for the same system may be combined to form a compound system decomposition that shows the interrelations of subfunctions more clearly.

Another type of functional decomposition can be called decomposition by block. A block stands for a subsystem that performs the same type of general function in different systems. Pahl and Beitz (1996) summarize the use of “generally valid functions” that are defined in terms of general applicability, physical effects or relationships between input and output after changes in type, magnitude, number, place and time. One set of the generally valid functions developed by Krumbauer are change, vary, connect, channel and store. The system decomposed is then represented by these functions. Zhang and Rice (1989) propose that any mechanical system can be represented by the following functional blocks: working block, driving block, transmission block, control block, support block, tribological block and auxiliary block.

Krischman, et al. (1996) define a different set of basic functions for decomposition by block. After analyzing a number of mechanical products, four basic types of functions are derived: motion, power/matter, control and enclosure. Then, a taxonomy is developed for elemental mechanical functions based on these four basic types of functions. The taxonomy is expressed by sentences that are verb-adjective combinations, like “convert rotary motion”, with a direction like “to linear motion”. Using this decomposition technique, three basic types of functions, motion, power/matter and control are placed at the highest level of functional hierarchy just below the main objective function. Control function is applied separately to the above three types of basic functions. In this way, the decomposition of most mechanical systems can start from the same basic hierarchy. Although this decomposition technique provides a basic decomposition structure, which can facilitate the decomposition process in many cases, it is not suited to all types of design and is not as flexible as decomposition by theme. Decomposition by block is best suited to mature routine design.

Besides decomposition by theme and decomposition by block, many researchers use decomposition by specific application. Designers would study the description of product requirements and/or the structure of previous products to develop the specific functional decomposition for the current system. This decomposition technique requires designers to have broad design experience and insight into the design problem. It is the most difficult type of decomposition technique for novice designers, but also the most flexible one. Even for experienced designers, it may take many iterations to arrive at a good decomposition hierarchy. Dixon and Poli (1995) in their structured design approach, Clausing (1993) in the Total Quality Development, and Suh (1990) in the Axiomatic Design method, all use functional decomposition by specific application.

The relations of the decomposition techniques discussed above can be summarized as Figure 1.

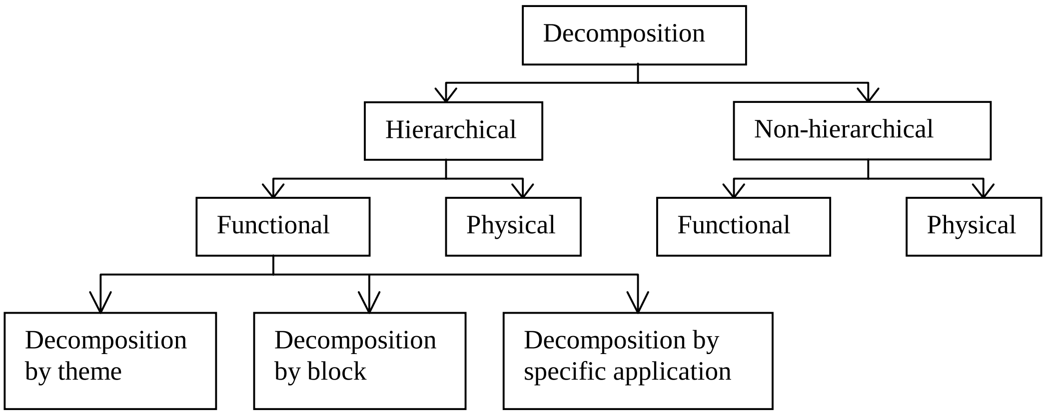

Figure 1. Decomposition techniques

Axiomatic Design

In the Axiomatic Design approach, Suh (90) divided the product development process into four domains that are connected by three mappings, as shown in Figure 2. The four domains are the customer domain, functional domain, physical domain and process domain. CAs, FRs, DPs and PVs in Figure 2 stand for Customer Attributes, Functional Requirements, Design Parameters and Process Variables, respectively. The successive mappings from one domain, "What we want to achieve", to the next right domain, "How we want to achieve it", are governed by two axioms:

The Independence Axiom: Maintain the independence of functional requirements.

The Information Axiom: Minimize the information content of the design.

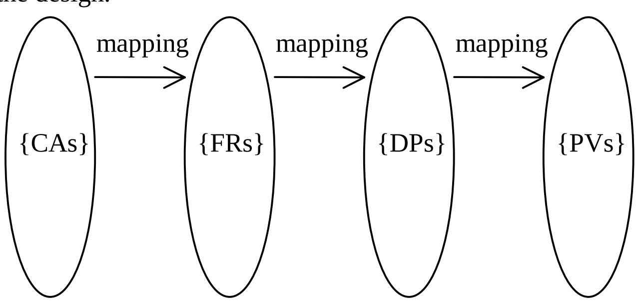

Figure 2. Four domains of design world (Adapted from Suh, 1995)

The conceptual design stage covers two mappings in Figure 2, mapping from CAs to FRs and from FRs to DPs. The mapping relationship between FRs and DPs can be represented by Design Matrix [A]:

{FRs}=[A]{DPs}.

The element A_{ij} of the design matrix [A] represents the relation between DP_j and FR_i. If DP_j has a strong influence on FR_i, then A_{ij} is non-zero, denoted by 'X'; if DP_j only has negligible or no influence on FR_i, the corresponding A_{ij} is zero. In order to satisfy the Independence Axiom, [A] must be either a diagonal or triangular matrix. A diagonal design matrix represents an uncoupled design, while a triangular matrix represents a decoupled design. All other matrices represent coupled designs that require redesign.

Although Axiomatic Design is an elegant design approach, it is not easy to apply. To find the "right" FRs is the most important and difficult step. The Axiomatic Design method does not seem to provide any formal measure to map from CAs to FRs. Functional requirements (FRs) are defined as the minimum set of independent requirements that the design must satisfy (Suh, 95). This definition is very general and makes the specification of FRs difficult. Another consequence of this general definition is that product development strategies are easily confused with FRs. For example, in the "lesson of Sunraycer" (Suh, 90), four FRs are used at the highest level of the design process: simplicity, efficiency, lightweight and reliability. These are actually strategies instead of FRs because they govern the design of every subsystem or even every component. There are no corresponding specific physical embodiments to fulfill these FRs. Second, as mentioned before, Suh uses decomposition by specific application. On the one hand, this decomposition method is highly adaptable to any design problem. On the other hand, it provides no practical guide on how to decompose a system. Therefore this decomposition technique relies heavily on designers' subjective understanding of the perceived needs and their design experience. Thus this decomposition technique contributes to the difficulty of specifying the "right" DPs that are at the same abstraction level as corresponding FRs. Third, in some cases, it is difficult to find the same number of DPs as FRs. To satisfy the Independence Axiom and obtain an uncoupled or a decoupled design, there must be the same number of DPs as FRs. It is ideal that every FR has one principal influencing DP and the diagonal element A_{ii} represents their relationship. However, it is common that one DP influences several FRs or several DPs influence one FR. It is difficult or sometimes impossible to specify a principal DP from a group of influencing DPs for one FR because none of the DPs' influences are negligible.

We can look at different types of DPs that reflect the nature of FRs from another perspective. There are at least three different kinds of DPs. First, a DP can be hardware, like "Motor drive" providing "Power supply" (Suh, 90). Second, a DP can also be one aspect of a physical embodiment. In the design example "Reduction of material cost" (Suh, 90), DP1 "Volume fraction of microvoid" and DP2 "Characteristic dimension of the microvoid" satisfy FR1 "Reduce the material cost by 20%" and FR2 "Maintain toughness of the plastic part", respectively. DP1 and DP2 are different aspects of microvoids. Third, a DP can be a solution that involves the cooperation of several pieces of hardware. The DP to satisfy the FR "Adjust the temperature in fridge" could be "A control which turns on and off a fan according to a thermostat". The variety of types of DPs can increase the confusion to designers when they learn the Axiomatic Design method.

PROPOSED APPROACH

Based on the above observations, we propose the following conceptual design process based on the Axiomatic Design method with the following enhancements.

1. Use the House of Quality to Translate the Perceived Needs from Customer Language into Engineering Language

The House of Quality (Hauser and Clausing, 1988), the first phase of Quality Function Deployment (QFD), is an excellent tool to translate customer needs into engineering specifications. By studying the needs from all customers, including users, producers, marketing/salespersons, etc., the House of Quality provides a categorized list of key design requirements. This is a translation process requiring that no extra information be added when the customer needs are transformed into engineering specifications, so that the engineering specifications can be solution-neutral, which is also the requirement of FRs.

Engineering specifications provide a good basis for developing FRs, but it may not be appropriate to use them directly as FRs for variant design. There are several reasons. First, engineering specifications are derived from customer needs that only address the needs users notice or care about. Many important basic functional requirements may be regarded as implicit, so they are not mentioned explicitly. Second, the customer needs are generally at a low abstraction level while the decomposition hierarchy starts from a high abstraction level. Third, some engineering specifications are not independent from each other as required of FRs, like "check force on level ground" and "check force on 10° slope" (Suh 90). Fourth, the customer needs can come from company managers or producers who may give such requirements as design for manufacturability, servicability, etc., which are design strategies rather than performance requirements.

Other researchers have also tried to associate QFD with Axiomatic Design. Clausing (1993) suggests that the Axiomatic Design method can be used in specifying the detailed piecepart requirements at the second phase of the QFD method. Bascaran et al. (1994) propose to use the Independence Axiom as an enhancement to QFD and combine the design matrix of Axiomatic Design and relation matrix of QFD to form an enhanced QFD relation matrix. However, the advantage of putting these two matrices from two methods together is not clear.

On the one hand, the House of Quality provides a systematic way of capturing design needs, which, as previously noted, Axiomatic Design lacks. On the other hand, Axiomatic Design reveals the intricate structure of a design by creating the FR-DP design matrix governed by the Independence and Information Axioms. Recognizing this, the approach proposed here uses the systematic method in the House of Quality to identify engineering specifications that can be used as the starting point for Axiomatic Design. Then, FRs are generated based on these engineering specifications and Design Matrices are created to reveal the overall structure of the design.

2. Use Decomposition by Theme to Specify the Basic FRs

As discussed before, Axiomatic Design uses decomposition by specific application, contributing to the difficulties of applying the Axiomatic Design method. Besides decomposition by specific application, there are two more functional decomposition methods: decomposition by theme and decomposition by block. As pointed out in the previous section on functional decomposition, decomposition by theme is more flexible than decomposition by block, clearer and easier to apply than decomposition by specific application. Therefore, decomposition by theme is chosen in the proposed approach to help specify the Basic Functional Requirements (Basic FRs) of a design. Quality Functional Requirements (Quality FRs) are generated from the engineering specifications identified in the House of Quality.

To explain what Basic FRs and Quality FRs are, the method of capturing design intents is shown in Figure 3.

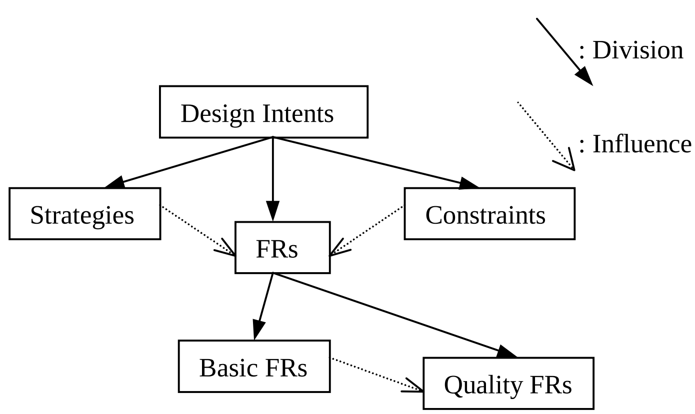

Figure 3. Hierarchy of design intents

Design intents that are a collective set of needs from all sources can be divided into three categories: strategies, FRs and constraints. A strategy is the overall design policy that regulates the design direction of every subsystem and piecepart, like "design for simplicity and efficiency". Constraints here refer to the limits or bounds on design, like size, weight and cost. Both strategies and constraints have influences on the specification of FRs. Functional requirements can be further divided into Basic FRs and Quality FRs. Basic FRs describe "what a product does", while Quality FRs describe "how well the product performs". For example, the moving ability of a car is a Basic FR, and how smoothly and quickly the car runs are Quality FRs. One Basic FR generally has several Quality FRs associated with it. The Basic FR provides the central idea of what a subsystem will do, while the quality FRs provide different aspects of measuring the performance of the Basic FR. Why are they called Quality FRs? According to Webster's Ninth New Collegiate Dictionary, the most relevant definition for quality is "degree of excellence". Although Basic FRs are essential to the performance of a product, it is the satisfaction of its Quality FRs that determines the degree of excellence, or the quality of the product.

3. Assign Quality FRs to Basic FRs

Engineering specifications generated in the House of Quality can be a subset of the design intents. If the customer needs come from the extended users, including actual users, manufacturers, marketing persons, etc., the design intents would be reasonably complete. However, engineering specifications often do not have complete Basic FRs because of the nature of the House of Quality. Decomposition by theme can be used at this stage to get Basic FRs so as to obtain complete design intents.

As design intents, engineering specifications are categorized into strategies, constraints, Quality FRs and possible Basic FRs. Since Quality FRs are used to describe how well Basic FRs are performed, it is reasonable to assign the Quality FRs to Basic FRs, as shown in Figure 4. One Quality FR can be assigned to several Basic FRs. Basic FRs are independent from each other and Quality FRs within a Basic FR are also independent from each other. It should be recognized that the Basic FRs have a hierarchical nature. Therefore, by assigning Quality FRs into Basic FRs, the Quality FRs are guaranteed to also have a hierarchical nature.

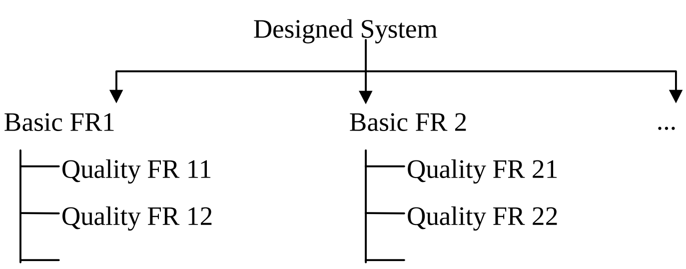

Figure 4. Assignment of Quality FRs to Basic FRs

4. Build Basic and Quality Design Matrices

Since there are Basic FRs and Quality FRs, there should be corresponding Basic DPs and Quality DPs when applying the Axiomatic Design method. After Basic FRs are specified, Basic DPs are found to satisfy Basic FRs. Then the Quality FRs generated from engineering specifications are refined according to Basic DPs and assigned to different Basic FRs. After that, Quality DPs can be found or developed to fulfill the Quality FRs. Basic DPs are generally principles, subsystems or subassemblies, while Quality DPs are different aspects of a subsystem that may be expressed as components or parameters.

The design matrices that represent mapping relationships between FRs and DPs are also different from the original design matrices described by Suh (1990) since we have two different kinds of FRs and DPs. There are three possible mappings: Basic, Single Quality and Cross Quality. Basic mapping is used to find the relationships between Basic FRs and DPs. Single Quality mapping is used to build design matrices for Quality FRs within one Basic FR. Cross Quality mapping is used to build design matrices for the same Quality FRs assigned to several Basic FRs. By building and analyzing these three kinds of design matrices, designers can have a three-dimensional understanding of design problems.

The concepts of Basic FRs and DPs, Quality FRs and DPs,

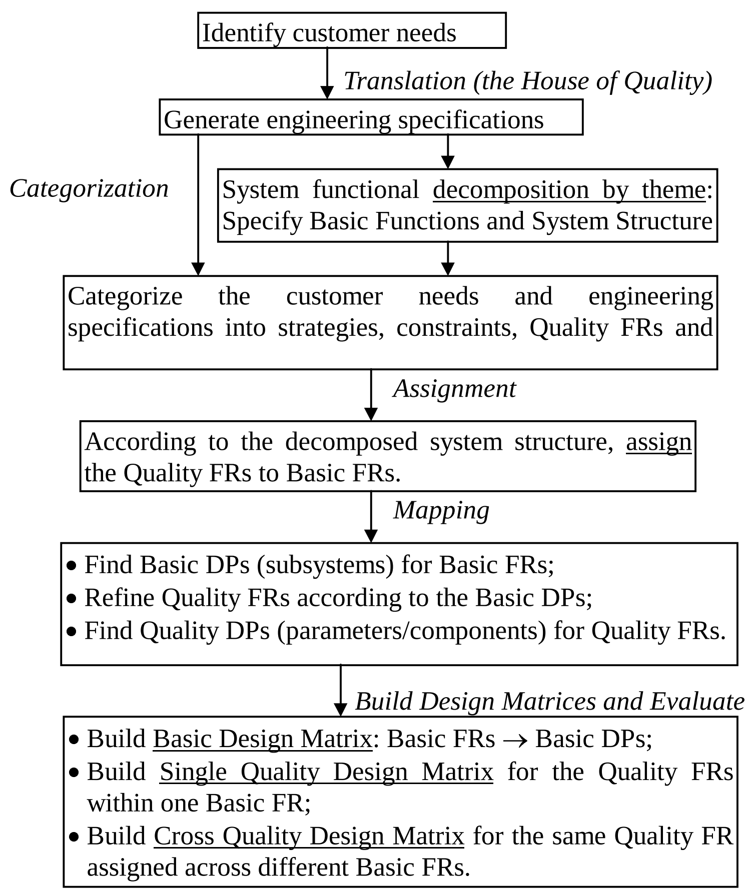

Figure 5. The Enhanced Axiomatic Design Process

Customer needs \ Engineering Specifications	High machining accuracy of mold	Good mold surface finish	Enough strength to undertake processing pressure	Low molded-in shear stress	Molds remain closed during injection	Easy to release molded product	Good venting	Fast heat exchange	Uniform temperature distribution	Uniform shrinkage of injected material	Good filling pattern	Resistance to corrosion and abrasion	Satisfaction of required properties by chosen materials	Easy to replace worn parts	Compatible design of the interface of mold with injection machine
High dimensional accuracy	X		X	X	X	X	X		X	X	X				
High surface quality		X	X	X	X	X	X		X	X	X				
Molded parts have good physical properties				X			X		X	X	X				
Repeatability			X												
Short cycle time								X							
Long service life			X									X			
Wear resistance												X	X		
High reliability			X												
Easy and fast maintenance														X	
Compact size and weight													X		
Compatible with injection machines															X

Table 1. Customer needs and engineering specifications of injection mold design

and the building of Basic Design Matrix, Single Quality and Cross Quality Design Matrices will be illustrated by an example in the next section.

The enhanced Axiomatic Design process can be summarized as Figure 5.

AN EXAMPLE — INJECTION MOLD DESIGN

1. The House of Quality

Injection mold design is presented as an example to illustrate the concepts and design process discussed above. Through discussions with mold purchasers, designers and references to mold design handbooks (Rosato and Rosato, 1995) (Menges and Mohren, 1993), a simple list of customer needs and engineering specifications is generated in Table 1, using the principle of the House of Quality. In this case, we only care about whether the relationship between a customer need and an engineering specification is negligible or not. If it is not, an “X” will be placed in the corresponding position in the table — we do not distinguish between strong, medium and weak relationships.

2. Find the Basic FRs through Decomposition by Theme

The major flow of a mold is the flow of the injected plastic material. Therefore, the theme of functional decomposition here is material flow. By following the melt flowing in a mold in the temporal order, five basic FRs and DPs can be specified. Besides the five Basic FRs and DPs, one more Basic FR and DP should be added according to experience. They are FR: supporting the mold, and DP: base with clamping system.

Receiving melt → sprue;
Distributing melt → gates and runner;
Forming molded part → cavity and core;
Cooling molded part → cooling system;
Removing molded part → ejection system;
Supporting mold → base with clamping system.

Thus, the system structure and Basic Design Matrix could be:

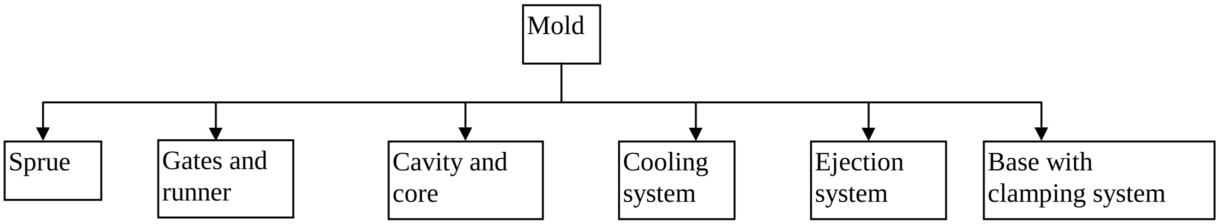

Figure 6. Mold structure

$$\begin{bmatrix} \text{Receiving melt} \\ \text{Distributing melt} \\ \text{Forming molded part} \\ \text{Cooling molded part} \\ \text{Removing molded part} \\ \text{Supporting mold} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \text{Sprue} \\ \text{Gates and runner} \\ \text{Cavity and core} \\ \text{Cooling system} \\ \text{Ejection system} \\ \text{Base with clamping system} \end{bmatrix}$$

Note that the above is an uncoupled design.

3. Categorization and Assignment

As shown in Figure 5, the next step is to categorize engineering specifications into strategies, constraints, Quality FRs and possible Basic FRs. As discussed above, the House of Quality is not used for revealing the Basic FRs that can be obtained through the decomposition by theme. In this example, the engineering specifications do not have any Basic FRs.

The customer need, “high reliability” is actually a strategy because it requires designers to pay attention to the reliability aspect of every component and assembly. Another customer need, “compact size and weight”, can be treated as constraints on product size and weight. The engineering specifications in Table 1 are independent from each other because they are at a relatively high abstraction level. Since they satisfy the independence requirement of FRs, these engineering specifications can be directly assigned as Quality FRs to different Basic FRs, as shown in Table 2.

It should be noted that some Quality FRs are assigned to several Basic FRs, but these Quality FRs have different corresponding Quality DPs for the different Basic FRs.

4. Design Matrices and Evaluation

As discussed before, there are three possible design matrices. Besides the Basic Design Matrix, the Single Quality Design Matrix and the Cross Quality Design Matrix can also be formed. The Basic Design Matrix for the whole system is built in a previous section 'Find the Basic FRs through Decomposition by Theme'.

The Single Quality Design Matrix is built for the Quality FRs assigned to one Basic FR. It describes the structure of the design of one subsystem that satisfies that Basic FR. The Basic FR, 'Forming molded part', with twelve Quality FRs assigned to it, as listed in the corresponding column of Table 2, is chosen to form a Single Quality Design Matrix as an example. The original Single Quality Design Matrix is shown in Table 3, which is a coupled design. By using the matrix manipulation method introduced by Suh et al. (90), the new design matrix can be obtained, as shown in Table 4. The new design matrix is a decoupled design.

BASIC FRS	Receiving melt (Sprue)	Distributing melt (Runner and gates)	Forming molded part (Cavity and core)	Cooling molded part (Heat exchange system)	Removing molded part (Ejection system)	Supporting mold (Base and clamping system)
Quality FRs			High machining accuracy of mold			
			Good surface finish			
			Enough strength for the processing pressure			Enough strength for the processing pressure
		Low molded-in shear stress	Low molded-in shear stress			
						Molds remain closed during injection
			Easy to release molded parts		Easy to release molded parts	
			Good venting			
				Fast heat exchange		
			Uniform temperature distribution	Uniform temperature distribution		
			Uniform shrinkage of molded part	Uniform shrinkage of molded part		
		Good filling pattern	Good filling pattern			
			Resistance to corrosion and abrasion		Resistance to corrosion and abrasion	
			Correct choice of mold material			
		Easy to replace worn parts	Easy to replace worn parts		Easy to replace worn parts	
	Compatible interface of mold with injection system					Compatible interface of mold with injection system

Table 2. Assignment of Quality FRs to Basic FRs

FRs	Single Quality Design Matrix	DPs
[1] High machining accuracy of mold	1 0 0 0 0 0 0 0 0 0 0 0 0	Machining methods
[2] Good mold surface finish	0 1 0 0 0 0 0 0 0 0 1 0 0	Surface finishing methods
[3] Enough strength under processing pressure	0 0 1 0 0 0 0 0 0 0 0 0 0	Wall thickness of cavity
[4] Low molded-in shear stress	0 0 0 1 0 0 1 0 0 0 0 0	Rounded sharp corners
[5] Easy to release product	0 0 0 0 1 0 0 0 0 0 1 1 0	Eject-ability of core & cavity geometry
[6] Good venting	0 0 0 0 0 1 0 0 0 0 0 0 0	Venting system design
[7] Uniform temperature distribution/gradient	0 0 0 0 0 0 1 0 0 0 0 0 0	Consistency of wall thickness of molded part
[8] Uniform shrinkage of injected material	0 0 0 0 0 0 1 1 0 0 0 0 0	Mold geometric shape
[9] Good filling pattern	0 0 0 0 0 0 0 0 1 0 0 0 0	Mold flow path
[10] Resistance to corrosion & abrasion	0 0 0 0 0 0 0 0 0 0 1 1 0	Material for core and cavity
[11] Correct choice of mold material	0 0 0 0 0 0 0 0 0 0 0 1 0	Plastic material
[12] Easy to replace worn parts	0 0 0 0 0 0 0 0 0 0 0 0 1	Assembly measures of core & cavity

Table 3. Original Single Quality Design Matrix For the Basic FR "Forming molded part"

FRs	Single Quality Design Matrix	DPs
[1] High machining accuracy of mold	1 0 0 0 0 0 0 0 0 0 0 0	Machining methods
[3] Enough strength under processing pressure	0 1 0 0 0 0 0 0 0 0 0 0	Wall thickness of cavity
[6] Good venting	0 0 1 0 0 0 0 0 0 0 0 0	Venting system design
[7] Uniform temperature distribution/gradient	0 0 0 1 0 0 0 0 0 0 0 0	Consistency of wall thickness of molded part
[4] Low molded-in shear stress	0 0 0 1 1 0 0 0 0 0 0 0	Rounded sharp corners
[8] Uniform shrinkage of injected material	0 0 0 1 0 1 0 0 0 0 0 0	Mold geometric shape
[9] Good filling pattern	0 0 0 0 0 0 1 0 0 0 0 0	Mold flow path
[11] Correct choice of mold material	0 0 0 0 0 0 0 1 0 0 0 0	Plastic material
[10] Resistance to corrosion & abrasion	0 0 0 0 0 0 0 1 1 0 0 0	Materials for core and cavity
[5] Easy to release product	0 0 0 0 0 0 0 1 1 1 0 0	Eject-ability of core & cavity geometry
[2] Good mold surface finish	0 0 0 0 0 0 0 0 1 0 1 0	Surface finishing methods
[12] Easy to replace worn parts	0 0 0 0 0 0 0 0 0 0 0 1	Assembly measures of core & cavity

Table 4. New Single Quality Design Matrix

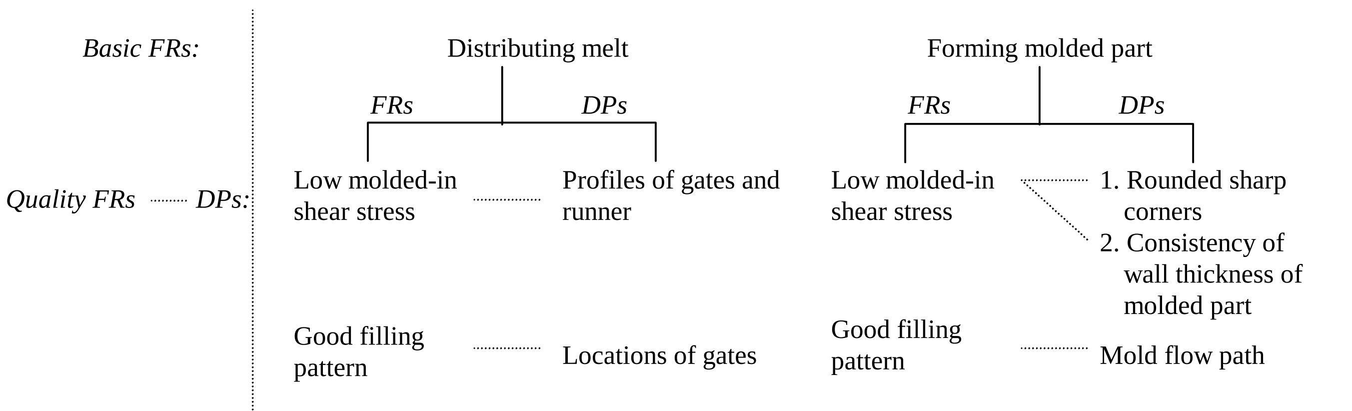

Figure 7. Same Quality FRs assigned to different Basic FRs

A Cross Quality Design Matrix is built for the same Quality FR that is assigned to several Basic FRs. This matrix shows how one Quality FR that is related to several subsystems is satisfied by the different parameters from different subsystems. It is usually difficult to create a square matrix when a designer finds that an FR is influenced by several DPs while applying Axiomatic Design. By analyzing how the FR is associated with different subsystems and specifying the influencing DPs in the different subsystems, the Cross Quality Design Matrix can be created with new insight of the design, and the difficult task of creating a square matrix is avoided.

The Cross Quality Design Matrices for “Good filling pattern” and “Low molded-in shear stress” are presented as examples. From Figure 7, it can be seen that these two Quality FRs are both influenced by different DPs from two subsystems, "Gates and Runner" and "Cavity and Core".

According to Figure 7, the Cross Quality Design Matrix for “Good filling pattern” can be generated as the following uncoupled design.

$$\begin{bmatrix} \text{Good filling pattern influenced} \\ \text{by gates and runner} \\ \text{Good filling pattern influenced} \\ \text{by core and cavity} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \text{Locations of gates} \\ \text{Mold flow path} \end{bmatrix}$$

In the same way, the Cross Quality Design Matrix for “Low molded-in shear stress” is:

$$\begin{bmatrix} \text{Low molded-in shear stress} \\ \text{in Gates and Runner} \\ \text{Low molded-in shear stress} \\ \text{in Core and Cavity} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} \text{Profiles of runner and gates} \\ \text{Rounded sharp corners of} \\ \text{core and cavity} \\ \text{Consistency of wall thickness} \\ \text{of molded part} \end{bmatrix}$$

The above is a redundant design. However, the two Quality DPs “Rounded sharp corners” and “Consistency of the wall thickness of the molded part” contribute to the satisfaction of the Quality FR “low molded-in shear stress” in the same direction. They both reduce the molded-in shear stress. There are no interactions or conflicts between them. Therefore, this matrix is acceptable.

DISCUSSION

The essence of this approach is breaking functional requirements down into Basic FRs and Quality FRs. The major difficulties of applying the Axiomatic Design method are the specification of appropriate FRs and the generation of DPs. These difficulties are due in part to the complex relationships and interactions between different FRs. Separating strategies and constraints from FRs is the first step required to reduce the complexity of using Axiomatic Design. The complexity of specifying FRs is further decomposed by distinguishing Basic FRs and Quality FRs. The Basic FRs are the core FRs of any system. It is very important to recognize them at the beginning of design because the overall structure of the designed product is represented by Basic FRs. It is like building the base and frame of a house first. The next step is to build the house beautifully, which is to specify and satisfy Quality FRs.

It is commonly recognized that functional requirements and their physical embodiments often have one-to-several or several-to-several corresponding relationships, instead of the desirable one-to-one relationship. One major reason for this is that one FR may be addressed by different subsystems at different operation stages and from different aspects. In the example of injection mold design, plastic material is injected through the sprue, runs through the runner, enters the cavity through gates, is formed and cooled in the cavity, and is finally ejected by ejectors. Therefore, some Quality FRs of the final product would be probably influenced by more than one subsystem. For example, "Easy to release molded parts" is influenced both by the geometry of core and cavity and the design of ejectors. This kind of interrelation is not favored in Axiomatic Design because it increases the possibility of obtaining a coupled design.

The proposed approach addresses this problem by assigning Quality FRs to different Basic FRs, and building Single Quality and Cross Quality Design Matrices. A Quality FR that is influenced by several Basic DPs is then addressed separately by different components in different subsystems. This increases the possibility of getting an uncoupled or decoupled design for a subsystem whose design is expressed by the Single Quality Design Matrix. On the other hand, how one Quality FR is fully satisfied by different components or parameters of different subsystems is represented by the Cross Quality Design Matrix.

The example in this paper shows that the hierarchy consisting of Basic FRs and DPs, and Quality FRs and DPs is still at a very abstract level. Questions on how to further decompose the hierarchy into more detailed levels and how the lower levels should be represented, are under study. In the proposed approach, only the Independence Axiom is used. Future work is also directed at how to incorporate the Information Axiom.

CONCLUSION

The presented design process is an enhanced Axiomatic Design process. It provides a structured method to progress from the recognition of customer needs to the evaluation of design concepts in the conceptual design stage. Based on the Axiomatic Design method developed by Suh, this approach proposes several enhancements that aim to improve the ease and clarity of the design process. First, it uses the House of Quality to translate customer needs into engineering specifications. Then decomposition by theme is employed to determine the Basic FRs of the design. After the engineering specifications are categorized into strategies, constraints, Quality FRs and possible Basic FRs, Quality FRs are assigned to different Basic FRs. Basic DPs and Quality DPs are then generated to fulfill the FRs. Three types of design matrices can be generated. Basic Design Matrix reflects the basic structure of the designed system. Single Quality Design Matrix reveals the nature of the design within each subsystem, while Cross Quality Design Matrix shows the interrelationships of different subsystems by describing how they satisfy the same Quality FR.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Industrial Research and Development Institute (IRDI) and Materials and Manufacturing Ontario (MMO).

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