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Axiomatic Design for ‘X’ : An Integrated Methodology for Product Design

التصميم البديهي-السيني: منهجية مندمجة لتصميم المنتج

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ملخص

يقدم التصميم البديهي فوائد عديدة لتصميم المنتج، ولكنه لا يشمل كل العوامل على مدى دورة حياة المنتج. يقترح هذا البحث دمج التصميم السيني لتحسين نتائج التصميم البديهي بالإضافة إلى قياس أداء التصميمات المقترحة في منهجية سميت هنا التصميم البديهي-السيني. وهذه الفكرة تمكن من إضافة إحتياجات إستخدام وتصميم عديدة كمتطلبات وظيفية للمنتج أو كبديهيات تصميم بالإضافة إلى قيود التصميم في إطار مرن لتصميم المنتج. والأكثر من ذلك أن هذه الفكرة يمكن أن ينتج عنها نماذج رياضية قوية لتصميم المنتج بدمج متطلبات المنتج الكمية والنوعية. ويعتبر هذا البحث أساس لخلق إتجاهات جديدة في بحوث تصميم المنتج.

ABSTRACT

The *Axiomatic Design* (AD) introduces several benefits for product innovation, but it doesn’t account for all required concerns in product lifecycle. Integrating *Design for X* (DFX) is proposed here to enhance the results of AD and measure the performance of proposed product designs. The introduced methodology is referred to as *Axiomatic Design for X* (ADFX). This idea enables adding several design and usage requirements as functional requirements and/or design axioms in addition to design constraints in a flexible framework for product design. Furthermore, this idea can inspire robust mathematical models for product design by agglomerating objective and subjective product requirements. This paper provides a base for other directions in the product design research.

Keywords: Axiomatic Design; Design for X; Design performance index

1. BACKGROUND

1.1. Axiomatic Design

The AD theory follows four successive domains: *customer domain, functional domain, physical domain, and process domain* as (Suh 1995a, b). The relationship between domains are Whats and Hows according to the precedence relationship. Thus, the design process can be defined as mapping from the “What” domain to the “How” domain. The process of mapping isn’t unique; the solution varies with a designer’s knowledge base and creative capacity. So, alternative design solutions can be obtained. Once the customer attributes (CAs) are identified, they can be translated into functional requirements (FRs) in the functional domain. This translation must be done within a “solution-neutral environment.” This means that FRs must be defined without ever thinking about something that has already been designed or what the design solution should be. In order to satisfy these FRs, design parameters (DPs) are conceived in the physical domain. This mapping process between functional and physical domains is typically a one-to-many process; thus, for a given FR, there can be many possible DPs. However, the FRs may subject to definition errors which can be classified as declared in Thompson (2013). Finally, the product is produced in terms of DPs through the process variables (PVs) in the process domain. For further

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details, refer to Suh 2003 and Ferreria et al. (2013). The mapping process is often expressed by the design equation

$$\{FRs\} = [A]\{DPs\} \quad (1)$$

where $[A]$ is known as design matrix that relates FRs to DPs and characterizes the product design through some design axioms.

Goodness of the design solution can be evaluated by compliance with Suh’s two fundamental design axioms. Axiom 1– *independence axiom*: maintain the independence of the FRs; that reduces excessive interactions. Axiom 2– *information axiom*: minimize the information content of the design; that increases the probability of success of the product. To satisfy Axiom 1, $[A]$ must be either diagonal or triangular. When $[A]$ is diagonal, each of the FRs can be satisfied independently by means of its respective DP; such a design is uncoupled design. When $[A]$ is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence; such a design is a decoupled design. Any other form of $[A]$ is called a full matrix and results in a coupled design. The FR, DP, and PV can be decomposed into hierarchies. However, contrary to the conventional view of decomposition, they cannot be decomposed by remaining in one domain. One must zigzag between domains to decompose them (Suh 1995a, b; Albano et al. 1999). Axiom 2 provides a quantitative means of measuring the merits of a given design. Information is defined in terms of the *information content* I, that is related in the simplest form to the probability, p, of satisfying the given set of FRs as

$$I = \log\frac{1}{p} = -\log p \quad (2)$$

The units of I depend on the base used for taking the logarithm. If log base two is used then the units are bits; if the natural log is used then the units are nats. Any log base can be used as long as it is consistent (Brown 2006). Even for the same task, defined by a set of FRs, it is most likely that each designer will come up with different designs, which are acceptable in terms of the independency. However, the discovery of design axioms has improved the process of product development in companies around the world (Nordlund et al. 1996; Albano et al. 1999; Suh 2003; Park 2007).

1.2. Design for X

The DFX is a family of methods generally used at the early stage of product design, where X may represent a lifecycle process or a special design requirement. The DFX includes *Design for Manufacture* (DFM), *Design for Assembly* (DFA), *Design for Reliability* (DFR), *Design for Environment* (DFE) and so on. The DFM and DFA are often integrated (DFMA). Implementation of DFX has shown many benefits for robust and simple product design with improved manufacturing time, cost, and quality (Yung and El-Haik 2003; El-Haik and Roy 2005; Gumus 2005). For our purpose, DFM, DFA, and DFR are focused here.

Design for Manufacture and Design for Assembly—The DFM provides information for the designers about manufacturing methods that match the required attributes with various process capabilities to avoid incorrect choices that later would lead to loopbacks. The DFA resolves the possible problems in the assembly process and assure low assembly time and cost with high productivity (Gumus 2005; Wodajo 2012). For further details, refer to Santos (2012) and Kuo et al. (2001).

The assembly cost of a product depends on the total number of parts, and ease of their handling, inspection and fastening. Boothroyd (2005) introduced an index, E_{ma}, to measure the product *assembleability* as

$$E_{ma} = \frac{N_{min} \times t_a}{t_{ma}} \quad (3)$$

where N_{min} is the theoretical minimum number of parts, t_a is the ideal assembly time for one part, and t_{ma} is the estimated total assembly time. For variable assembly time this can be modified to

$$E_{ma} = \frac{\sum_{i=1}^{n} t_i}{t_{ma}} \quad (4)$$

where n is the number of parts to be assembled, and t_i is the assembly time of part i. The *manufacturability*, M, can also evaluated by comparing the estimated manufacturing cost, C_m, of the product with the estimated economical manufacturing cost, C_e, as follows

$$M = \frac{C_e}{C_m} \quad (5)$$

Design for Reliability—The DFR provides information for the designers about the product structure, the elementary functional requirements and reliability estimation to ensure a design with high reliability. The reliability, R, of a product is an important indicator of the product's quality. Thus, it represents a main functional requirement of the product. A case for DFR implementation exists in Ognjanovic and Milutnovic (2013).

Integrating AD with other methods such as *Design Structure Matrix* (Tang et al. 2009) and *Reliability Matrix* (Citti et al. 2000) proved enhancement for AD. Axiomatic Design for Reliability appeared in Citti et al. (2000). This paper demonstrates a general methodology for integrating AD with DFX (§2) to avoid violating other customer attributes through the implementation of AD. The 'X' is considered in parallel with Axiom 2. Concluding remarks are stated in §3.

2. AXIOMATIC DESIGN FOR X

The proposed ADFX methodology follows the AD theory restricted by 'X' such that, Axiom 1 is implemented first for FRs and DPs and then Axiom2 beside 'X' are implemented as a group. In other words, 'X' becomes as a set of axioms. An index, D, is proposed here to primarily measure the degree of dependency as

$$D = \frac{n_x}{n} \quad (6)$$

where n is the number of FRs and n_x is the number of active cells in the design matrix. The minimum value of D occurs when the matrix is diagonal (uncoupled design) and the maximum value of D occurs when the design is fully coupled. This formula can be easily modified to compare the dependency of different designs having different number of FRs. Thus and based on DFA, DFM, and DFR, the best design becomes that has lower information content I, higher assembleabiliy E_{ma}, higher reliability R, higher manufacturability M, and lower dependency D. A design *performance index* P can be designed as

$$P = \frac{E_{ma} \times R \times M}{\hat{I} \times D \times C} \quad (7)$$

where $\hat{I}$ is proposed as a convert for I using log base two and integer multiplier (such as 10s) to agree with the values of the other factors; and C is a measure for other unconsidered 'Xs', that is set here to 1. In this way, benefits of AD and DFX can be obtained. This index becomes a general rule to differentiate different designs. (Notice that, for appropriateness, several convert methods or scales can be proposed for the elements of this formula.)

EXAMPLE

Fig. (1-a) shows a cake type *CD-case* exists in Lee et al. (2004). The purpose is to redesigned to integrate the advantageous functions of other CD cases. Therefore, they analyzed the DPs of the current design in consideration of FRs. It is found consists of a base for supporting CDs, a column for arraying CDs, a cover for protecting CDs against the damage or contamination from outside, and a lock mechanism for fastening the cover to the base. Thus, the current design has four FRs and four DPs as

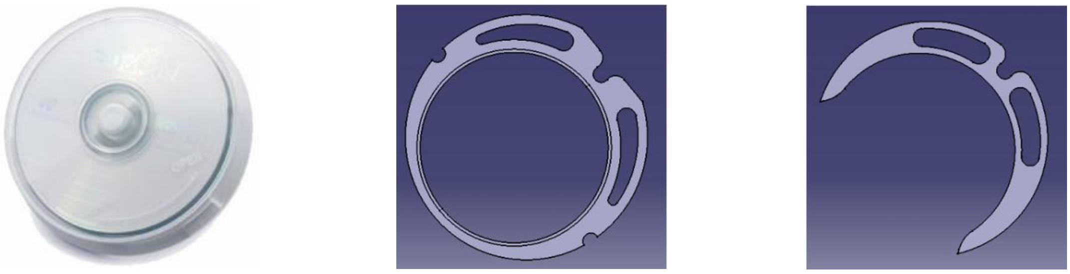
FR1: supporting CDs.
FR2: arraying CDs.
FR3: protecting CDs from damage or contamination.
FR4: fastening the base and the cover.

DP1: a base.
DP2: a column.
DP3: a cover.
DP4: a lock mechanism.

They identified that the current design is decoupled. In the function of supporting CDs, the column is related with the base and the lock mechanism is physically integrated to the base and the cover as appear in the design equation

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} x & x & 0 & 0 \\ 0 & x & 0 & 0 \\ 0 & 0 & x & 0 \\ 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix}$$

They proposed an addition functional requirement FR5 for enabling individual access to each CD. Therefore, the CD holders shown in Fig. (1.b and 1.c) are two proposed as alternatives for holding CDs. The round CD holder rotating around a column makes it possible to individually identify each CD and to take in or out CDs perpendicularly. The holder has a thin rim and a round arm to support a CD. The crescent CD holder rotating around a column makes it possible to individually identify each CD and to take in or out CDs horizontally. The holder has a thin slot and a crescent arm to support a CD. The volume of the case is limited to three times of the contained CD and the weight is limited to one time of the contained CD.



(a) Cake type CD-case. (b) Round CD holder. (c) Crescent CD holder.

Fig. 1. Improving the design of cake type CD-case

The FRs and DPs of the cake type CD-case with round holders are defined as

FR1: supporting CDs.	DP1: a base.
FR2: arraying CDs.	DP2: a column.
FR3: protecting CDs from damage or contamination.	DP3: a cover.
FR4: fastening the base and the cover.	DP4: a latch.
FR5: enabling individual access to each CD.	DP5: a round CD holder
FR51: holding CDs individually.	DP51: a round holder arm.
FR52: enabling rotation of each holder.	DP52: a holder hole.

The FRs and DPs of the cake type CD-case with crescent holders are defined as

FR1: supporting CDs.	DP1: a base.
FR2: arraying CDs.	DP2: a column.
FR3: protecting CDs from damage or contamination.	DP3: a cover.
FR4: fastening the base and the cover.	DP4: a latch.
FR5: enabling individual access to each CD.	DP5: a crescent CD holder
FR51: holding CDs individually.	DP51: a crescent holder arm.
FR52: enabling rotation of each holder.	DP52: a holder hole.

Lee et al. differentiated both designs based on only the information content because both have the same design matrices as

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{Bmatrix} = \begin{bmatrix} x & x & x & 0 & x \\ 0 & x & x & 0 & x \\ 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{Bmatrix}$$

and

$$\begin{Bmatrix} FR51 \\ FR52 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP51 \\ DP52 \end{Bmatrix}$$

Using ADFX to differentiate the designs—Both Cake type CD-case designs have the same design matrices and hence they have the same degree of dependency, $D = 1.83$ by using formula (6). The performance index of each design is evaluated using formula (7) as shown in Table 1. The results show that CD-case with crescent holders are the best. Notice that the required information are inducted and approximated carefully.

Table 1. Performance calculations of the CD-case designs.

CD-case design	$\hat{I}$	E_{ma}	R	M	P
Cake type CD-case with round holder	4	0.97	0.92	0.85	0.1036
Cake type CD-case with crescent holder	2	0.80	0.95	0.92	0.1910

More benefits can be achieved by integrating AD method with some the powerful DFX methods. This integrated approach uses the fundamental rules of axiomatic design, the independence axiom and the information axiom, and starts to implement the axiomatic design method driven by customer needs; this integrated approach also takes into consideration some of the general or special design requirements included in the group of design for X, mainly DFA, DFM, and DFR.

3. CONCLUSION

The requirements in AD are usually defined by mapping CAs to FRs and constraints that may fail if additional types of requirements are needed. The best design comes from AD may be not acceptable for some usages Therefore, AD should be enabled with other methods to enhance the AD results, which hasn't received considerable attention in the literature. The design structure matrix is often used for integration. This paper proposed integrating DFX into AD to enable adding most of customer and producer needs in the product design such as manufacturability, assembleabiliy, reliability, recyclability, and so on. Several designs can be differentiated using the proposed methodology as demonstrated by using a design example. This paper presents a new stimulating opportunity for creative designs.

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