Tool Development for Evaluation of Quantitative Independency Between FRs in Axiomatic Design

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ABSTRACT

Axiomatic Design is the one of many useful methods for making a good design. In this method, the independency of Functional Requirements (FRs) is an important property to determine whether the design is good or not. Until now so many designers have decided the independency between FRs by their own decisions. The way depending on inspiration is simple and fast, but it can not be considered as a precise conclusion. Also there are not exact rule that evaluate the quantitative independency between FRs. This paper will show the way to evaluate the quantitative independency of FRs from the comparison between FRs of lower levels, and develop more efficient and objective tool in Axiomatic Design.

Keywords : Axiomatic Approach, Functional Requirement, Design Parameter, Diagonal Matrix, Coupling Matrix, Triangular Matrix, Lower Level, Influence Component

1. Introduction

Designers go through many decision-making processes during the designing of a product. Many choices exist during these decision-making processes. In 1980, axiomatic design was introduced by Suh(MIT) as the best tool in producing the best design. Axiomatic design takes into account that the first stage designing plays a large role in determining the production period, defect rate and the product's final usage and it aims to provide a way that radically improves the final product's condition by connecting the design variables through axiom.

The evaluation of a design is done by two axioms. One of them is the axiom of independency that evaluates the interacting effects caused by the design variables and the other one is the axiom of information that evaluates the complexity of the design variables. Corollary and theorem, which are commonly considered useful in many designs, are also provided in the axiomatic approach.

The matrix is generally being used as a tool to draw the axiom of independency and the designer can recognize whether the design variables interact with each other or not. However, there is not a process or a tool to figure out the exact interacting effects between the design variables. Also, independency itself is being determined mostly by the intuition of the designer. Decisions based on intuition can lead to waste of time and material in the overall design by making the designer to take even unnecessary circumstances into account.

Therefore, this paper will try to verify which one of the two, objective judgement and design variables, has bigger influence on the design through the relationship between the higher level's independency and the lower levels. It will also compare the influence by inter-comparing the design parameters in the microcellular foaming process to verify this tool.

2. Axiomatic Design

2.1 Design Process

As it is shown in Fig. 1, design in the axiomatic design is defined as a mapping process that connects the requirements that the 4 areas of design require. The 4 design areas are (1)Customer Requirements: CRs, (2)Functional Requirements: FRs that actually realize (3)Design Parameters: DPs that are related to the FRs and lastly (4)Process Variables: PVs, the variable that is needed in the actual process.

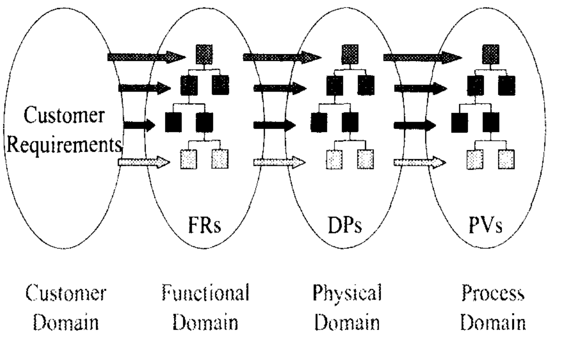

Fig. 1 Design Process

There are three important requirements in the modern designing process. They are the functional requirements that match the user's objective, the method to realize the functional requirements and the explicit design that applies this method. The axiomatic design can provide a evaluating standard that can be used in selecting the best design by applying axiom in the final design by dividing it into Functional Domain (FD) and Physical Domain (PD).

The restricting conditions that limit the functional requirements can be divided into the input constraining requirements, which is an artificial constrainment, and the system constraining requirements, which is a natural and scientific constrainment. As the constraining conditions increase the necessary functional requirements greatly decrease and the design gets simpler.

2.2 Hierarchical Structure

According to the rules of axiomatic design, the essence of the design process lies in the hierarchical structure. The designer starts the design from the functional requirements or overall requirements and the functional requirements can be classified according to the importance. Overall and general concept of the functional requirements is placed in higher level and the intricate and minute functional requirements are placed in the lower levels.

This structure is very useful because it efficiently organizes the designer's efforts. In order to select functional requirements of the lower levels that can satisfy the lower level design variables, the functional requirements of the higher levels must be satisfied by the higher level design variables. Additional creativeness is created through this process and exact evaluation can be made because the design process that began with the highest-level functional requirements recognizes a wide range of design variables and proposes new designs. First step in the selection of the low level functional requirements begins from the selection of high-level design variables. When the appropriate high level design variables are selected low level's functional requirements can be determined. This process of intersecting selection between functional requirements and design variables is necessary because each process's two areas are inter-related and inter-dependent. The hierarchical structure is expressed as a tree structure and FRs has a symmetrical structure to that of DPs. The hierarchical structure is shown in Fig. 2.

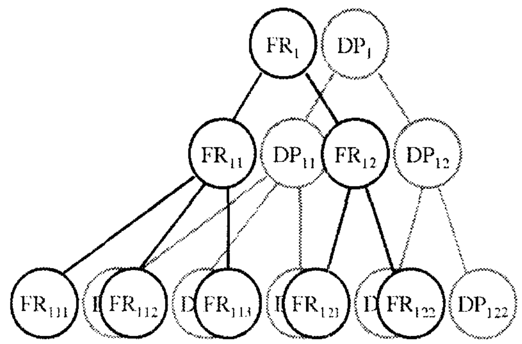

Fig. 2 Hierarchical Structure

2.3 Axiom of independence and independency

The axiomatic design was developed to help in selection useful designs. According to Suh(1990), two designs of axiom is a helpful tool in creating a new design. Two axioms exist and the first one is the axiom of independence related to the functional requirement's selection and the second one is the axiom of information, which provides a standard in evaluating the better design.

Axiom 1 : Axiom of independence

(Maintaining the independence of the functional requirements)

Axiom 2 : Axiom of information

(Minimal amount of information)

Of the two axioms listed above the axiom of independence is the most useful tool when evaluating the design in its concept process. Knowing, whether the functional requirement's independence is maintained in the proposed design or not, early can eliminate many needless designs in the early stages. On the other hand the axiom of information is used to compare designs that have already satisfied the independence more minutely.

The best method to clearly show the relation between the functional requirements and the design variables is to use the design matrix. The axiom of independence is considered foremost with the necessity of independence. It means that the functional requirements and the physical requirements correspond 1:1 and that changes in the physical requirements must bring about changes in the corresponding functional requirements. Functional requirements have a hierarchical structure and the design variables that satisfy it also constructs a similar hierarchical structure. Therefore one FR has only one DP.

What this means is that if one design variable is altered on basis of a functional requirement's change it will not make cause any changes to other functional requirements. However, in real situations it is hard to find one functional requirement being influenced by just one design variable. In this case it is hard to explain and therefore it is necessary, if possible, to make one functional requirement possessing one design variable. The matrix of the design variables and the functional requirements can be shown in three types.

2.4 Design Matrix

The relation between the functional requirements and the design variables can be expressed by the method of using design matrix [A]. In a similar way, by using design matrixes the relation between different fields can be shown.

$$\{CRs\} = [A]\{FRs\} \tag{1}$$

$$\{FRs\} = [B]\{DPs\} \tag{2}$$

$$\{DPs\} = [C]\{PVs\} \tag{3}$$

$$[B] = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ B_{n1} & B_{n2} & \cdots & B_{nn} \end{bmatrix} \tag{4}$$

Each matrix's element B_{ij} shows the relation between FR_i and DP_j. The design matrix marks X for the elements with deep relationship and O for non or weak relationship. This is a general method used to certify the independence of the design variables. Appropriate and clear method must be given to show the functional independence with exact numbers.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & X \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{5}$$

The matrix shown above (5) is called a coupled matrix and it is a design with no independence. If the functional requirement's independence is not maintained these designs will cause inappropriate changes to other functional requirements during any tries of the design variable alterations and will cause a poor result in the overall design process.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{6}$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{7}$$

The design matrix that satisfies the axiom of independence can be shown in either diagonal matrix (6) or triangular matrix (7). The diagonal matrix stands for uncoupled matrix, which satisfies complete functional axiom of independence and therefore, is most appropriate. In this case each functional requirements are affected by one design variable and the intended alterations of the design variables is made possible. The triangular matrix stands for decoupled design and if the design variables are organized into a specific order then the effects caused by changes in the design variables do not have to be considered.

3. The judgement of independence and quantification

3.1 The judgement of independence

In the axiomatic design the judgement of independence is an important process in the evaluation of the design and as it was listed in clause 2.4 a matrix is generally used in the judgement. So far, in the designs the focus was made on figuring out simply the independence by using a matrix and the variables consisting the matrix were generally picked by the designer's whim.

However, an evaluation of design without proper objective judging standards of independence can not certify itself with its results and consequently, there is no confidence on the design's usefulness. Therefore, an objective judgement on the independence in the axiomatic design must be considered as an important issue.

In the hierarchical structure of the design the relation between the functional requirements and the design variable which exist in the lower level can be used to judge the lower level's independence as shown in Fig. 3.

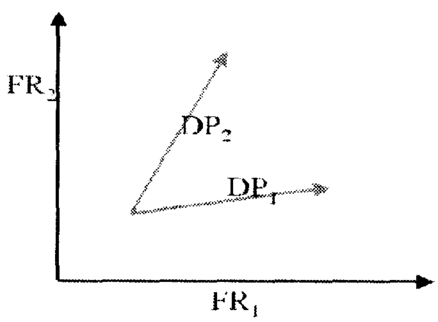

Fig. 3 Influence among the FRs of different branches

FR_1 : CD-Rom with 3,000-5,000 rpm
FR_2 : Minimization of vibration of CD-Rom

DP_1 : Current, (I)
DP_2 : Mass, (M)

It is possible to judge the influences if there exists a relation of a mathematical function between DPs and FRs. For example, if FR and DP were selected as it is shown in Fig. 3, FR_1 can be expressed as a mathematical equation of M and I. FR_2 also can be expressed as a mathematical equation of the number of rotations caused by I. In this case it is judged that the design variables have interrelationship.

However, FRs and DPs of the higher level hierarchical structure is an abstract and general concept that can bring hardships in the judgement of independence if a relation of function can not be identified as it was the case between the evaluation of inter independency in the lower level.

3.2 The judgement of independency in the higher level through the interrelationship between the lower level FRs

In the axiomatic design it is more often than not when the designer's intuition plays important role in designing. In most cases of the design process the selection of the design variables is done in the order of the higher level to the lower level and this naturally causes the decision of marking X or O in the matrix to start from the higher level. The meaning of the element tends to be abstract in the general higher level.

FR_1 : Increase in the amount of information
FR_2 : Stability in the data
FR_3 : Possibility of transfer

DP_1 : Increase in the total number of bit
DP_2 : Securing the exposure of records
DP_3 : Impact strength of the media

The FRs listed above is part of the higher level selection of the FRs through the development of a new information storing device. Although higher level gets concrete as it moves down to lower levels, the elements of the higher level are determined as it is listed above and that makes it hard to make sure if they have influence or not. In order to evaluate the independency between higher functional requirements the certification of lower level independency must be done first.

Fig. 4 shows the inter-relationship between parts of the lower concept in a big functional requirement. It is somewhat general and abstract in the higher levels but in the lower levels it is possible to see the interrelationship more clearly. The abstract design variables of the higher levels makes it possible to evaluate the independency of high level design variable by recognizing the lower level and the relationship between FR and DP in the lowest level.

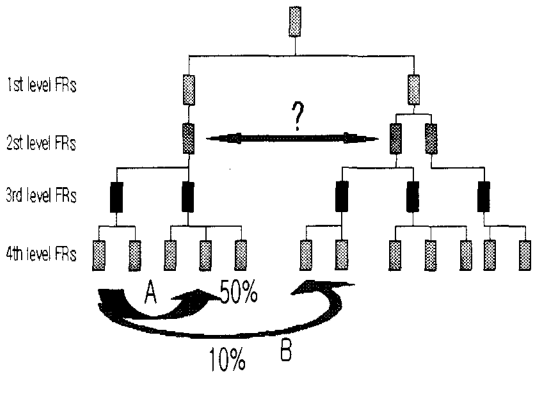

Fig. 4 Verification from interaction between the lowest components

The judgement of independency has been discussing the design variables of relating or same levels to verify the independency. However, in order to obtain a more objective evaluation of independency between the design variables, a verification of independency in lower levels in need. This can be expressed in the next summary.

Summary : If the higher level design variable have certain influences between one another then the inter influence between lower design variables can be found.

3.3 Quantification of independency

Quantification of independency means, if viewed as a relationship between FRs and DPs, being able to express the level of independency by numbers rather than simply marking the effects with the X's or O's which is being done in existing matrixes. To elaborate further, the numbers of independency is different from the amount of information, which is used to explain axiom 2, and it is an element that is used to find out the importance between the elements.

Through this, it is possible to judge how much the external design variables that effect FR really influences. It is also possible to determine which design variable to consider first obtaining independency when some FRs influences other FRs. In order to achieve quantification of independency investigation into two aspects can be made.

3.3.1 The evaluation of independency through the relationship between the elements

External Influence, as it is shown in Fig. 4, can be considered by comparing the effects between the lowest level design variables. Internal design appears in the lowest level therefore we can evaluate the influence by considering the influence between the FR, DP of the higher level and lower level.

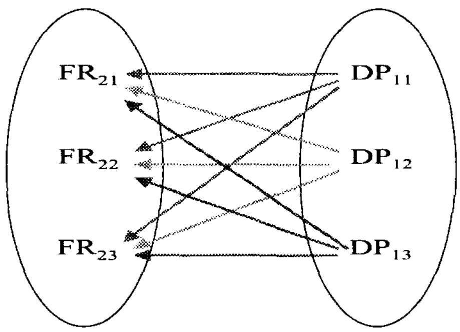

Fig. 5 Effect of FR_2 by DP_1

In Fig. 5 the amount of lower level's DP_{1s} that influence functional requirement FR2s were verified. In this case, it can be judged that the influence on FR_{2S} increases as the numbers of lower level's DP_{1S} increase.

3.3.2 Comparing independency between the elements

The method explained above evaluates independency simply through the number of these elements and impact factor is given following the real influence the elements have. This method puts the influence that DP's that correspond with FR, lower element's change has on FR's change as 1. With that as a standard this method compares influence through comparing the influence other DP has. As it is shown in Fig. 3 the influence is greater when the arrow's slope is bigger and the comparison between numbers are done inside the design domain with equal design.

The difference between maximum and minimum value of FR_1 while DP_1 is being changed x much : 1

The amount of change in the maximum and minimum value of FR_1 while DPs is being changed y much : S%

The x and the y that the designer gives can change according to the design domain. For example an equation can be given when the manufacturing speed is given between 100-200 rpm. S can be ruled as the influence DP_1 has on FR_1 and if this is greater than 100% it can have bigger influence on FR_1 than DP_1. In some cases, influences less than 1% occur and good results can be gotten even when the influence is overlooked.

The amount of changes in FR_1 through DP_1 is called I_1.

↓

The amount of changes in FR_1 through DP_2 is called I_2.

↓

The influence that DP_2 has is called S.

$$S = I_2 / I_1 * 100\%$$

↓

The total influence FR_1 gets through DPs

$$\text{Total } S = S_1 + S_2 + S_3 \cdots$$

Fig. 6 Flowchart of calculating total influence

4. The evaluation of influences between the elements in a Microcellular foaming process

4.1 Microcellular foamed plastic

The picture shown in Fig. 7 is an enlarged picture of the surface of microcellular foamed plastic. Plastic is a material that is being used to produce many products in present age. The effort to cut material cost is emphatically being requested because material cost is the largest part in the production cost.

Microcellular foaming process is a process developed to achieve material reduction and improve mechanical property. It is used to describe a plastic material with a minute hole when gases like CO_2, He, Ar or N_2 are dissolved into the polymer material to make one phase and after creating cells by causing thermodynamic instability inside the material. The size of the cells developed internally is measured in micrometers(μm) and it is called microcellular to distinguish itself from generally foamed plastic.

Fig. 7 Microcellular foamed Plastics

Microcellular foamed plastic has the advantage of reducing the materials and unlike existing foamed plastics, prevents decrease of mechanical property, caused by uneven foaming, from happening. Also, the micro cells inside drastically improves impact strength in impact absorption by absorbing external energy.

There are many different kinds of elements that influence the production of plastic through this microcellular foaming process. As it was discussed previously the independency between the elements can be evaluated and compared quantitatively by using the tool that is being used to evaluate and compare the influence the elements have between each other.

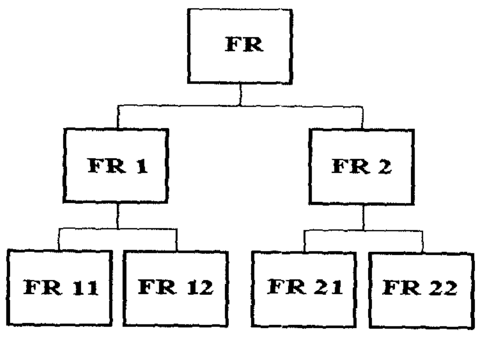

Fig. 8 Schematic of Functional Requirements

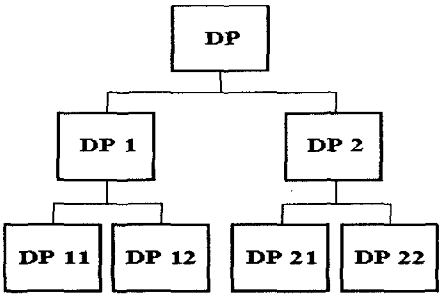

Fig. 9 Schematic of Functional Requirements

FR : Reduction of raw material
DP : Achieving high foaming magnitude

R/t = Radius over thickness of cavity
R = Radius of cavity
t = Thickness of cavity

4.2 Determining X and O in design matrix

The functional requirements of the microcellular foamed plastic is shown in Fig. 8. The marking of the X and O is appropriate to start at lower levels so the selection of the lower level matrix is,

FR_{11} : Obtaining space for the foaming
FR_{12} : Optimization of the nucleation device
DP_{11} : Adjustment of R/t in the mold system
DP_{12} : Adjustment of radius and length of nozzle

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \end{Bmatrix} = \begin{bmatrix} \times & \circ \\ \circ & \times \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \end{Bmatrix} \qquad (5)$$

Both FR_{11} and FR_{12} can select volume as their main variables. DP_{11} and DP_{12} can be shown with R/t and R, L as their main variables. Changes occurring in each DPs influence only corresponding FRs, therefore it can be shown as a decoupled matrix like equation (5).

FR_{21} : Achieving minute and intricate cells
FR_{22} : Achieving even sized cells
DP_{21} : High pressure drop rate
DP_{22} : Optimization of gas absorption pressure

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} \times & \circ \\ \circ & \times \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix} \qquad (6)$$

The differential between cell sizes and the cell size can be used as the main variable of FR_{21} and FR_{22}. Pressure drop rate and gas absorption pressure can be used as the main variable of DP_{21} and DP_{22}. Changes occurring in each DPs influence only corresponding FRs, therefore it can be evaluated as an appropriate design by being a decoupled matrix like equation (6).

Finally the influence between high levels FRs is made through analyzing the influence between lower levels. R/t of DP_{11} effects not only FR_{11}'s obtain of foaming space but FR_{21}'s minuteness and intricateness of the cells also. The relationship of influence in the lower levels is reflected in the higher levels and is expressed as a matrix.

FR_1 : Maximization of mass reduction
FR_2 : Smooth creation of bubbles
DP_1 : Optimized design of the mold system
DP_2 : Sufficient mixing of polymer and gas

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} \times & \circ \\ \times & \times \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \qquad (7)$$

Matrix (7) is a decoupled matrix that can prevent inter-influence between design variables through selective selection of the elements in DP_1.

4.3 Application of Quantitative measurement

Through the method discussed in clause 3.3.2, this paper will try to evaluate the effect R/t has on volume changes when it is changed by 1%. Other property's influence can be evaluated in the same way and objective comparison can be made possible.

Table 1 Foaming magnitude as R/t of cavity sample

R/t	Standard Sample (g)	Gas Assistant (g)	Foaming Magnitude (%)
82.5	3.5	3.2	9.1
41.3	7.0	5.9	15.5
27.5	10.8	8.8	18.7
20.6	13.9	10.6	23.2
16.5	17.5	11.5	34.4
13.8	20.8	12.3	40.8

In Table 1 R/t has the value of 13.8 - 82.5. In this case the Foaming magnitude is changed 31.7%. If this is assumed as 1 then the influence other design elements have on foaming magnitude can be compared by comparing it with the amount of change in the foaming magnitude through changes in the other element's design range.

Class of gas is another element that has influence on the Foaming magnitude. The influence that class of gas has is shown in Table 2.

Table 2 Foaming magnitude as gas change

	CO_2	N_2
ABS (200℃)	25.2 %	23.6 %
PMMA (210℃)	34.0 %	37.1 %

As shown in Table 2 the changes in the foaming rate following the changes of the class of gas is at 1.8%-3.1% while being under same conditions. When compared with the changes of 31.7% induced by R/t this is an amount of approximately 10% less and it is shown in Fig. 10. Through this evaluation it is possible to find out that the changes of R/t has bigger influence on foamed volume than changes in the class of gas. Normally the influence on the elements tends to decrease as the design domain shrink.

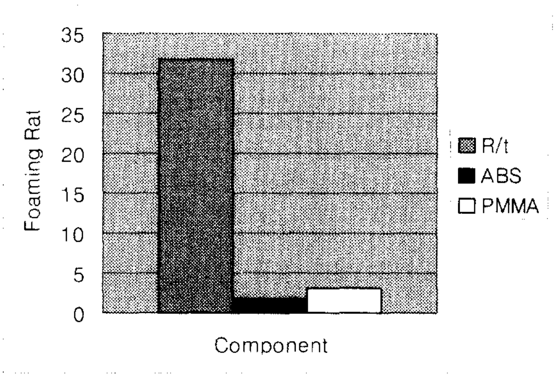

Fig. 10 Comparison of influence among each component

5. Conclusions

The evaluation of independency is an important process in the evaluation of the design and it is a logical process that can be proved through experiments and calculations rather than intuition. In the axiomatic design, design or process can be expressed in a gigantic hierarchical structure. The quantitative evaluation of the independency between the elements of the hierarchical structure can be used directly as a tool to determine whether the design is good or not. Furthermore, the verification of inter independency and comparison of quantitative independency in the design parameter through quantitative numbers give order of the design parameters. This paper presented a method of evaluation of inter influence in the overall design process through lower level structure's inter relationship, and also presented mathematical method of certifying superiority through the comparisons between quantitative elements independency. This will make selection of optimal design variables in the process of making one product possible and also enable objective comparisons between completed designs.

As the result of applying the evaluation of independency and the comparison standard in the microcellular foaming process it was find out that R/t has bigger influence on the foaming magnitude than selection of gas in the design process. The independency of design variables were also mutually compared. This could be applied in developing a tool that can compare the influence in the overall design process by using computers.

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References

1. Nam P. Suh, "The Principles of Design," The Oxford University Press, pp. 25-154, 1990.
2. William W. Tice, "The Application of Axiomatic Design Rules to an Engine Lathe Case Study," MIT, pp. 45-76, 1976.

3. Yun-Dong Hwang and Sung-Woon Cha, "Axiomatic Design of Mold System for Advance of Foaming Magnitude," Journal of KSME, Vol. 25, No. 4, pp. 637-644, 2001.
4. Yong-Rak Moon, Sung-Woon Cha and Jung-Wook Lee, "Development of New Concept Product Using Axiomatic Approach," Proceedings of the KSME Spring Annual Meeting A, pp. 542-547, 1999.
5. Sung-Woon Cha, "A Microcellular Foaming / Forming Process Performed at Ambient Temperature and a Super Microcellular Foaming Process," MIT, pp. 20-96, 1994.
6. M. G. Moon, "Axiomatic Approach to Engineering Design," MIT, pp. 62-68, 1980.
7. Dominick V. Rosato and Donald V. Rosato, "Injection Molding Handbook : The complete molding operation : technology, performance, economics," New York : Van Nostrand Reinhold, pp. 34-105, 1986.
8 MIT Axiomatic Design Team, "Applications of Axiomatic Design," Course Notes, MIT, pp. 12-14, 1996.
9. Yun-Dong Hwang, Sung-Woon Cha, Jae-Dong Yoon and Ji-Hyun Kim, "A Change of Foaming Magnitude as Thickness of Mold System," Journal of KSPE, Vol. 17, No. 10, pp. 186-191, 2000.