The Effect of Teamwork and Function-Oriented Thinking on Generated Ideas for Product Design

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Optimal designs in terms of function and cost are required for the product development and improvement design processes. A methodology that results in high-value design is needed by designers, because they have to generate many different ideas and to select the good ideas. Value Engineering is one of management technique that attempts to fill this need and is good for a wide variety of ideas developed through teamwork and function-oriented thinking. In this study, through the effect of teamwork and function-oriented thinking on generated ideas will be verified from the data of a company seminar through quantitative handling of the variety of ideas generated through practical use of information entropy.

1. Introduction

It is an essential requirement for corporate management to reduce manufacturing costs as much as possible. It is said that in product development and improvement, approximately 80% of manufacturing costs are determined at the detailed design stage.(1), (2) Therefore, design plays an important role in corporate management.

When designing a product, designers derive design solutions from market needs as well as from functional requirement concepts based on corporate policies.(3)-(5) To find solutions, designers search for different methods for developing each of the sub-functions that constitute the function of the product as a whole and choose an optimal combination of such methods.(5) These methods are developed from many ideas, and teamwork and function-oriented thinking are believed to be effective in developing a large number of ideas.(6)-(8) Function-oriented thinking used in Value Engineering (VE) is said to be effective in creating ideas.(6), (9) However, there is no quantitative data that shows the effect of such thinking. Meanwhile, from the perspective of business management, it is also necessary to maximize the investment efficiency of management resources, including man-hour.

Against this background, this study quantitatively analyzes the effects of teamwork and function-oriented thinking on ideas developed to review a wide range of design solutions in design processes. The aim of this study is to provide support for making decisions how to invest man-hour in the development of ideas and other creative activities.

2. Idea generation and functions in design processes

2.1 Functions in design methodology

The design methodology of Pahl and Beitz(5) is widely known as a representative example of design methodology. **Figure 1** shows the structure of conceptual design processes.(3) From requirement specifications, designers derive sub-functions required to meet the specifications, and then examine sub-mechanisms required to achieve the sub-functions. Designers integrate these sub-mechanisms in order to obtain a completed design solution. This thinking process in conceptual design is generally known as function-oriented idea development. In this study, the term “functions” is used to refer to these functions in design methodology.

2.2 Phases that require idea generation

The design methodology of Pahl and Beitz explains the design thinking processes engaged in by designers. In short, an actual design workflow consists of repetitions of analysis, integration and evaluation, which eventually lead to a final design draft. Designers brainstorm to generate multiple conceptual designs, evaluate these designs to choose one of them, and generate and refine the design into a specific form at the final stage, thereby bringing the design process to an end.(10) It is therefore important to generate as many ideas as possible in the brainstorming phase.

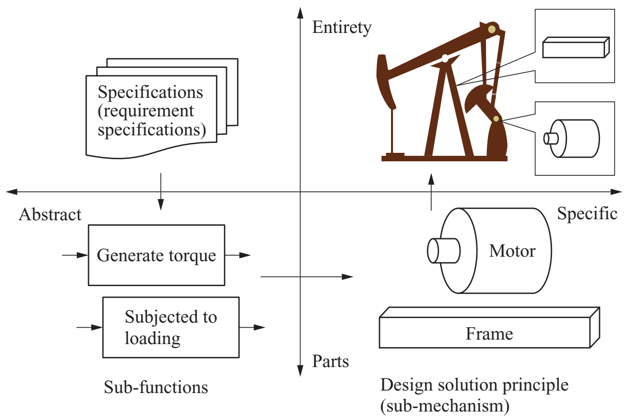

Fig. 1 Structure of conceptual design process(3)

2.3 Functions in VE

VE is one of the management techniques that focus on functions. VE specifies the functions and costs of products and services. This specifies the requirements of customers and users from functional aspects and brainstorms by using functions as a starting point for the generating of as many ideas as possible to create alternatives to existing products and services.(6) **Figure 2** shows the relationship between the user's requirement and functions. The user's requirement is to obtain brightness. The level of brightness to be achieved provides restrictions. In this example, the level of brightness is specified as 400 lux for health maintenance.

As shown in this example, VE defines the functions required by users and creates a functional diagram to show purpose-means relationships between the functions, thereby enabling divergent thinking called "idea generation."

The aim of this study is to quantitatively analyze the effects of teamwork and function-oriented thinking on idea generation.

3. Study method

3.1 Experiment design

In this study, we gathered data on ideas for reducing costs generated by training participants (subjects) during an in-house VE training course. We asked the subjects to generate ideas to reduce the costs of a tripod and a stapler in order to evaluate the effects of teamwork and function-oriented thinking on the diversity of ideas generated. In this study, teamwork refers to the process through which multiple members collaborate with each other to generate as many ideas as possible. The diversity of ideas and the method for evaluating the diversity will be explained in **Section 3.4**.

3.2 Complexity of the products targeted for idea development

Figures 3 and **4** show examples of functional diagrams of a tripod and a stapler, the products used for idea generation. A functional diagram is a diagram that shows purpose-means relationships between sub-functions that are developed to achieve the functions of a product as a whole. Note that the purpose-means relationships between the functions of parts are relative. In a functional diagram, purpose-means relationships form a tree structure that spreads from left to right. VE uses a functional diagram to evaluate the validity and value of the sub-functions of a product and specifies functions that provide a starting point for idea generation. A functional diagram describes relationships between functions. In this study, however, we also use functional diagrams to show the complexity of products.

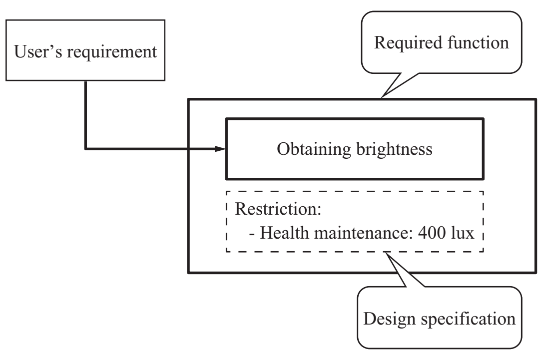

Fig. 2 Relationship between users' requirements and functions

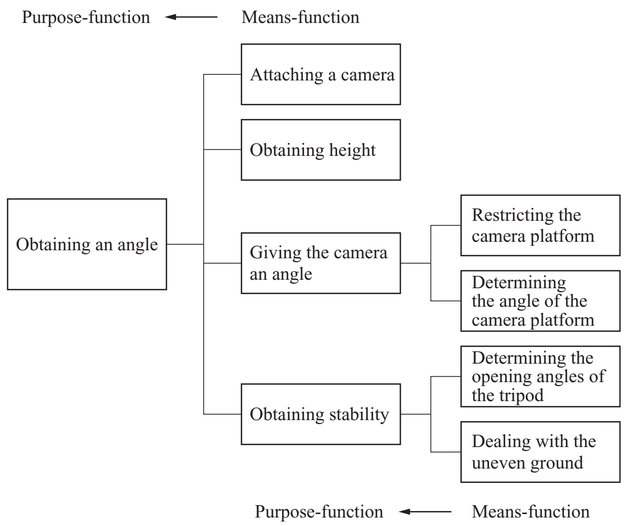

Fig. 3 Example of functional diagram for a tripod

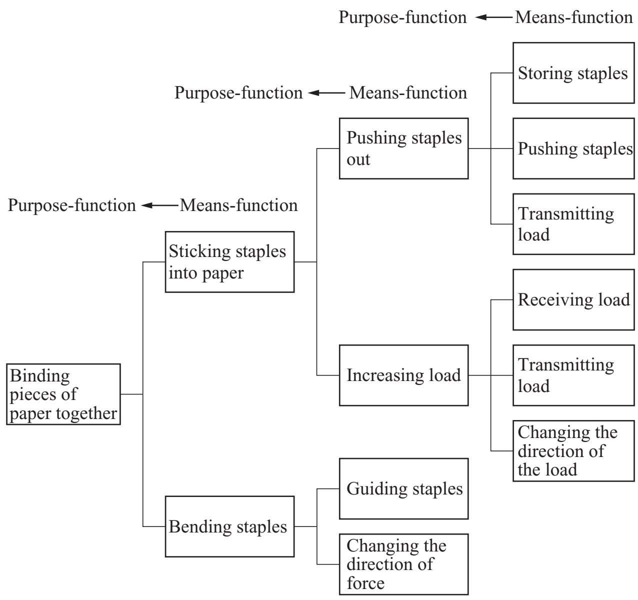

Fig. 4 Example of functional diagram for a stapler

A comparison between the functional diagrams for a tripod and a stapler shows that the diagram for a tripod has three layers while that for the stapler has four. This leads us to conclude that a stapler is more complex than a tripod in terms of purpose-means relationships between functions as well as in terms of linked operations between functions.

3.3 Idea generation steps in the experiments

Subjects followed the steps shown below to generate ideas by using the patterns shown in **Table 1**. The time available for idea generation was three minutes in all experiments.

Step 1: Forming teams

We divided six to seven subjects into two teams of three or four. **Table 1** shows an example with six

Table 1 Cost reduction task for examinees

Experiment 1-1	Individual work: A, B, C Tripod Without prior knowledge of the main function	Teamwork: D, E, F Stapler Without prior knowledge of the main function
Experiment 1-2	Teamwork: A, B, C Stapler With prior knowledge of the main function	Individual work: D, E, F Tripod With prior knowledge of the main function
Experiment 2-1	Individual work: G, H, I Stapler Without prior knowledge of the main function	Teamwork: J, K, L Tripod Without prior knowledge of the main function
Experiment 2-2	Teamwork: G, H, I Tripod With prior knowledge of the main function	Individual work: J, K, L Stapler With prior knowledge of the main function

(Note) The time for idea generation was three minutes in all experiments.

subjects A through F and another six subjects G through L. In experiment 1-1, we divided subjects A through F into two teams (A through C and D through F).

Step 2: Idea generation (Experiment 1-1)

We asked subjects to generate ideas individually and as a team without telling them the top-level functions of the tripod and stapler. In experiment 1-1 shown in **Table 1**, subjects A through C each worked individually to generate cost-reduction ideas for a tripod. Subjects D through F worked in a team of three to generate cost-reduction ideas for a stapler.

Step 3: Idea generation (Experiment 1-2)

We told the subjects that the function of a stapler is to bind pieces of paper together and the function of a tripod to obtain a camera angle. We changed target products, individual members and teams to generate ideas. In experiment 1-2 shown in **Table 1**, subjects A through C worked in a team of three to generate cost-reduction ideas for a stapler. Subjects D through F each worked individually to generate cost-reduction ideas for a tripod. We used different target products in experiments 1-1 and 1-2 to avoid the effects of learning about the products.

Step 4: Forming teams (Changing members)

Step 5: Idea generation (Experiment 2-1)

Step 6: Idea generation (Experiment 2-2)

In steps 4 through 6, we changed target products and subjects and conducted similar operations as in steps 1 through 3. We conducted experiments 2-1 and 2-2 in the same way as experiments 1-1 and 1-2. We changed target products to avoid biasing the relationships between target products and idea generation approaches. Also, to avoid the effects of learning about the products, we replaced subjects A through F with subjects G through L.

3.4 Method for quantitatively evaluating idea generation

The final goal of the design process is to generate an alternative that fulfills the function and cost requirements at the same time. During the interim stages, it is necessary to generate as many diverse ideas as possible. In this study, we evaluated the diversity and number of ideas generated using the following approach.

Figures 5 and **6** show examples of structures of the ideas generated. These figures show that the number of ideas is six in both structures, while the number of categories into which the ideas are classified is two. Although the numbers of ideas and categories are the same in the two structures, the quality of ideas cannot be regarded as being the same in **Figs. 5** and **6**. Suppose, for example, that a team obtained three ideas, "red," "blue" and "yellow," which are all classified into the category "changing the color of bottles," and another team had the three ideas, "changing colors," "changing shapes" and "changing storage places," when generating ideas for creating a function to identify the content of a bottle. Although the number of ideas obtained is three in both cases, the diversity of the three ideas in the latter case can be regarded as greater than in the former.

Therefore, to meet the need of evaluating both the diversity and number of ideas at the same time, we developed equation (1) shown below and used it to evaluate the ideas generated. This equation represents the diversity of ideas by applying the information entropy theory.[11] The equation was formulated by adding the numbers of ideas and categories to the original equation used (by Verhaegen et al.) to evaluate the diversity of ideas.[12] In equation (1), entropy reaches a maximum when the number of ideas in a category is the

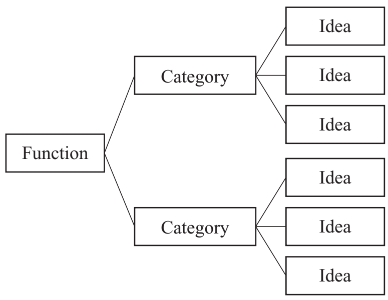

Fig. 5 Example of generated idea structure 1

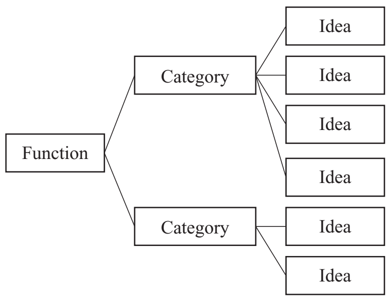

Fig. 6 Example of generated idea structure 2

same for all categories. In this study, when the numbers of ideas differ between categories, we regard categories with smaller numbers of ideas to be capable of generating more ideas. Therefore, entropy does not reach a maximum in such a case. Entropy becomes lower in such a case than when the number of ideas is the same for all categories, reflecting the level of diversity.

$$Q = -N_i N_c \sum_{j=1}^{N_c} p_j \log_{N_c}\left(p_j\right) \cdots\cdots\cdots (1)$$

Q : Quantity of ideas
N_i : Number of ideas developed
N_c : Number of idea categories
p_j : Percentage of ideas in category j relative to N_i

Subjects generate ideas about a function to be improved and obtain N_i ideas. These ideas are classified into N_c categories. **Figure 7** shows ideas generated and their categories. In this example, three ideas were generated for function_1 and these ideas were grouped into two categories. Any difference between numbers of ideas included in different categories causes entropy to become smaller. Therefore, equation (1) can be used to evaluate whether the numbers of ideas generated and their categories are large and whether there is a difference in the number of ideas between different categories, i.e., whether there is any bias in perspectives.

3.5 Evaluation of the quantity of ideas generated

From data on ideas generated in experiments, we calculated the quantity of ideas Q using equation (1) to evaluate it. The quantity of ideas Q was calculated by using the following procedures:

Procedure 1: We classified ideas obtained into categories. **Figure 8** shows the ideas and categories generated for a tripod.

Procedure 2: We substituted the numbers of categories and ideas into equation (1).

4. Results of the experiments

As a result of analyzing data obtained by using mathematical quantification method class 1 (regression analysis with dummy variables), we obtained the following regression equations for the quantity of ideas Q. Dummy variables used in equations (2) and (3) are shown in **Table 2**.

Regression equation for the quantity of ideas for a stapler (coefficient of determination: 0.64)

$$Q_s = 23.97 + 3.45x_1 - 18.98x_2 \cdots\cdots\cdots (2)$$

Regression equation for the quantity of ideas for a tripod (coefficient of determination: 0.27)

$$Q_t = 26.38 - 6.14x_1 - 13.77x_2 \cdots\cdots\cdots (3)$$

The coefficient of determination was 0.64 for the regression model for a stapler and 0.27 for the model for a tripod. The accuracy of the model was low, particularly for tripods. Therefore, we did not use the estimated model for the quantity of ideas for a tripod in this study. This will be considered further in the next section. From the estimated regression model for the quantity of ideas for a stapler, which had a coefficient of determination higher than that of the model for a tripod, we calculated the quantity of ideas accounted for by whether or not functions were presented and by differences between teamwork and individual work. The results of the calculation are shown in **Table 3**. These results lead us to conclude that generating ideas as a team and performing functional analysis can generate more ideas.

5. Consideration

In this study, we obtained two estimated models regarding the quantity of ideas. The coefficient of determination was higher for staplers, which are more complex in system structure, than tripods, which are simpler in system structure.

The functional diagram for a tripod in **Fig. 3** shows a three-layer structure. As functions that serve as means to achieve the top-level function (obtaining a camera angle), we have mounting a camera, obtaining height, giving the camera an angle and obtaining stability. In addition, there are functions required to achieve these functions in the next lower layer. In this case, higher-level functions can be achieved even if individual functions operate independently from each other. In other words, the function of the product as a whole and functions performed directly by parts are close to each other within the hierarchical structure. Therefore, subjects were able to generate ideas by arriving at the top-level function (obtaining an angle) in their thought process or by subconsciously thinking of the function of the product merely by looking at the actual product or its parts, even without prior knowledge of its top-level function. In contrast,

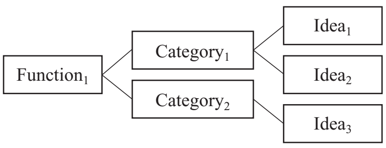

Fig. 7 Example of categories for generated ideas

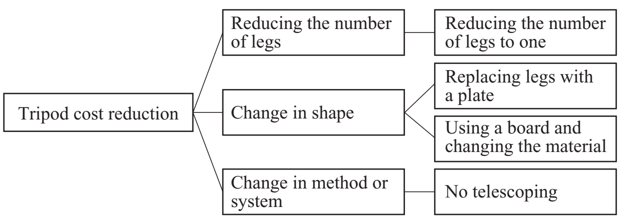

Fig. 8 Example of categories for generated idea (tripod)

Table 2 Dummy variables

x_1: With or without prior knowledge of the main function	x_2: Teamwork
Function told: 1	Yes = 0
Function not told: 0	No = 1

Table 3 Statistical inference of idea quantity Q by regression model

Prior knowledge of the main function	Work composition	Quantity of ideas	Rank
Yes	Teamwork	27.42	1
No	Teamwork	23.97	2
Yes	Individual work	8.44	3
No	Individual work	4.99	4

the functional diagram for a stapler in **Fig. 4** shows a four-layer structure. To obtain the top-level function (binding pieces of paper together), it is necessary to stick a staple through paper and bend the staple. Sticking a staple through the paper requires two different layers of functions. Furthermore, some of the functions need to be coordinated with each other, which involves a large number of parts. This leads us to conclude that, unlike a tripod, the functions of parts and the function of the product as a whole are far apart from each other in this case. Therefore, subjects tend to focus on improving the functions of easily observable parts and have difficulty in developing a perspective for re-examining the system in its entirety if they have no prior knowledge of the function of the system as a whole. In other words, to generate ideas for improving products with a complex structure, teamwork is effective in increasing the diversity of ideas, which is further increased by function-oriented thinking.

6. Challenges for the future

In this study, we did not discuss how functions should be defined or how ideas should be generated. In particular, definition of functions requires experience and skill. Inexperienced designers may slow down operations, causing problems. In the future, we plan to develop methods for definition of functions required to create high-value products in design processes and specific procedures for generating ideas.

7. Conclusion

In this study, we conducted experiments on the development of cost-reduction ideas for a tripod and a stapler. We defined the diversity and number of ideas generated as the quantity of ideas in order to develop a method for quantitative analysis and evaluation. As a result, we obtained estimated regression models regarding the quantity of ideas Q. At the same time, based on quantitative data, we showed the advantage of teamwork and function-oriented thinking in increasing the Q value, thereby confirming what was known through experience.

We also showed that in addition to teamwork, function-oriented thinking is effective in generating ideas in the design of a system with complex structures or functions.

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