A Hierarchical Technology Element Decomposition for Co-design Works

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***Abstract*—This paper introduces a method of technology element decomposition (TED), which can be used for co-design works. The method originated with the Japan Aerospace Exploration Agency (JAXA), and has been used to support product innovation through transfer of space technology, promotion of industry-university collaborations, and so on. Through the MOT Practicum conducted between JAXA and Ritsumeikan University, the method has been adapted for general use. TED consists of three phases. First, a product is conceptually decomposed into hierarchical layers (scenario, purposes, functions and measures), allowing everyone to understand its structural relations at a glance. Second, multiple scenarios (combinations of Who, Where, When, and What) are generated, assuming the product's application to new use contexts. Finally, necessary and unnecessary purposes, functions, and measures are added to or removed from the structure to conceptualize a new product. We conducted workshops to examine the effectiveness of the method for group-oriented product design activities. The method particularly benefits understanding of both the global picture and the product details among nonengineers, which facilitates co-design activities without the need for specialized technical knowledge. We believe the method to be useful for collaborations among technical experts and sales teams as well, promoting innovation through diversified viewpoints.**

I. Introduction

A. Research bacground

In recent years, design thinking has gained attention as a method for developing creative ideas. Design thinking is an approach that seeks to grasp customers' essential requirements through observation and direct experience, to construct hypothetical solutions to satisfy these requirements, and to quickly and repeatedly verify the hypotheses using a simple prototype [1]. Creative idea generation is essential to new product and business development and ultimately innovation [2].

In design thinking, collaboration among individuals from different backgrounds is considered an essential factor for success [3]. However, even when multiple brainstorming sessions with diversified members are held, knowledge gaps among the members sometimes hinders further collaboration at the product conceptualization stage. Technically understanding a specific product is challenging even for engineers, especially those in other technical domains. It is all the more difficult for nonengineers. Thus, simple applications of design thinking cease to progress even if the design team includes supporting engineers. Thus, a method is needed that can facilitate collaboration regardless of technical specialty.

B. Research purpose

The purpose of the present paper is to introduce a method of hierarchical technology element decomposition (TED) that can be used for co-design works. Fig. 1 shows a typical graphic structure used in TED. The method conceptually decomposes a product into scenario, purpose, function, and measure layers. Because purposes of a product may differ according to user context of the product, a scenario is considered using the 4W framework (Who, Where, When, and What). TED result is expected to visualize essential product features and to facilitate better understanding [4]. Thus, we believe that it is an effective method for generating new product ideas, especially in co-design works between engineers and nonengineers, who usually have a low degree of technical knowledge. The proposed method is expected to be a feasible solution to bridge the knowledge gap between collaborators from different technical domains as well.

C. Origin of Technology Element Decompotiion

TED originated with the Japan Aerospace Exploration Agency (JAXA) and has been used to generate and develop new products by transferring space technologies to nonspace sectors. It is also expected to promote industry-university collaborations. The method, which was originally applied by aerospace engineers, has been modified for general-purpose application through the MOT Practicum conducted from 2015 to 2018 between JAXA and Ritsumeikan University [4][5].

Fig. 2 shows an example TED application at JAXA. The organization co-designed a cooling vest in collaboration with private companies by transferring space technology [6]. An extra-vehicle activity (EVA) space suite was decomposed using the method for extracting transferable technologies. For example, the space suit as a system can be decomposed into three sub-systems: an outer protection unit, a pressurized suit, and underwear. The underwear as a system can be further decomposed into several technical sub-systems, one of which is the body temperature control system. Because air circulation is impossible in the space environment, water circulation technology is used to maintain astronauts' body temperature.

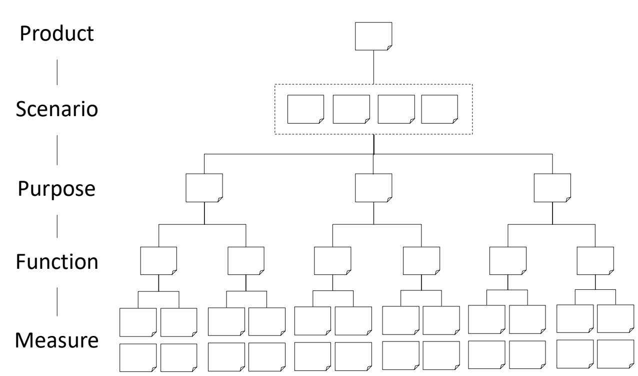

Fig. 1. A typical graphic structure used in TED

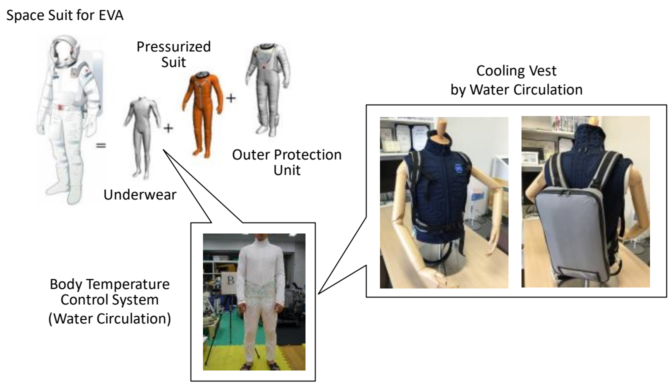

Fig. 2. An example of TED application at JAXA (Created based on [6])

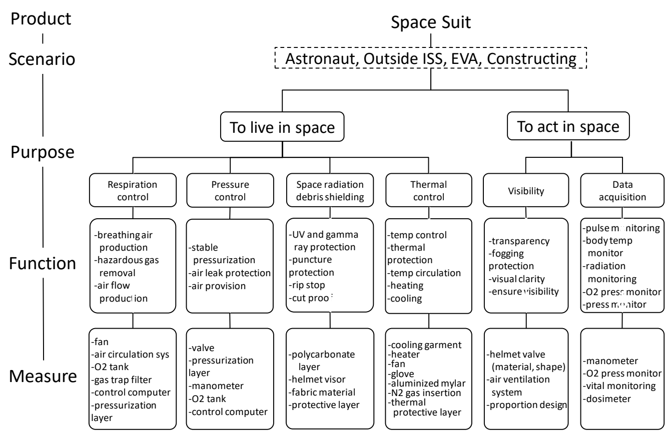

Fig. 3. Technology element decomposition in the exmaple of space suit

Potentially transferable technology is easier to be identified using the TED graphic structure (Fig. 3). Taking advantage of this technical knowledge on how to allocate water circulation tubes around the human body, JAXA and its collaborators developed a cooling vest as a commercial product [7]. Today, it is used in critical working environments, such as firefighting, which like space cannot utilize air circulation for cooling [6].

II. LITERRATURE REVIEW

Decomposition is one of fundamental techniques in sicence. It is often used when an object is too complex to be analyzed individually. We tend to breakdown the whole into its sub-elements for better understanding of the details. Such analytical approach is generally adopted in various academic and practical fields. Decomposition is a key for understanding.

Industrial Engineering (IE) and System Engineering (SE) are typical fields where decomposition is often conducted for product design activities. Several methodologies have been developed such as Logic Tree (LT), Quality Function Deployment (QFD), Value Engineering (VE), Functional Diagram (FD), Facntional Analysis (FA), Function Analysis Systems Technique (FAST) and TRIZ and so on.

Logic Tree is the most common method of decomposition used in business practices. They generally use hierachical graphic structure to decompose a higher-level element into lower-level sub-elements. It is often said that LT results must be mutually exclusive and collectively exhaustive (MECE) to maintain logical correctness of decomposition [8]. While LT can be used for general purpose, TED is targeted especially for co-design work through decompostion of a product.

QFD is a a method to link voices of customer with technical features of a product using a graphical matrix called house of quality. According to Yoji Akao, one of the developers of QFD, the purpose of the mehotd is to assure that “true customer needs are properly deployed throughout the design, build and delivery of a new product” [9]. It is an effective tool for decision-makers and industry managers to understand new products at early products development and planning stages [10]. Although quantification of qualitative customer voices is a key strength of QFD, we think that the matrix operation is too difficult for biginners to understand at grance. Thus, QFD is not likely to be suitable for a co-design work with a mixed group of engineers and nonengieers. TED does not include quantification in its process for simplification.

Value Engineering (VE) is a series of methods for enhancing values of a project analyzing its function and cost relations. It was introduced in the 1960s in construction industry and has been widely used in various fields so as to effectively reduce costs and enhance values for customers [11]. Functional Diagram (FD), Funcitonal Analysis (FA) and Function Analysis Systems Technique (FAST) are common VE methods for anlyzing functions. They generally put the ultimate purpose of a product on the top of diagram and hierachically decomposes its element functions from the viewpoint of purpose-mean relation. Why-How laddering technique is often used in the process [1]. A combinational usage of FA and Causal Loop Diagram (CLD) is also proposed by Delgado-Maciela et al. [12] to model inventive problems. These VE methods have some similarity to TED but they also indicate importance of sytematic decomposition in engieering design acitvities.

Rachwan et al. [13] states that there is significant cost reduction effect by introducing VE techniques, ranging between 20% to 30% percent of the element cost. However, since the primal purpose of VE is to generate feasible alternatives that can balance costs and pricing [14], it is not suitable for co-designing innovative product concepts. It is no doubt that consideration of costs in the early stage of product developement is critical for success [11] but it also likely to hinder creative idea generation. Therefore, TED is intentionally designed to put cost cosideration aside.

TRIZ is the theory of inventive problem solving developed by Genrich Altshuller. It is effective techniques not only for supporting the initial stages of engineering design but also in the domain of business and services [15]. However, since the thoery is complex and requires a volume of knowledges to understand, it is not often used in innovation activities as well as its exploitation has resulted in several unsuccessful experiences [2][16]. Use of TRIZ for concept generation is effective only when “designers master the theory proficiently” [2][15]. Thus, TRIZ is not likely to be suitable for a short workshop conducted in one day or so. TED is a simple process and does not require any preliminary knowledges. Simplicity and easiness to understand are core value of TED.

TABLE I. COMPARIZON OF DECOMPOSITION-RELATED METHODS

	Methodologies				
Advantages	**LT**	**QFD**	**VE**	**TRIZ**	**TED**
Decomposition	X	X	X	X	X
Visualization	X	X	X		X
Understanding	X		X		X
Product Ideas		X	X	X	X
Biz. development			X	X	
Innovation				X	X

Table 1 shows our initial evaluation of those methodologies in terms of decompositon, visualization, understanding, product idea creation, business development and innovatoin. The strength of TED is highligted and effectiveness for group-oriented design activities is examined through a trial workshop in the end.

III. PROCESS OF TECHNOLOGY ELEMENT DECOMPOSITION

The TED method is generally conducted in three phases: decomposition, scenario mixing, and reconfiguration. During phase 1, a product is conceptually decomposed into hierarchical layers (scenario, purposes, functions, and measures), allowing everyone to grasp the structural relations at a glance (Fig. 1). During phase 2, multiple scenarios (combinations of Who, Where, When, and What) are generated, assuming the product's application to new use contexts. The original scenario is replaced with one of the new scenarios to drive product innovation. During phase 3, necessary and unnecessary elements (purposes, functions, and measures) are added to or removed from the original structure to conceptualize a new product. The following example uses a wall clock to demonstrate the process of the method.

A. Phase 1: Decomposition

During phase 1, a product is decomposed through five steps: scenario setting, purpose-level decomposition, function-level decomposition, measure-level decomposition, and integration of the results.

1) Step 1: Scenario Setting

The first step in the decomposition process is scenario setting. It clearly defines the user context of the product using the 4W framework (Who, Where, When, and What). *Who* refers to the typical user of the product, *Where* to the typical location of the product's usage, *When* to the typical circumstances or time of usage, and *What* to the typical activity taken by the user. In the example of a wall clock, we may set a possible scenario of a housewife (Who), a living room (Where), daytime (When), and watching (What). Because TED is a method of hierarchical decomposition, the results are shown visually, as in Fig. 4.

2) Step 2: Purpose-level Decomposition

With the preset scenario in mind, it is then necessary to consider *what the user essentially wants to do with the product*, and to express this in the form of a basic verb (plus a simple noun, if necessary). In the example of the wall clock, we can identify the purpose to "know time", assuming a single-purpose system (Fig. 3). For multi-purpose systems, multiple purposes may be expressed. During step 2, the basic verb identified as the purpose is also be further concretized using modifiers (adjectives or adverbs), considering detailed user requirements with respect to the purpose. Two or more subdivided concretized requirements can be assigned numbers or symbols so that they are easy for third parties to distinguish. In the example of a wall clock, we can identify three subdivided requirements: to know time *correctly*, to know time *everywhere*, and to know time *comfortably*. The results are shown visually as in Fig. 5.

3) Step 3: Function-level Decomposition

Continuing to keep the preset scenario in mind, step 3 decomposes the purpose at the function level.

It is necessary to consider *what the product (or system) must be able to do to meet the purpose*. Functions are ideally described using short descriptors or phrases such as 'being *x*' or 'being able to do *x*'. Technical experts may consider the product's functions from the perspective of engineering (e.g., durability, flexibility, etc.). In the example of a wall clock, we may define the functions for knowing time correctly as time indication, time adjustment, and power supply. The results are shown visually as in Fig. 6.

4) Step 4: Measure-level Decomposition

Continuing to keep the preset scenario in mind, in step 4 functions are decomposed into the concrete measures by which they can be realized. Such measures are expressed in terms of materials, parts, skills, and so on. The relations between functions and measures should be discussed while actually disassembling the product. In the example of a wall clock, we may define the measures necessary to realize the time indication function as the hands, dial, and index. For precise expression, hands can further be decomposed into the hour hand, minute hand, and second hand; or the dial can be decomposed into the board, numbers, and brand logo. The results are shown visually as in Fig.7.

5) Step 5: Integration

To conclude phase 1 of the TED method, all information derived through steps 1 to 4 must be compiled to develop a hierarchical diagram indicating the relations among the purpose-function-measures levels. When reviewing the whole diagram, it is important to consider whether necessary elements are missing or unnecessary elements included. In the example of a wall clock, the final diagram can be organized as in Fig. 8. This provides a clear, systemic understanding of the product's features by identifying its purposes, functions, and measures.

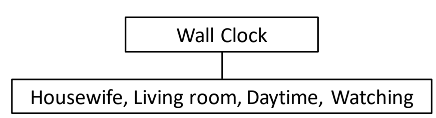

Fig. 4. An example of scenario setting

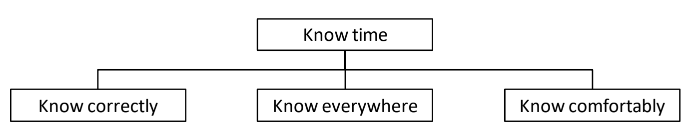

Fig. 5. An example of purpose-level decomposition

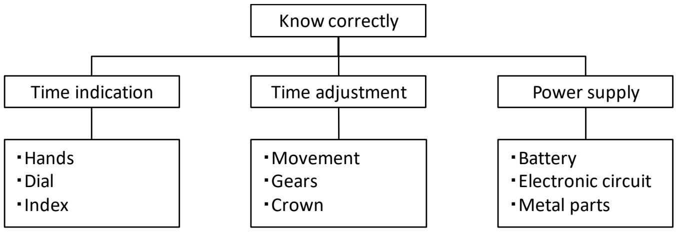

Fig. 6. An example of function-level decomposition

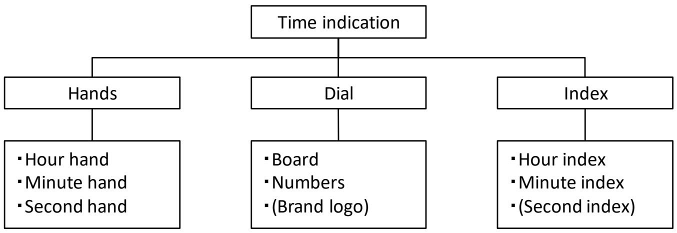

Fig. 7. An example of measure-level decomposition

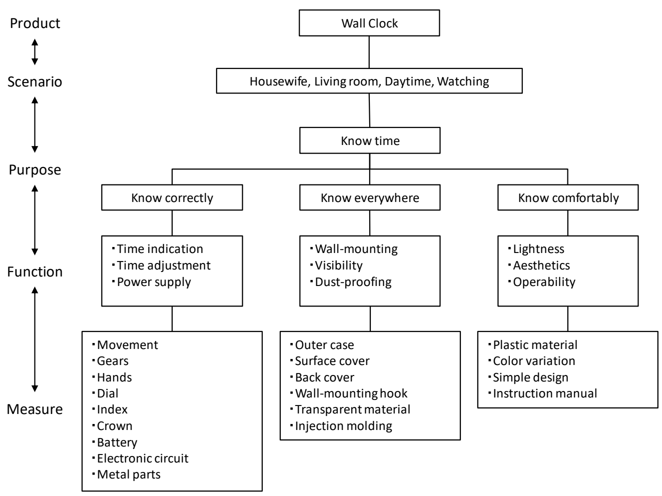

Fig. 8. An example of the technology element decomposition method applied to a wall clock

B. *Phase 2: Scenario Mixing*

The second phase of the TED process is scenario mixing. During this phase, the preset scenario identified in step 1 of phase 1 is replaced with another scenario to facilitate product innovation. As described previously, a scenario is a certain combination of Who, Where, When, and What components that describes the context surrounding the product users. To generate scenarios efficiently, a method called "scenario graphs" is introduced in TED [4][5].

A scenario graph begins with identifying a core function of the product [1]. The core function is placed at the center of the diagram. The second step is to ask who the possible users of the product are. Brainstorming with use of sticky notes can be used to list as many potential users as possible. The third step is to ask where the potential locations for use of the core function might be, and the fourth step is to list the possible activities associated with these locations. The final step is to consider when or under what circumstances the product may be used. This information is mapped out on a diagram, as in Fig. 9, so that possible combinations of the 4W's can be identified. After as many scenarios as possible have been generated, a few of the most innovative are chosen reconfigure the product.

C. *Phase 3: Reconfiguration*

The third phase of the TED process is reconfiguration. The original structure of the product is conceptually renovated based on a new scenario. Several scenarios can be selected from the scenario graph for this purpose.

During the reconfiguration phase, the original preset scenario (Who, Where, When, and What) is replaced with one of the new scenarios to drive product innovation (Fig. 10). Thus, the phase 1 results are used again to reconfigure the original product. The strength of this method is this reuse of phase 1's results. This allows a combined team of engineers and nonengineers to share common knowledge and perspectives on the product, allowing them to promptly initiate realistic discussions [1]. Nonengineers are able to discuss technical functions and measures based on a fundamental understanding. This greatly facilitates co-design works among individuals from diversified backgrounds.

Keeping the new scenario in mind, the original structure is reconsidered to identify necessary and unnecessary elements. Fig. 10 illustrates how the reconfiguration process proceeds. Necessary purposes, functions, and measures can be added to the original structure to reconfigure it into a new product concept. Similarly, unnecessary original purposes, functions, and measures can be removed from the reconfiguration.

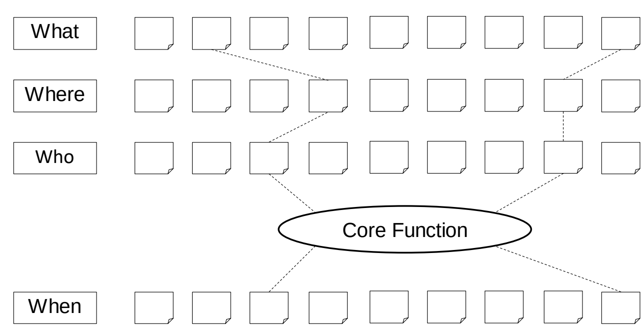

Fig. 9. Scenario graph framework

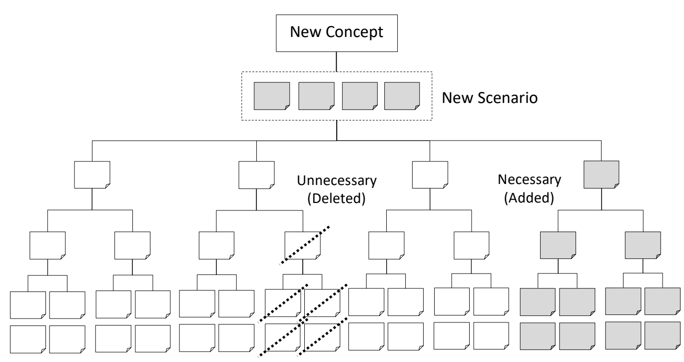

Fig. 10. Adding and removing elements from the original structure during the reconfiguration phase

IV. METHOD IN PRACTICE

Fig. 11. TED method workshop at Panasonic Wonder Lab

The method was examined in practice in cooperation with the largest Japanese electronic appliance manufacturer, Panasonic. A half-day workshop was held in Osaka, Japan, on December 17th, 2017 (Fig. 11), involving 38 participants from different backgrounds, including Panasonic engineers [4]. The group intentionally included a mixture of engineers and nonengineers to examine the effectiveness of the method. The three phases of the TED process were explained at the start of the workshop, after which participants collaboratively decomposed one of Panasonic's products in groups of four or five. One of Panasonic's products, an electric toothbrush Pocket Dlotz (Fig.12) was used for this examination.

A. *Results*

Fig. 13 shows an application result to the electric toothbrush provided in the workshop. During phase 1 (decomposition), the scenario was set as ladies (who), office (where), after lunch (when), and brushing (what). After analyzing the product's essential user requirements, the purpose was defined broadly as "to brush teeth" and more specifically as to brush teeth quietly, to brush teeth longer, to brush teeth quickly, and to brush teeth fashionably. The need for a fashionable appearance is derived from the main users of the preset scenario, namely ladies. Because it is meant to be used at the office after lunch, operation must be quiet and quick. The longer duration of time refers to the durability of the product and its ability to brush longer in daily use.

To brush quietly, it is necessary for the product to be soundproofed and to incorporate a motor with a soft sound. To brush longer in in daily use, the product must be easy to hold, or the user may tire; for longer durability, the product must be waterproof and allow the brush head to be exchanged when it wears out. To brush quickly, the product must turn on instantly and feature strong vibration, which can reduce brushing time. To brush fashionably, considering that its main users are ladies, the product should have a feminine appearance and bright coloring. Concrete measures were identified through decomposition of the physical electric toothbrush product into pieces (Fig. 14). The results were integrated into a single diagram, as shown in Fig. 13.

During phase 2 (scenario mixing), the preset scenario was replaced by a new scenario selected from the scenario graph results: housewives (who), kitchen (where), cooking (when), and cleaning (what). During phase 3 (reconfiguration), necessary and unnecessary elements of the product were reconsidered in light of the new scenario. The main purpose of the product was changed from brushing teeth to brushing vegetables, since it was meant to be used in kitchen to remove chemicals from food. Because it is meant to be used inside the home (in the kitchen), the purpose of brushing fashionably can be removed as unnecessary. In contrast, the new purpose of brushing any shape object is necessary, because individual vegetables are not consistent in shape and the brush must be able to accommodate a variety of vegetables. Therefore, the brush interface must be flexible enough to brush vegetables of any shape. To realize this flexible function, the new product must have flexible material, a wide brush surface, and an extended brush head and grip. Fig. 15 shows the new brush product concept and its configuration. An electric toothbrush is transformed into a new vegetable washer concept product, taking advantage of the original product's structure.

Fig. 12. An electric toothbrush (image source: Panasonic)[17]

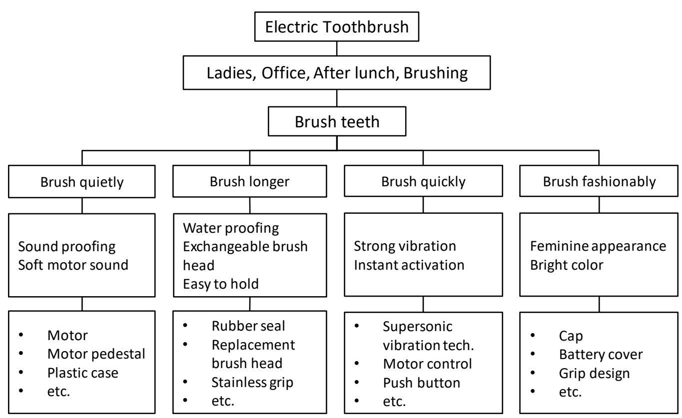

Fig. 13. Original decomposition results for an electric toothbrush

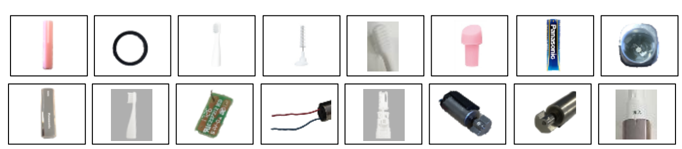

Fig. 14. Decomposition of physical product (Panasonic electric toothbrush)[8]

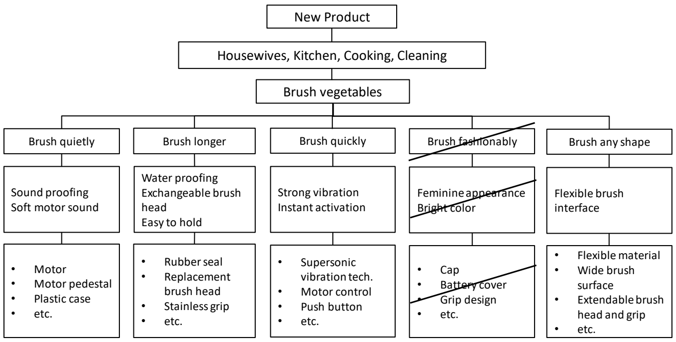

Fig. 15. Reconfigurated diagram for new product based on an electric toothbrush

B. *Evaluation and Discussion*

An anonymous questionnaire was conducted after the workshop, evaluating the following questions using a 5-point Likert scale (5: *Strongly agree*, 4: *Agree*, 3: *Neither agree nor disagree*, 2: *Disagree*, 1: *Strongly disagree*):

- Q1: Is the method effective for decomposing a product?
- Q2: Is the method effective for visualizing a product?
- Q3: Is the method effective for third parties to understand a product?
- Q4: Is the method effective for creating new ideas about a product?
- Q5: Is the method effective for thinking about new businesses for a product?
- Q6: Is the method effective for innovating based on a product?

Table 2 shows the results of the questionnaire. All 38 of the participants in the workshop responded to the questionnaire, for an effective response rate of 100%. As an overall trend, scores were relatively high for Q1 (decomposition), Q2 (visualization), and Q3 (understanding), but decreased for Q5 (business development) and Q6 (innovation).

These results indicate that the method is very effective for decomposing and visualizing a product. It is consistent with our previous demonstration results [5]. Moreover, the workshop participants felt that the systematic visualization of the method was useful for helping third parties to understand even unfamiliar technical products. The method is thus expected to be useful for co-design works among individuals from different backgrounds. In the workshop, most groups included a mixture of engineers and nonengineers.

However, the participants felt that the method was relatively less effective for developing new business (Q5) and innovation (Q6). It is expected that a half-day workshop was too short to generate innovative ideas for new business; however, the results imply that the method requires more improvement in terms of business development application. Notably, the total standard deviation of Q5 and Q6 was higher than that of Q1 through Q4. This implies that with respect to Q5 and Q6, some participants thought highly of the method, whereas others did not. In addition to extending the workshop time, more study is necessary to make a conclusion regarding the effectiveness of the method for new business and innovation.

V. CONCLUSIONS

The present study introduced a technology element decomposition (TED) method applied to co-design works and conducted a workshop at Panasonic to examine the effectiveness of the method for group-oriented design activities. Since most of TED applications have been written in Japanese so far, we expect that the present paper help readers worldwide apply the method to their own domains.

Through the workshop, the method was found to be effective, especially in allowing third parties to understand a product's technical features. After the three-phase approach was introduced, workshop participants were able to identify transferable technology elements of the product during the first stage. This contributed to the development of new product concepts among groups with diversified members. The method particularly benefits nonengineers in understanding both the global picture and the details of a product, facilitating co-design activities without the need for specialized technical knowledge. We believe the method is useful for collaboration among technical experts and sales teams, promoting innovation based on diversified perspectives.

A limitation of this research is highlighted by a suggestion we received that although the method is effective for conceptually renovating an existing product, much more must be done to achieve product commercialization in the market. For more practical use in business, the method should be integrated with business model generation considering the products in potential markets. Future workshops will determine the effectiveness of the method for business development purposes as well as product innovation.

TABLE II. QUESTIONNAIRE RESULTS

Age		**Question**					
		Q1	***Q2***	***Q3***	***Q4***	***Q5***	***Q6***
20s (n=8)	**Ave.**	4.50	4.75	4.63	3.88	4.13	4.13
	SD	0.50	0.43	0.48	0.78	0.60	0.93
30s (n=12)	**Ave.**	4.25	4.58	4.33	4.42	4.08	3.92
	SD	0.43	0.49	0.47	0.64	0.64	0.28
40s (n=11)	**Ave.**	4.27	4.73	4.73	4.09	3.64	3.64
	SD	0.62	0.45	0.45	0.67	0.48	0.64
50s (n=7)	**Ave.**	4.14	4.29	4.43	4.00	4.14	4.00
	SD	0.35	0.45	0.49	0.53	0.99	0.93
Total (n=38)	**Ave.**	4.29	4.61	4.53	4.13	3.97	3.89
	SD	0.51	0.49	0.50	0.69	0.71	0.72

Acknowledgment

We thank the Japan Aerospace Exploration Agency (JAXA) for co-developing technology element decomposition method for general-purpose applications. We also thank Panasonic for providing the opportunity to conduct an experimental workshop utilizing the method. The first report on the workshop was presented at the Japan MOT Society conference in March 2018 [4], Yamaguchi University, Japan. We are very thankful to the valuable feedback received from the audience.

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