PROPOSAL OF CLUSTER ANALYSIS METHOD FOR PRODUCTS CONSIDERING EXPLORATION AND EXPLOITATION IN ENGINEERING DESIGN

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ABSTRACT

It is important for organizations to balance exploration and exploitation in order to respond quickly and sustainably to the needs of society and users in a rapidly changing business environment. However, there is insufficient research on design methods to balance exploration and exploitation in product design, and a method to objectively identify the product groups to be balanced has not yet been established. In this paper, on the basis of the characteristics of exploration and exploitation in design, a cluster analysis using functional and attribute distances between products is proposed. To validate the proposed method, it was applied to past product cases in which the relationship between exploration and exploitation was known. The results showed that in the cases of cameras, in addition to known product groups forming large clusters, reasonable minor classifications that had not been identified were also obtained. This indicates that the proposed method is capable of analyzing reasonable clusters in the cases and is potentially effective in identifying product groups taking into consideration the relationship between exploration and exploitation.

Keywords: Exploration and exploitation, Design methods, New product development, Innovation, Semantic data processing

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1 INTRODUCTION

1.1 Exploration and exploitation in design

It is an important challenge for companies and organizations to respond quickly to rapidly changing business environments to generate sustainable profits. In response to this situation, the field of business administration has focused on organizational ambidexterity (O'Reilly and Tushman, 2019), which is an organization's ability to balance exploration and exploitation. Exploration and exploitation are different organizational activities. Exploration is the act of expanding cognition far beyond the scope of one's own organization's existing cognition, while exploitation is the act of continuously diving deep into and refining one's own organization's knowledge in a certain field. They have different characteristics, and exploration enables the development of new business areas despite high costs and uncertainty of success, whereas exploitation makes it difficult to develop new business areas but provides stable profits. However, it has been reported that organizations, especially mature companies, are prone to a "success trap" in which their activities are biased toward exploitation, and they cannot adapt to changes in the business environment (O'Reilly and Tushman, 2019).

The discussion of exploration and exploitation can be found in not only business administration but also the fields of evolutionary algorithms (Črepinšek et al., 2013) and biological sciences (Cohen et al., 2007), and it is considered important to balance exploration and exploitation in product design. This is because it is considered possible to respond quickly and sustainably to changes in the demands of users and society by balancing exploitation and exploration. The early stages of product design often involve balancing digging deep into one's own knowledge to design better products as an extension of existing products and achieving new functions or user experiences beyond one's own cognitive scope. This is structured as a discussion of exploration and exploitation that balances two different policies under conditions of variability and uncertainty. Figure 1 shows examples of the exploration and exploitation of cameras and TVs. In these examples, various factors can cause a product to succeed or fail, and it is difficult to predict in advance whether a product will be more successful in exploration or exploitation. However, it is important to balance exploration and exploitation in product design in both cases because doing so allows organizations to respond quickly and sustainably to changes in uncertain future needs.

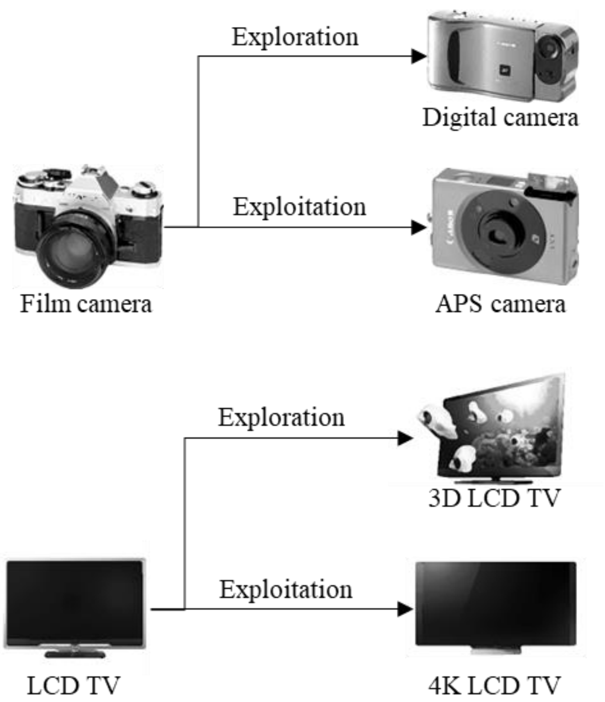

Figure 1. Exploration and exploitation in product design. Cameras (top) and TVs (bottom) as examples. APS, Advanced photo system; LCD, Liquid crystal display.

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1.2 Previous studies and the purpose of this study

Analyzing whether a product design is an exploration or exploitation, as well as directions and magnitudes of exploration and exploitation, is an important issue. However, most of the previous studies in business administration are concerned with organizational learning and leadership (O'Reilly and Tushman, 2013; Petro et al., 2019; Chakma et al., 2021), and technical discussion based on information about the design object is insufficient. On the other hand, design methods for managing product variety and flexibility have been studied in design engineering (El Maraghy et al., 2013; Saleh et al., 2009), but no design method that balances different design policies of exploration and exploitation has been established to meet uncertain future needs. In addition, there are studies on cluster analysis for product family design and the evaluation of design novelty and creativity (Jiao et al., 2007; Sarkar and Chakrabarti, 2011), but studies from the viewpoint of balancing exploration and exploitation are insufficient.

Against this background, in this study, we address design methods and their applications for achieving exploration and exploitation in product design. In actual product design, there are various types of exploration and exploitation, so when discussing them from the product design perspective, it is necessary to define multiple product groups to be discussed. This is because evaluating how other product groups have changed relative to one product group is necessary, which is the basis for comparison. In the case of the camera example described in the previous section, the film camera as a reference and the advanced photo system (APS) camera and digital camera as objects of relative comparison are necessary to discuss exploration and exploitation.

In the analysis of past cases, the classification of products is already known, so the relationship between exploration and exploitation can be discussed in terms of that product group. However, when analyzing current and unknown cases to support exploration and exploitation, the basis and objects for comparison are not clear in advance. Therefore, it is necessary to identify three or more product groups from the entire target product regarding exploration and exploitation as a prerequisite to enable the discussion of exploration and exploitation.

We previously reported on the definitions of exploration and exploitation in design and their quantitative evaluation based on past product cases (Okamoto and Murakami, 2022), but we have yet to identify clusters of current and unknown products. Therefore, this study aims to develop a product cluster analysis method that considers the relationship between exploration and exploitation based on design documents. This paper reports a clustering method based on functional and attribute distances between products and the validation results by applying the proposed method to past product cases.

The method proposed in this paper will enable organizations to discuss exploration and exploitation with respect to appropriate product groups even when the relationship between them is unclear, and the product groups to be evaluated are not known in advance. If this method is used in the actual design, organizations such as design companies or engineering departments in manufacturers would be able to discuss the relationship between the exploration and exploitation of new design plans while referring to the current and previous designs. The method is also expected to assist organizations in achieving both exploration and exploitation.

2 DEFINITIONS AND CHARACTERISTICS OF EXPLORATION AND EXPLOITATION IN DESIGN

In business administration, the kinds of organizational activities included in exploration and exploitation have been determined (March, 1991). In this study, however, we define exploration and exploitation in design by focusing on how design objects have changed due to organizational activities rather than the activities themselves to provide a more objective and quantitative classification. Here, exploration is defined as "design with qualitative change", and exploitation is defined as "design with quantitative change", based on the idea that exploration of a design organization tends to bring qualitative change to the product and exploitation tends to bring quantitative change to the product. One example of an ambidextrous organization is the photographic film manufacturer (O'Reilly and Tushman, 2019), where exploitation of existing photographic film led to the design of quantitatively improved APS film, and exploration led to the design of qualitatively different imaging systems and even pharmaceutical and cosmetic products. This definition is not a discrete classification of exploration and exploitation using absolute criteria but a basic concept for the relative positioning of multiple products based on continuous indicators.

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Furthermore, on the basis of these definitions, the characteristics of exploration and exploitation in design are organized from the perspective of general design theory (Tomiyama and Yoshikawa, 1985). In general design theory, a feature refers to a utility, property, or similar entity stored under an entity such as a product. It includes concepts related to the functions and attributes of entities. Here, the functions of an entity are peculiar behavior that manifests correspondent to a circumstance when the entity is exposed to the circumstance. Attributes of an entity are properties that can be observed by scientific means (Tomiyama and Yoshikawa, 1985). Both of them can be expressed by a combination of items and values. For example, "auto-focus function: available" and "number of pixels: 20 megapixels" for a camera represent a function and attribute of the camera, respectively. The way of expressing a value of a feature differs depending on the item. Still, the presence or absence of an item and qualitative expressions are generally used for functions. In contrast, a range of values and quantitative expressions are used for attributes in many cases. In this study, we focus on this point and discuss exploration and exploitation by associating exploration, that is, qualitative changes in design, with changes in words that represent items of functions, and exploitation, that is, quantitative changes in design, with changes in numerical values that represent the values of attributes.

We conclude this chapter by discussing the dimensional nature of exploration and exploitation. Although balancing exploration and exploitation requires a design considering resource allocation and physical constraints, the relationship between exploration and exploitation is inherently independent. This is because in actual product design, not only the design of exploration and design of exploitation but also design that is both exploration and exploitation and design that is neither exploration nor exploitation is conceivable. This can be illustrated by the example of the disk drive cited in the innovator's dilemma (Christensen, 2001). The sustaining and incremental innovation of the large disk drive is exploitation, as the functions remain the same, but the attribute values have improved. Disruptive innovation from large to small disk drives can be described as exploration since the required functions have essentially changed, and the attribute items and values have changed accordingly. On the other hand, the sustaining and radical innovation of large disk drives can be considered a design of exploration and exploitation, as the technology to achieve the functions is changed while the attribute values are improved simultaneously. Furthermore, the product design that makes superficial revisions for marketing and other reasons, with no essential change in functions or attributes, can be considered neither exploration nor exploitation. These examples show a certain independence between exploration and exploitation, which can be considered dimensional concepts. Considering these properties, this study quantitatively evaluates the degree of exploration and exploitation using different metrics.

3 PRODUCT CLUSTER ANALYSIS CONSIDERING EXPLORATION AND EXPLOITATION

3.1 Overview of cluster analysis

On the basis of the characteristics of exploration and exploitation in design, in this chapter, we propose a method of cluster analysis of products focusing on words that represent functions and numerical values that represent attributes. This study performs the cluster analysis of products considering exploration and exploitation by the following procedure (Figure 2).

First, product data to be analyzed should be collected in preparation for the analysis. Although there is no specification of the type or format of design documents to be used in this method, the design documents to be selected must include information on functions and attributes. This is because the distance between product groups used in cluster analysis is derived from words representing functions and numerical values representing attributes. For example, in the validation of the proposed method described in the next chapter, information on functions was obtained from product descriptions, and information on attributes was obtained from product specification tables.

Cluster analysis based on the functional distances of products is then performed. Here, set, which is a set of words representing functions, is extracted from the collected product data based on grammatical features. Furthermore, the words are converted into vectors by word embedding, and the functional distances between products are defined to obtain clusters C_f. Cluster analysis based on functional distances between products is detailed in Section 3.2.

Cluster analysis based on product attribute distances is then performed. Here, numerical values representing the attributes are extracted from the collected product data to obtain vectors of attribute

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values $\boldsymbol{v}$ for each product. Then, after processing missing values and standardizing the data, the attribute distances between products are defined, and cluster C_a is obtained. Cluster analysis based on product attribute distances is described in detail in Section 3.3.

Finally, the cluster analysis results based on the functional and attribute distances of the products are integrated to identify product clusters that consider exploration and exploitation. The integration of clusters is detailed in Section 3.4.

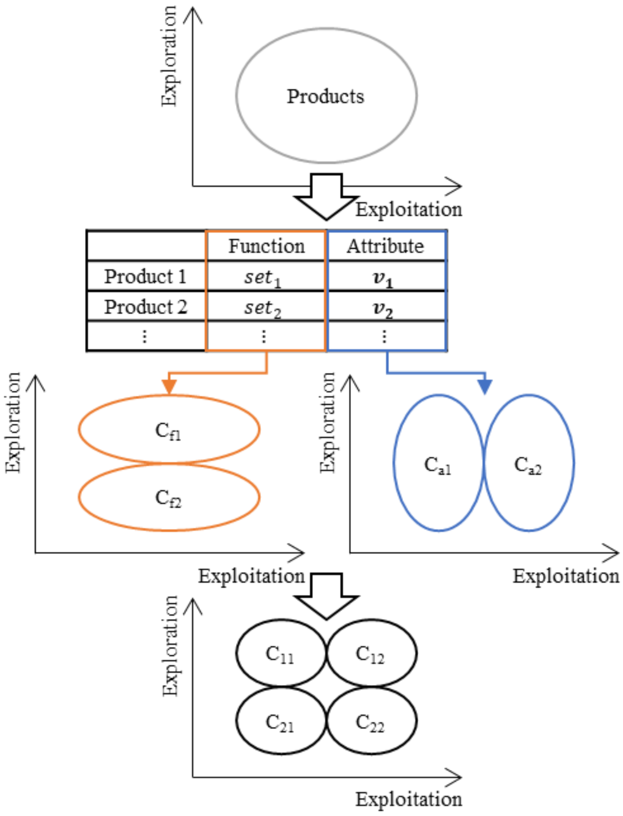

Figure 2. Overview of cluster analysis of products considering exploration and exploitation

3.2 Cluster analysis based on functional distances of products

In cluster analysis based on the functional distance of a product, words representing functions are first extracted from the collected product data on the basis of grammatical features. Although a function can usually be expressed as a combination of a noun and a verb (Pahl and Beitz, 1996), design documents written in natural language use various grammatical expressions. For this reason, in this study, we apply extraction rules that focus on the parts of speech and the dependence of words that describe actions to extract various expressions that describe functions in design documents comprehensively. Specifically, morphological analysis is performed on the design documents to search for words whose part of speech is either a verb, a noun with a verbal root, or a suffix that makes a word root into a verb or a noun with a verbal root. Although words that describe actions are basically verbs, non-verbs are also searched since sentences contain words other than verbs that semantically describe actions. Next, we perform a dependency parsing on the design documents to extract clauses, phrases, and compound words that include the searched words. In this way, sets of words that describe the functions of each product can be obtained.

Second, vectorization of words by word embedding and exclusion of unnecessary descriptions are performed because the words extracted on the basis of grammatical features contain similar expressions and are redundant as sets of words that describe product functions. Here, vectors of clauses or phrases are obtained by vectorizing each word that constitutes the extracted clauses or phrases by word embedding (Mikolov et al., 2013) and taking the sum of the vectors. Hierarchical clustering is then performed by the Ward method (Ward, 1963) using the cosine distance between the vectors to exclude redundant descriptions in the same cluster. For details of language processing methods, such as extracting words that represent functions based on morphological analysis and dependency parsing and

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excluding redundant descriptions by clustering words, please refer to the previous works (Okamoto and Murakami, 2022).
Finally, functional distances between products are defined, and clustering is performed. In this method, functional distances between products are defined as the semantic distances between sets of words that describe the functions of the products. Although the Jaccard or Dice coefficient is commonly used for the similarity of word sets, these indices calculate the similarity from the ratio of words that strictly match two sets and do not consider semantic similarity. This method uses the following equation to evaluate the distance between word sets to consider semantic similarity.

$$d(set_A, set_B) = 1 - \frac{\sum_{i=1}^{n_A} \max_j\left(sim(\boldsymbol{w_{Ai}}, \boldsymbol{w_{Bj}})\right) + \sum_{j=1}^{n_B} \max_i\left(sim(\boldsymbol{w_{Ai}}, \boldsymbol{w_{Bj}})\right)}{n_A + n_B} \tag{1}$$

In this equation, the distance between set_A of word vectors $\boldsymbol{w_{Ai}}$ $(i = 1 \cdots n_A)$ that describe the function of product A and set_B of word vectors $\boldsymbol{w_{Bj}}$ $(j = 1 \cdots n_B)$ that describe the function of product B is calculated using the cosine similarity $sim(\boldsymbol{w_{Ai}}, \boldsymbol{w_{Bj}})$ of the word vectors. This distance takes values ranging from 0 to 2, depending on the semantic similarity between the two sets of words. It takes the value 0 when all elements of the two sets are the same and 2 when the sets are semantically completely different and consist only of inverse vectors. Using this distance function, we perform hierarchical clustering by the Ward method (Ward, 1963) to identify clusters based on the functional distance of the products. The designer can determine the threshold for dividing the clusters after checking the dendrogram obtained from the analysis.

3.3 Cluster analysis based on product attribute distances

In cluster analysis based on product attribute distances, numerical values representing attributes are first extracted from the collected product data, and vectors of attribute values are obtained for each product. Here, on the basis of the concept of "metrization of attribute space" in general design theory (Tomiyama and Yoshikawa, 1985), a combination of attribute values of a product is considered as a point in the space defined by attribute item axes. For example, a product with the attributes "power consumption, 3W; volume, 150mm^3; weight, 0.2kg" is treated as a point (3, 150, 0.2) in a three-dimensional space defined by the power consumption–volume–weight axes.
Next, missing value processing and normalization of the data are performed. Although the items of the acquired attribute vectors may differ among products, this analysis uses the items that all target products have in common since it is difficult to specify values for attributes that a product does not inherently have. For example, it is inappropriate to consider items such as the number of pixels for a film camera. In addition, missing values that exist after the items are aligned are complemented by the average value of all products. Furthermore, since the range of values taken by each attribute item differs, the attribute values are standardized so that the mean of each item has a zero variance of 1.
Finally, the attribute distances between products are defined, and clustering is performed. In this method, the distances between two products are defined as the Euclidean distances between the n-dimensional vector $\boldsymbol{v_A}$ representing the attributes of product A and vector $\boldsymbol{v_B}$ representing the attributes of product B, as in below.

$$d(\boldsymbol{v_A}, \boldsymbol{v_B}) = \sqrt{\sum_{i=1}^{n} (v_{Ai} - v_{Bi})^2} \tag{2}$$

This distance is used to perform hierarchical clustering by the Ward method (Ward, 1963). Here, the threshold for dividing the clusters can be determined after the designer checks the dendrogram obtained from the analysis. Through these processes, cluster analysis based on the attribute distances of the products is performed.

3.4 Integration of clusters

The procedures described in the previous sections yield clusters based on functional and attribute distances of products. By integrating these two cluster analysis results, our method identifies product groups considering the similarity of function and similarity of attributes, namely, exploration and exploitation. Specifically, new subdivided clusters are defined by combining classification based on functional distances and classification based on attribute distances, and each product is reclassified. For example, a product in cluster C_{a1} based on attribute distances and in cluster C_{f2} based on functional distances is classified into a new cluster C_{12} (Table 1). By integrating the results of the two

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cluster analyses, we can retain product groups with similar functions and attributes while identifying product groups with similar functions but different attributes and product groups with similar attributes but different functions.

Table 1. Example of defining new clusters by integrating two clusters

		Clusters based on function distance	
		C_{f1}	C_{f2}
Clusters based on attribute distance	C_{a1}	C_{11}	C_{12}
	C_{a2}	C_{21}	C_{22}

4 VALIDATION OF THE PROPOSED METHOD

4.1 Validation method

To validate this cluster analysis for products considering exploration and exploitation as described in the previous chapter, it was applied to product descriptions and product specification tables of past products for which the relationship between exploration and exploitation has been clarified. Here, the method was validated by comparing the results of cluster analysis with the product groups that were previously identified. This validation analyzes information on products with distinct product groups using documents obtained from a single manufacturer. Therefore, it is not possible to validate the impact of differences in descriptions among manufacturers on cluster analysis or the impact of intermediate and difficult-to-classify products such as a digiana clock or a vacuum cleaner that can also be handy. However, it allows us to validate whether the method is inherently capable of identifying product clusters in terms of exploration and exploitation.

Specifically, compact cameras using 35mm film (basis), digital cameras (exploration), and APS cameras (exploitation) were selected as target products for this validation, which included 21 products released between 1991 and 1995, 13 products released between 1996 and 2000, and 13 products released during the same period, respectively. Information on the functions and attributes of these products was obtained from the manufacturers' product pages (Canon Inc., 2022). Ginza (Megagon Labs, 2022) was used for morphological analysis and dependency parsing, and word2vec (Mikolov et al., 2013) (Japanese model: chive (Works Applications, 2022)) was used for word vectorization by word embedding.

4.2 Results of cluster analysis and discussions

Morphological analysis of the target product description yielded 5904 words. In addition, 869 words were obtained by automatically extracting words that describe functions but were reduced to 728 words by excluding redundant expressions. The extraction of attribute values yielded 13 items common to all products. Using these data, we conducted cluster analyses to define the thresholds for cluster division, and as a result, four clusters based on functional distances and five clusters based on attribute distances were identified, as shown in the dendrogram in Figure 3. Furthermore, the results of the two cluster analyses in Figure 3 were integrated, and the numbers of products belonging to the newly defined integrated clusters are shown in Table 2.

Although clustering is an unsupervised classification method, we evaluated the proposed method by creating a confusion matrix for multiclass classification by comparing the results with the previously known product groups (Table 3). Here, products belonging to cluster C_{ai} $(i = 1 \cdots 5)$and cluster C_{fj} $(j = 1 \cdots 4)$ in Table 2 were classified as belonging to cluster C_{ij}. As shown in Table 3, the previously known product groups, such as C_{12} mainly for digital cameras, C_{44} mainly for APS cameras, and C_{51} mainly for film cameras, form large clusters, and were generally classified as intended. The results were also reasonable for the false-negative products in Table 3 that were classified differently from the previously known classifications. For example, cluster C_{22} included three products in the early stage of digital camera release that had different attributes, such as larger dimensions owing to the use of dry cell batteries than other digital cameras. In addition, clusters C_{31} and C_{33} included film cameras with a unique cylindrical appearance, whose depth dimensions and weight differed significantly from those of other film cameras. Furthermore, cluster C_{43} comprised a limited-edition product whose descriptions of functions differed from those of ordinary products, such as "apply produce sense luxury". Thus, even for the false-negative products, the results were reasonable when the product data were reviewed.

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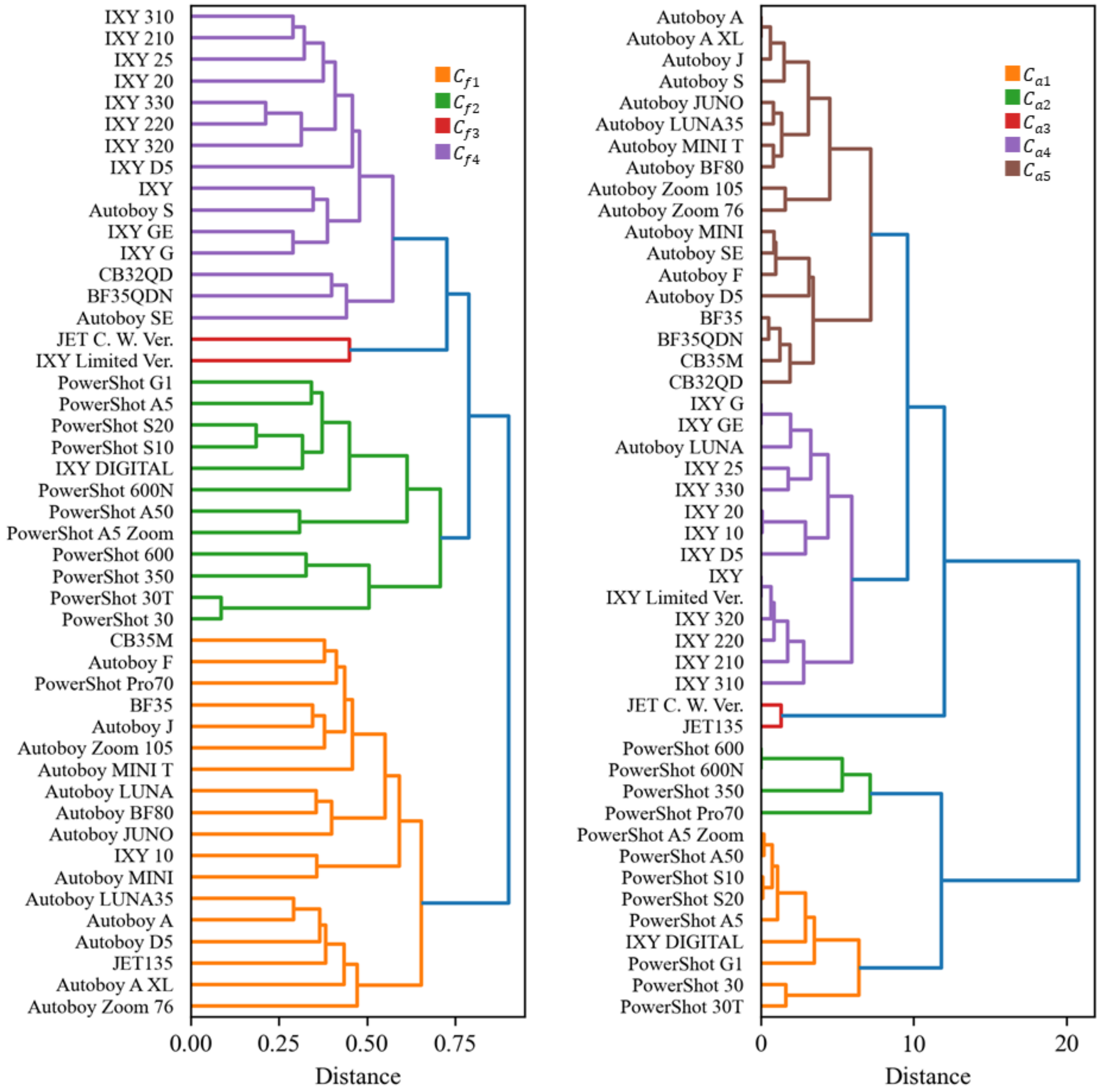

Figure 3. Dendrograms based on function distance (left) and attribute distance (right)

Table 2. Numbers of products classified into newly defined integrated clusters

	C_{f1}	C_{f2}	C_{f3}	C_{f4}
C_{a1}	0	9	0	0
C_{a2}	1	3	0	0
C_{a3}	1	0	1	0
C_{a4}	2	0	1	11
C_{a5}	14	0	0	4

Table 3. Confusion matrix for multiclass product classification

	C_{12}	C_{21}	C_{22}	C_{31}	C_{33}	C_{41}	C_{43}	C_{44}	C_{51}	C_{54}
Film camera	0	0	0	1	1	1	0	0	14	4
APS camera	0	0	0	0	0	1	1	11	0	0
Digital camera	9	1	3	0	0	0	0	0	0	0

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In addition to being consistent with the classification of exploration and exploitation of film cameras, digital cameras, and APS cameras, the results of this cluster analysis indicated reasonable minor classifications that were not previously identified. Therefore, the product cluster analysis method is valid for these product cases, indicating that it may be effective for identifying product groups considering exploration and exploitation.

On the other hand, we discuss the expected limitations of the method, which were not clarified in this validation, from the viewpoint of the input data to the method. Since this method is intended to organize product groups to be designed from the perspective of exploration and exploitation and to support decisions in the early stages of design, it is assumed that the input data will have various problems when used in actual design. For example, there may be cases where the quantity of descriptions or the number of products is not sufficient because of the early stage of the design process. In this case, although the analysis will yield certain conclusions, the accuracy of the evaluation may decrease if the number of function words or attribute items is small, and statistical validity may not be ensured if the number of products is small. It is also assumed that the variance of the distance between products may vary greatly among product groups. In this case, it is possible to deal with this to some extent by setting clustering thresholds, but it may not be possible to deal with the case where the variation is extremely different from one product group to another. Furthermore, in the case of incomplete design documents containing a lot of erroneous or missing information, the unsupervised method may not perform an adequate cluster analysis. In either case, our future work will include testing the limitations of this cluster analysis method by applying it to other new or unknown products.

In addition, some issues can be anticipated when this method is practically used in a company. This method analyzes whether the direction of product design and development is exploration or exploitation, and thus the subject is a technical discussion rather than a business or organizational discussion. On the other hand, while the actual design in a company would involve innovation management, including technical and organizational perspectives, the exploration and exploitation decisions may be affected by, for example, a conflict between product development and enterprise needs. Under such a decision-making influenced situation, since the selection of input data and the setting of clustering thresholds are determined by the designer's judgment in this method, it is undeniable that the designer's intentional determination of input data and thresholds may affect the clustering results. Therefore, prospects include standardization of input data and threshold determination methods to ensure fair and effective use of this method. Finally, the direction and magnitude of exploration and exploitation for appropriately clustered product groups will be evaluated.

5 CONCLUSION

In this study, we proposed a cluster analysis method of using functional and attribute distances of products based on the characteristics of exploration and exploitation in design. The proposed method was validated by applying it to past product cases. The validation results showed that the film camera, digital camera, and APS camera product groups, for which the relationship between exploration and exploitation was known in advance, formed large clusters and reasonable minor classifications that were not previously revealed. This indicates that the proposed method can evaluate the functional and attribute distances of the products and analyze the reasonable clusters for these product cases and that the method appears to be potentially effective in identifying the product groups considering the exploration and exploitation relationship. In future works, expanding the target of validation to new other products, developing how the method is used in the actual design, and evaluating the direction and magnitude of exploration and exploitation of clustered product groups will be addressed.

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