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A IMPROVEMENT METHOD OF CONCEPTUAL DESIGN IDEAS USING DATA ENVELOPMENT ANALYSIS

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ABSTRACT
The designers often are required to derive ideas of the products satisfying requirements of users and market. To accomplish to derive good design, it is important to have much information for previous designs and collaborate with the other designers. At an early stage of design process, several designers have to derive ideas considering its evaluation in cooperation. In this stage, some existing methods to support thinking processes among several persons are useful. However, it is difficult to give a direction for discussion because a reasonable evaluation of ideas is difficult and it is also difficult for the evaluation to be accepted by the other designers. In this study, we propose a method to support generating various and effective ideas in conceptual design process. The ideas are mathematically defined to have factors of evaluation and features and numerically treated in these factors space. Data Envelopment Analysis (DEA) is applied for ideas having many factors of evaluation to derive reasonably a scalar value for evaluation result. DEA gives us a segment of many ideas and from this segment we can discuss a new idea. To support deriving a new idea, we have identified nonlinear mathematical model between factors of evaluation and features and optimization method was applied for the identified model. The proposed method is applied for the experiment and we could confirm the effectiveness of the proposed method.

Keywords: Conceptual Design Support, Data Envelopment Analysis, Visualization of Ideas

1. INTRODUCTION
At an early stage of design process, it is required to discuss many ideas derived from design requirements using designer's knowledge and experiences. Especially, at conceptual design stage, many designers often discuss together about design problem and discuss ideas considering its effectiveness. However, according to increasing the complexity of the functions of products and variety of consumer's needs and market in recent years, it becomes difficult for designers to discuss about ideas by only conversations and figures. Then it is important to support designers giving a reasonable evaluation and segment of ideas. The evaluation and segment are useful to determine a direction of a new idea. The evaluation gives us a superiority or inferiority of an idea for the other ideas. The segment gives us a limitation of complicated requirements for design to be considered to derive a new idea. These evaluation and segment are useful for designers in the derivation process of ideas that often wastes the time because of the inertia of designer's thinking process [3].

There exist some methods for the conceptual design process. Brainstorming (1963)[1] is one of powerful fundamental procedure to discuss many ideas among several designers and there are variations considering its giving direction for discussion. However, it is difficult for designers to evaluate and give a segment of ideas through discussion among designers. The direction for the deriving ideas is useful to derive ideas keeping its variety. Unified Structured Inventive Thinking （USIT） [3] is one of the design methods that supports designer to derive many ideas with variety finding the nature of design problem. In this method, the combination of derived ideas is recommended considering the properties of derived ideas. However, it is not easy for designer to select the candidate for the combination and it seems to be useful to calculate the segment or candidate numerically and give designers this information for a discussion of a new idea.

Kobayashi and Miyashita [4,5,6] proposed the visualization method of ideas in its evaluation space using Data Envelopment Analysis (DEA). This method shows the relation among ideas using network forms and the unified evaluation value for some evaluation index. This visualized relation of ideas contributes to select ideas for combination of ideas to derive a new idea. However, according to proceed the derivation of many ideas, the visualized relation of idea often becomes difficult to recognize the relation because of the complexity of the visualized result. Then, it is necessary to support designer in recognition process and derivation process of new ideas from the visualized relation of ideas. In this study, we will propose the method to support derivation process from the visualized relation using DEA. Through the experiment, we will confirm the effectiveness of our study.

2. PROPOSED METHOD

2.1 Formulation of idea

The idea derivation process is activity that requires high intelligence and the idea often comes to appear in functions, figures and drawing in engineering design. Then, the idea itself is not easy to materialize. In this study, we consider ideas as functions of products and products in design process are thought to be evaluated. This evaluation process is done by questionnaires for designers. The expected performance of products is also measured by questionnaires. Using questionnaires, we define ideas to have two types of values shown in table 1.

Table 1 The defined value of idea

Names of Index	Explanation	Notation
Evaluation Index (EI)	The index measured by questionnaires for all ideas and maximization or minimization is required for successful design. For example, "practical use" and so on.	x^k_i (to be minimized), y^k_j (to be maximized) $k = 1, .. ,N$ (number of idea)
Performance Index (PE)	The index measured by questionnaires for some ideas and maximization or minimization is not required for successful design. For example, "size", "cost" and so on.	z^k_i $k = 1, .. ,N$ (number of idea)

2.2 Abstract of direction

The proposed method needs the evaluation of ideas derived from brainstorming. First of all, the evaluation index is derived from design requirements and divided into two groups. First one is named as evaluation item (EI) and second one is as performance item (PI) shown in table 1. The evaluation index can be derived using ISM for all design requirements. EIs are taken from super ordinate items in ISM and PIs are taken from subordinate items in ISM. EIs and PIs are analyzed by DEA explained in section 2.3 to derive a scalar value that shows the efficiency of ideas. The relation between EIs and PIs is identified using Neural Networks and desired ideas that have optimized value of EIs and PIs are derived using Genetic Algorithms. The process flow of the proposed method is shown in figure 1.

Step 1: Brainstorming is done and obtains many ideas
Step 2: The ideas are evaluated by EIs using questionnaires for designers. Then, the ideas are quantitatively evaluated.
Step 3: The ideas are analyzed using DEA. DEA can offer us a unified evaluated value that can be considered as total evaluation among EIs. The relation of ideas in the evaluation space is shown as network form.
Step 4: All ideas are evaluated again by PIs using questionnaires for designers referring to the evaluated value by DEA.
Step 5: EIs and PIs are modeled using neural networks and calculate better ideas using Genetic Algorithm.
Step 6: Check the number of idea. If the number of idea is sufficient, the design process is terminated. If insufficient, back to step 2.

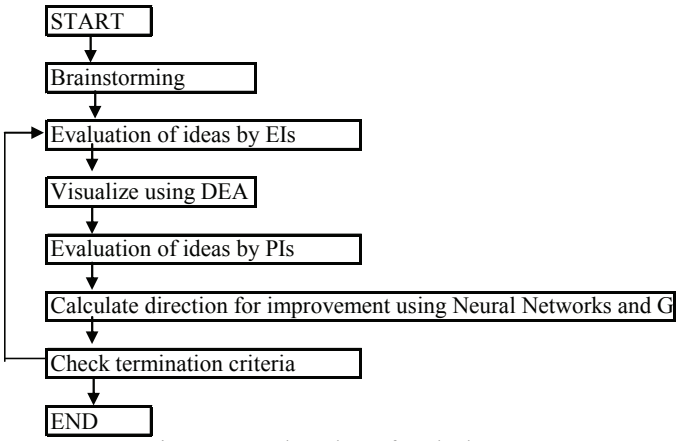

Figure 1 Flow chart of method

2.3 Data envelopment analysis (DEA)

The proposed method was based on Data Envelopment Analysis proposed by Cooper (1968) in economical field [7]. DEA is a method to evaluate Decision Making Unit quantitatively. In DEA, the input value to be minimized and output value to be maximized is required. After evaluation by DEA, we can have some properties of DMU. In this study, we consider DMU as ideas and we use the evaluation and the improvement direction of ideas. The evaluation value is called the efficiency in DEA was defined as equation (1). The x^k_j and y^k_i is the minimized and maximized values of EIs shown in table 1. The u^k_i and v^k_j are weight values for x^k_j and y^k_i for the scalar value that express efficiency of k-th idea θ^k .

$$\theta^k \equiv \frac{\sum_{i=1}^{n} u_i^k y_i^k}{\sum_{j=1}^{m} v_j^k x_j^k} \qquad (1)$$

The efficiency and the improvement direction of k-the idea are calculated by determination of weights. Solving following optimization problem, we can determine the weights considering the other ideas, which are idea^l (l=1,.., k-1, k+1,.., N).

Find u_i^k, v_i^k such that

$$\text{maximize}_{\theta^k} \equiv \frac{\sum_{i=1}^{n} u_i^k y_i^k}{\sum_{j=1}^{m} v_j^k x_j^k} \qquad (2)$$

subject to

$$\frac{\sum_{i=1}^{n} u_i^k y_i^l}{\sum_{j=1}^{m} v_j^k x_j^l} \le 1 \qquad (l=1,..,N) \qquad (3)$$

$$u_i^l \ge 0 \qquad (i=1,..,n) \qquad (4)$$

$$v_j^l \ge 0 \qquad (j=1,..,m) \qquad (5)$$

Through transforming into a dual problem shown below, we can solve this optimization problem by the simplex method. We can get the efficiency θ^k and the improvement direction θ^k in the dual problem without determining weights by designer. Weights of k-th idea are given to get the best values considering the other ideas and number of combination of weight values is not exceed the number of ideas. This number of combination is used to categorize the ideas. The efficiency takes 1.0

if evaluated the best and takes 0.0 if evaluated the worst. In figure 2, the illustrative explanation in the case having y_1 and y_2 is shown. The efficiency θ^F is defined as the ration of distance OF/OF'. The line AB, BC and CD express the pareto frontier with different weight values. The ideas located within the triangle OAB, OBC and OCD take same values of weight to be evaluated highly. Then we can categorize according to the value of weights.

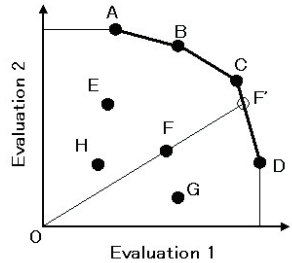

Fig. 2 Evaluate Idea (EIs: y_1, y_2) with DEA

2.3 Estimation of new ideas

The relation between EIs and PIs are mathematically modeled by neural networks shown in figure 3. EIs are taken as output $\boldsymbol{x}$, $\boldsymbol{y}$ and PIs are input $\boldsymbol{z}$ in three layered neural networks. The learning process of neural networks is done by back propagation. Then, using simple Genetic Algorithm, the new ideas are derived to satisfy the desired value of EIs. The fitness function in GA is taken as equation (4).

$$f = w_1 f_1 + w_2 f_2 + w_3 f_3 + \ldots + w_n f_n \qquad (4)$$

In equation (4), w_i is weight values and these weight values are decided by the results from DEA. From DEA, we can obtain several combination of weight vector. In DEA, the values of the weight give us the direction of the ideas in evaluation space shown in figure 4. Figure shows the expected search area by GA using the weights that are calculated by line C-D. Using different weight values iteratively, several directions that improve the evaluation values are searched. The search area is defined to avoid the extrapolation of identified relation using NN.

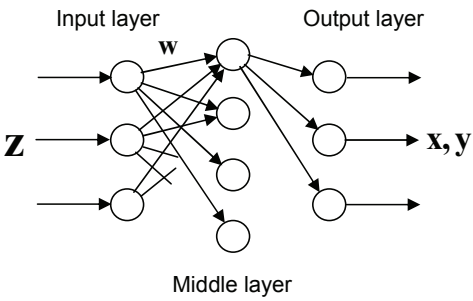

Fig. 3 Multilayer Perceptron

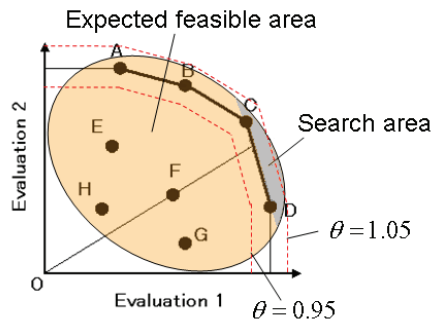

Fig. 4 Expected search area

The calculated results (optimized value of x_i and y_j and design value z_k) by GA show the values of EIs and PIs. The designers should consider the idea that shows the values of calculated EIs and PIs. Supporting these process, keywords or short sentence imagined from the values of EIs and PIs are firstly decided and from the decided keywords or short sentence, designers derive the new idea.

3. DESIGN EXPERIMENTS

3.1 Problem setting

Design problem of handy phone considering "addition of new function" was discussed by 6 young designers. Ten designers are divided into two groups. First group has treated the problem only using brainstorming and second group has treated the problem using proposed method within time limitation. The EIs are "realization", "utilization" and "novelty" of the idea. The PIs are "frequency of use", "age range of customer", "price", "size" and "complexity". The learning rate is taken as 0.7, the inertia factor is 0.8 and the allowance of error limit is 0.1 in the neural networks. In GA, the crossing rate is taken as 0.15, the mutation rate is 0.01 and the generation limit is 100.

3.2 Result of experiments

We can obtain 20 ideas through brainstorming. Table 2 shows the several ideas from brainstorming and the evaluated value by a questionnaire. In the questionnaire, there are three evaluation index shown in table 2 and the result is normalized from 0.1 to 0.9.

Table.2 A portion of ideas and evaluated values

Ideas	Feasibility	Utility	Novelty
Command input by sound	0.545	0.757	0.723
Completely water proof	0.723	0.465	0.100
Position detection	0.812	0.392	0.545
Projector for videos	0.189	0.392	0.812
Identification	0.456	0.903	0.456
Card Key	0.456	0.903	0.634
Synchronization with PC	0.901	0.757	0.189
GPS	0.901	0.611	0.100
Credit Card function	0.901	0.611	0.100
Portable Air Cleaner	0.100	0.319	0.812
Health measurement	0.901	0.319	0.545
Ashtray	0.545	0.246	0.901
Electrical Pet	0.901	0.246	0.278

Table 3 shows the evaluated value and weight vector calculated by DEA. There are nine ideas that scored efficiency not equal to 1.0. From weight values of these ideas, we can obtain five pareto frontiers with weight values shown in table 4

Table 3 Efficiency and weight calculated by DEA

Ideas	Feasibility	Utility	Novelty	Efficiency
Command input by sound	0.557	0.567	0.371	0.9618
Completely water proof	1.110	0.000	0.000	0.8024
Position detection	0.250	0.305	0.875	0.9012
Projector for videos	0.561	0.342	0.982	0.9012
Identification	0.000	1.107	0.000	1.0000
Card Key	0.000	0.515	0.844	1.0000
Synchronization with PC	0.312	0.950	0.000	1.0000
GPS	1.110	0.000	0.000	1.0000
Credit Card function	1.110	0.000	0.000	1.0000
Portable Air Cleaner	0.000	0.000	1.110	1.0000
Health measurement	0.852	0.000	0.426	1.0000
Ashtray	0.000	0.000	1.110	1.0000
Electrical Pet	1.110	0.000	0.000	1.0000

These weight values are used for the fitness function shown in equation (4) in GA. Figure 5 shows the hierarchical structure of pareto frontier 2. The three ideas shown in left side in figure 5 is the best ideas evaluated by DEA and these ideas form the pareto frontier 1. The idea shown in right side is inferior idea the three ideas in EIs. The left side is the calculation result by GA using NN identified response surfaces. If the balance among the ideas on pareto frontier is different from each other, it is considered that there is distance between ideas and we can expect to derive a new idea as the interpolation between ideas. The designers are encouraged to derive new ideas from hierarchical visualization of idea for each pareto frontier.

Table.4 Evaluation function of Pareto frontiers

	Weight 1	Weight 2	Weight 3
Pareto frontier 1	0.312	0.950	0.000
Pareto frontier 2	0.557	0.567	0.371
Pareto frontier 3	1.110	0.000	0.000
Pareto frontier 4	0.561	0.342	0.982
Pareto frontier 5	0.250	0.305	0.875

From the hierarchy representation of idea, the designers could derive 9 new ideas considering evaluation space in total. Table 5 shows the number of ideas derived from the pareto frontier.

Table.5 Number of derived ideas

Pareto frontier 1	3	Pareto frontier 2	2
Pareto frontier 3	2	Pareto frontier 4	1
Pareto frontier 5	1		

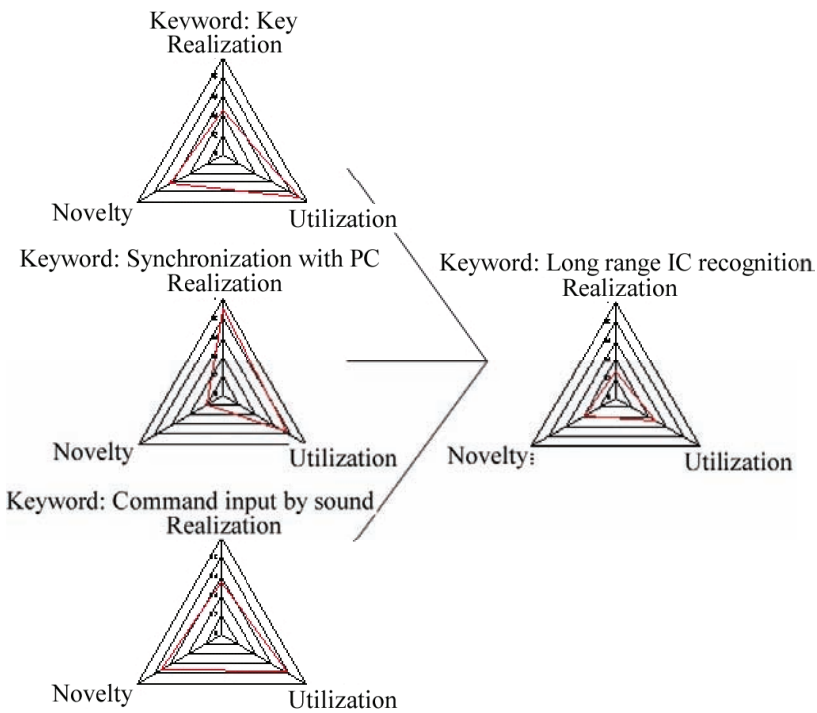

Fig. 5 Hierarchy graph of Pareto frontier 2

All ideas evaluated PIs again using questionnaires. The PIs are subordinate evaluation index and these are useful for derivation of new ideas because of designers can easily recognize its feature. In this example, we arranged five PIs shown in table 6. The weight values of PIs for all ideas are calculated by DEA shown in table 7 and given for the neural networks and developed the mathematical model between PIs and EIs. The neural network was designed so as to minimize error index. Then, we could obtain the neural network that has seven units in middle layer. The GA was applied for deriving new ideas using the fitness function shown in equation (4) for each pareto frontier. Then, we can have five new ideas according to the number of pareto frontiers shown in table 8 to 12.

Table.6 Performance items

PI 1	Frequency of Use
PI 2	Age range of customer
PI 3	Price
PI 4	Complexity
PI 5	Size

Table.7 Weight calculated by DEA

Idea	Rp1	Rp2	Rp3	Rp4	Rp5
Command input by sound	0.580	0.500	0.500	0.600	0.340
Completely water proof	0.180	0.580	0.660	0.100	0.580
Position detection	0.500	0.340	0.180	0.300	0.180
Projector for videos	0.340	0.260	0.900	0.200	0.820

From the result of Pareto frontier 1 in table 8, we could recognize that PI1:"frequency of use", PI2:"age range for customer" and PI4:" Complexity "have high values rather than the others. Then, we consider this category as "luxury" with "complexity" and have given the keyword as "many functions by software". Referring this keyword, designers could derive four new ideas. From the result of Pareto frontier 2 in table 4, we could recognize that PI2 and PI3 have low values rather than the others. Then, we consider this category as "specialized simple function with low cost" and "Small but complexity" then we have given the keyword as "functions for special customer with intelligent device". From this keyword, designers can derive four new ideas. In total, designers could derive 20 new ideas from five pareto frontiers.

Table.8 Optimum value of direction for new ideas

	Rp 1	Rp 2	Rp 3	Rp 4	Rp 5
Pareto frontier 1	0.537	0.961	0.0196	0.612	0.0314
Pareto frontier 2	0.565	0.0314	0.00392	0.992	0.745
Pareto frontier 3	0.0118	0.498	0.267	0.0392	0.847
Pareto frontier 4	0.620	0.0471	0.961	0.827	0.486
Pareto frontier 5	0.553	0.0392	0.0588	0.961	0.925

3.3 Discussion of result

(1) Comparison with other methods

We have compared new ideas derived from two design teams. The derived new ideas are evaluated again in EIs space and then calculated the weight and efficiency by DEA. If the efficiency is high (we defined the threshold as 0.95), we could consider that the derived new design is superior to the other ideas. The compared method is brainstorming done by the other design team; they can obtain 33 ideas in this case. The ideas obtained from are also evaluated by DEA. Table 9 shows the result the number of the superior ideas. From table 8, we can confirm that the number of proposed design by the proposed method is greater that the brainstorming. Then, we could consider that there are some overhead for the calculation of NN, GA and DEA, the proposed method can support designers to derive suitable idea for improvement in EIs space.

Table.9 Success number of idea by two methods

	Brainstorming	Proposed Method
Pareto frontier 1	2	4
Pareto frontier 2	2	0
Pareto frontier 3	1	3
Pareto frontier 4	1	4
Pareto frontier 5	1	3

(2) Variety of idea

It is important to drive ideas with variety. Then, the best ideas derived from each frontier are confirmed. Table 10 shows the best ideas except from pareto frontier 2. The result from pareto frontier 2 was accepted in this case because the extrapolation error in neural network is not small. The four ideas were compared in figure 6. In this figure, we can confirm that the value of the proposed ideas have different weight values. Then, it is considered that the variety of the proposed idea is sufficient large.

Table.10 Evaluated weight value for new ideas

	Idea's keyword	Feasibility	Utility	Novelty
Pareto frontier 1	Navigation	0.901	0.903	0.100
Pareto frontier 3	Attachment for wall	0.901	0.173	0.812
Pareto frontier 4	Text recognition	0.367	0.757	0.723
Pareto frontier 5	Perfume	0.812	0.684	0.812

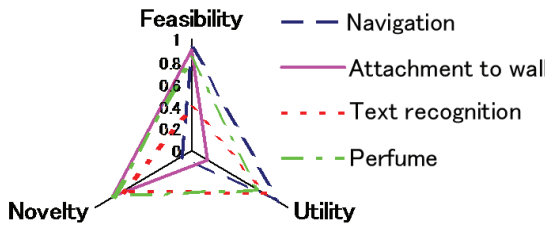

Fig. 6 evaluated value balance of ideas

(3) Error of approximation

From table 9, the number of new ideas from pareto frontier 2 was zero. We showed the estimation error of neural network in table 11 to confirm this phenomenon. In table 11 the error is larger than pareto frontier 1, 3 and 4 and this trend is same with the number of new ideas shown in table 9. Therefore, it seems to succeed to drive new idea if the estimation error of neural network is small. However, in the case of pareto frontier 5, the estimation error is largest among all, but the number of the new ideas is not zero. In this case, we could consider that the better ideas were obtained accidentally in idea derivation process by designers. To confirm the relation between the estimation error and the effectiveness of the proposed method, the average error between successful ideas that have high efficiency greater than 0.95 and failed ideas that have low efficiency lower than 0.95 in table 12.

Table.11 Average of error

	Average of error
Pareto frontier 1	0.175
Pareto frontier 2	0.396
Pareto frontier 3	0.265
Pareto frontier 4	0.242
Pareto frontier 5	0.473

Table.12 Average estimation error between successful and failed ideas

	Success	Fail
Average of error	0.281	0.378

4. CONCLUSION

In this paper, we have proposed the design method to support the derivation process of ideas using neural network, genetic algorithm and data envelopment analysis. The DEA was used for evaluation of ideas that have several evaluation indexes to obtain single evaluated value and the location in the evaluation index space. The neural network was used for approximation of the relation between the weights of evaluation items and the weights of performance items and then GA was used for optimization using mathematical model approximated by NN and gives designers the direction of improvement of ideas. The proposed method was compared with traditional method, brainstorming. Here, the number of successful ideas and failed ideas was compared and we have showed the efficiency of the proposed method. We could obtain following remarks.

(1) An Evaluation index and Performance index obtained from ideas could contribute for generation of a new idea.
(2) The number of successful ideas has increased using the proposed method comparing the previous method.
(3) The estimation error in Neural Networks was not large and has the relation with the contribution of the proposed method.

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