Design Optimization of Product Forms using Neural Networks: a case study of cellular phones

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Abstract: The purpose is to examine the design optimization on product forms. The optimum combinations of form elements of a product are examined using the grey relational analysis model. To predict and infer the design optimization in the future, Neural Networks models are used. This study focuses on investigating and categorizing of various cellular phones in the consuming market. Fifty-four cellular phones are used as experimental samples and a form elements table, inclusive of nine items and twenty-seven categories, is generalized from the experimental samples. The results of the case study show that the grey relational analysis can find the most important form element and can rise up Neural Networks prediction ability. The results are summarized in three points. First, the “top shape” element of product forms primarily affects the “Simple-Complex” kansei words from the grey relational analysis. Second, we discard the less influential elements of product forms to simplify the model structure, and particularly to have a better prediction ability. Third, the errors of the root mean square of Neural Networks show that the simple model has the higher prediction consistency on the “Simple-Complex” kansei words.

This study can develop a decision support system to product designers as an important reference for their design work. It can help the designers do the best choice as they design new products’ form. Although the cellular phones are chosen as the object of the case study, this methodology can be used to develop other products.

Keywords: Design Optimization, Product Form, Kansei Engineering, Neural Networks, Grey Relational Analysis.

1. Introduction

The design process is a black box all the while. We describe a system whose inner messages are unattainable using the concept of “black box”. Therefore, “black” means we know nothing about its inner messages. And, we do not really understand what the product elements are. There are various product elements to cause the different feeling or image of the consumers. But, which has a greater influence on the image of the consumers?

The concepts of consumer-oriented design or human-centered design in the product design field are more and more emphasized. Some designers and scholars propose the “user friendly” [4] concepts as an important reference for their design work. In Japan, the methodology of Kansei Engineering [8] is to explore the relationship between the feeling of the consumers and the elements of the products. In other words, it is a consumer-oriented technology for new product development [5]. Kansei Engineering is defined as “translating technology of a consumer’s feeling and image for a product into design elements [8].” Therefore, some studies [6, 7] examine the relationship between the form and image of products and find the design optimization. This study uses the grey relational analysis model [3] and Neural Networks models [9]. The optimum combinations of form elements of a
product are examined using the grey relational analysis model. To predict and infer the design optimization in the future, Neural Networks models are used.

This study can develop a decision support system [10] to product designers as an important reference for their design work. It can help the designers do the best choice as they design new products’ form. Although the cellular phones are chosen as the object of the case study, this methodology can be used to develop other products.

2. Method

Kainsei Engineering has four points: (1) how to grasp the consumer’s feeling (Kansei) about the product in terms of ergonomic and psychological estimation, (2) how to identify the design characteristics of the product from the consumer’s Kansei, (3) how to build Kainsei Engineering as an ergonomic technology, and (4) how to adjust product design to the current societal change or people’s preference trend [8].

In this study, we use the concept of kainsei engineering to extract the representative experimental samples, including representative cellular phone’s samples, and a form elements table.

2.1 Extracted representative cellular phone’s samples

The cellular phone is chosen as the object of case study because it is the most popular consuming e-product in the current market. This study focuses on investigating and categorizing of various cellular phones in the consuming market. Fifty-four cellular phones are used as experimental samples and a form elements table, inclusive of nine items and twenty-seven categories, is generalized from the experimental samples.

The process includes nine steps: (1) chooses fifty-four cellular phones, inclusive of thirty cellular phones in the prior study [11, 12] and twenty-four cellular phones which enter the market in 2000/07~2001/02; (2) make fifty-four small paper cards according to the original size of each cellular phone; (3) separate fifty-four small paper cards into seven to twelve groups with similarity degree by fifteen subjects (8 males and 7 females) using the K.J. method; (4) build a similarity matrix from the separation results; (5) transfer the similarity matrix into a dissimilarity matrix due to the statistics need; (6) proceed with the Multiple Dimension Scaling (MDS) Analysis according to the dissimilarity matrix data; (7) choose the structure of six dimension because of the Stress=0.10 and RSQ=0.865; (8) proceed with the Cluster Analysis according to the MDS results; (9) extract thirty-three representative cellular phone’s samples from the Cluster Analysis shown as in Fig.1.

2.2 Extracting form elements table

In this study, the product form means not only outline shapes, but also product elements. This study has two primary procedures to extract form elements table. In the first procedure, five design experts individually write
down the context of the form elements of cellular phones according to their plentiful experience. We collect and
generalize a preliminary result from the experts’ opinions, inclusive of two groups, “form essential components”
and “form process manners”. The “form essential components” indicates the size and shape of outline components 
that can make up the cellular phone, such as buttons, icons, a screen or a body shell. The “form process manners”
indicates the relationship between the outline components, for example, the equidistance arrangement of the 
buttons or the size rate of the screen and the body shell. In the second procedure, five experts make up the focus 
groups [4] to discuss and examine the preliminary result. The similar components and items are combined or 
discarded. The form elements table includes nine items and twenty-seven categories, shown as in Table 1.

Table 1. The form elements Table

<table>
<thead>
<tr>
<th>Items</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Top Shape (X1)</td>
<td>Line (X11)</td>
<td>Curve (X12)</td>
<td>Arc (X13)</td>
<td>Irregular (X14)</td>
</tr>
<tr>
<td>2. Body Shape (X2)</td>
<td>Parallel Line (X21)</td>
<td>Raised Curve (X22)</td>
<td>Concave Curve (X23)</td>
<td></td>
</tr>
<tr>
<td>3. Bottom Shape (X3)</td>
<td>Line (X31)</td>
<td>Curve (X32)</td>
<td>Arc (X33)</td>
<td></td>
</tr>
<tr>
<td>4. Length and Width Ratio of Body (X4)</td>
<td>Wide Ratio 2:1 (X41)</td>
<td>Middle Ratio 2.5:1 (X42)</td>
<td>Slender Ratio 3:1 (X43)</td>
<td></td>
</tr>
<tr>
<td>5. Function Buttons Style (X5)</td>
<td>With Large Button (X51)</td>
<td>Symmetry Style (X52)</td>
<td>Other Style (X53)</td>
<td></td>
</tr>
<tr>
<td>6. Number Buttons Arrangement (X6)</td>
<td>Regular (X61)</td>
<td>Irregular (X62)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Screen Size (X7)</td>
<td>TV Ratio 4:3 (X71)</td>
<td>Movie Ratio 16:9 (X72)</td>
<td>Other Ratio (X73)</td>
<td></td>
</tr>
<tr>
<td>8. Screen Mask and Function Buttons (X8)</td>
<td>Independence (X81)</td>
<td>Function Buttons Dependence on Screen Mask (X82)</td>
<td>Interdependence (X83)</td>
<td></td>
</tr>
</tbody>
</table>
9. Outline

Division Style (X9)

<table>
<thead>
<tr>
<th>Normal Division (X91)</th>
<th>Rim Division (X92)</th>
<th>Special Division (X93)</th>
</tr>
</thead>
</table>

Table 2 lists the distribution condition of the thirty-three representative cellular phones samples in the nine items and twenty-seven categories. In the Table 2, the number 1, 2, 3, or 4 indicates the categories of each item individually. For example, the number 1 of the “Top Shape” item indicates the “Line”, and the number 2 indicates the “Curve”, and the number 3 indicates the “Are”, and the number 4 indicates the “Irregular”.

We can use Table 2 to proceed with the analysis of the grey relation and Neural Networks. On the other hand, we use the S.D. method with seven degrees to proceed with the experiment of kansei works evaluations by the fifteen subjects. The “Simple-Complex” kansei works is adopted from the prior study [11, 12], because it has the highest perception consistency among the “Simple-Complex”, “Leisure- Formal”, and “Handsome-Rustic” kansei works.

Table 2. The kansei evaluations matrix

<table>
<thead>
<tr>
<th>Cellular Phone</th>
<th>Item 1</th>
<th>Item 2</th>
<th>Item 3</th>
<th>Item 4</th>
<th>Item 5</th>
<th>Item 6</th>
<th>Item 7</th>
<th>Item 8</th>
<th>Item 9</th>
<th>Cellular Phone</th>
<th>Simple-Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

3. Results and Discussions

This study uses the grey relational analysis to examine the optimum combinations of form elements and Neural Networks to predict the design optimization. Therefore, we introduce and discuss the grey relational analysis and Neural Networks as follows.

3.1 Grey Relational Analysis
Deng initially presented the grey system theory [3] that has been successfully used in any amount of fields [1, 2]. The results of the studies show that the ability of grey system theory effectively deals with incomplete and uncertain information. The grey system theory include five primary topics: grey generating, grey relational analysis, grey forecasting, grey decision making, and grey control.

The grey relational analysis is used to determine the relationship between two series of stochastic data in a grey system. For reference series xo and comparative series xi, the function is used to calculate relation parameters of two series at a certain time point. The grey relational grade between two series at a time point k is called grey relational coefficient $\rho_{oi}(k)$:

$$
\rho_{oi}(k) = r(x_0(k), x_i(k)) = \frac{\min_{i} \min_{k} |x_0(k) - x_i(k)| + \xi \max_{i} \max_{k} |x_0(k) - x_i(k)|}{\max_{i} \max_{k} |x_0(k) - x_i(k)| + \xi \min_{i} \min_{k} |x_0(k) - x_i(k)|}
$$

where $\rho \in [0,1]$ is the distinguishing coefficient to control resolution scale, typically taken as 0.5. With relation parameters, we can calculate grey relation grade of each comparative series xi to reference series xo.

$$
r(x_0, x_i) = \frac{1}{n} \sum_{k=1}^{n} r(x_0(k), x_i(k))
$$

In this study, the comparative series xi are represented the form items as shown in Table 1, and reference series xo is represented the evaluation average of the “Simple-Complex” kansei words as shown in Table 2.

The procedure of the grey relational analysis involves the following seven steps:

Step 1: Denote the original series by

$$
x_i = (x_i(1), x_i(2), x_i(3), \ldots, x_i(n)), \quad i = 1, 2, 3, \ldots, 9.
$$

Step 2: Normalize the data of the series by the initializing method.

Step 3: Calculate the series of $|x_0(k) - x_i(k)|$.

Step 4: Calculate the value of $\max_{i} \max_{k} |x_0(k) - x_i(k)|$ and $\min_{i} \min_{k} |x_0(k) - x_i(k)|$, and then obtain $\max_{i} \max_{k} = 2.43$, and $\min_{i} \min_{k} = 0.00$.

Step 5: Set the the distinguishing coefficient $\rho = 0.5$.

Step 6: Calculate the grey relational coefficient of the series.

Step 7: Calculate the grey relational grade of the series, and obtain the $r(x_0, x_i)$ as follows:

$$
r(x_0, x_1) = 0.811, \quad r(x_0, x_2) = 0.755, \quad r(x_0, x_3) = 0.714, \quad r(x_0, x_4) = 0.794, \quad r(x_0, x_5) = 0.795, \quad r(x_0, x_6) = 0.751, \\
r(x_0, x_7) = 0.681, \quad r(x_0, x_8) = 0.758, \quad r(x_0, x_9) = 0.659.
$$

When $x_i$ equals $x_0$, the coefficient of grey relation is $r(x_0(k), x_i(k))=1$. This shows that $x_i$ is highly related to $x_0$. If $r(x_0, x_i) > r(x_0, x_j)$, then the factor $x_i$ is closer to the reference factor $x_0$ than the factor $x_j$. According to the grey relational grade, the result shows that the “top shape” element ($r(x_0, x_1) = 0.811$) of product forms primarily affects the “Simple-Complex” kansei words. In the next place, the “function buttons style” element ($r(x_0, x_5) = 0.795$) and the “length and width ratio of body” element ($r(x_0, x_4) = 0.794$) are also more influential than other elements of product forms. In other words, the combination of the $x_1$, $x_4$, and $x_5$ elements is the optimum combinations of form elements of the cellular phones. The result indicates that the consumer perception prefers the “Simple-Complex” image when the combinations are $x_1$, $x_4$, and $x_5$ elements of product form. On the contrary, the “outline division style” element ($r(x_0, x_9) = 0.659$) is the least significant one on the “Simple-Complex” kansei words among the nine form elements. And, the “screen size” element ($r(x_0, x_7) = 0.681$) and the “bottom
shape” element \((r(x_0, x_3) = 0.714)\) are both smaller than 0.75.

These results can help the product designers understand the consumer’s perception of form for the corresponding product image. They can also be used to examine the effect of the corresponding product image for a given combination of product form. The product designers can use the design support information to find out the optimal combination of product form in terms of a given product image.

### 3.2 Neural Networks

Neural Networks have several different kinds of algorithms. The "Back-propagation Neural Network" also called "Back-error Propagation Algorithm", is the effective and most frequently used supervised learning algorithm [9]. This kind of network structure belongs to "the feed forward neural networks". A multilayer network normally composes of many neuron units in several layers, there are always one input layer and one output layer and usually one hidden layer between them, as shown in Fig. 2.

There are two modes of operation for Back-propagation Neural Network - the learning process and the recall process. During the learning process, Neural Networks take the learning samples and then check the learning process repeatedly. The recall process is the procedure of categorization or prediction, which according to the results of learning to evaluate the possible result of another sample, in another word, to predict the result of different samples in the future. In this study, we develop two NN models for the learning process, called the NN\(_1\) model and the NN\(_2\) model.

The twenty-seven categories of the nine form elements table are as the input variables of the NN\(_1\) model. To simplify the model structure of Neural Networks, we discard the less influential elements of product forms as the NN\(_2\) model, including the “bottom shape (x\(_3\))” element, the “screen size (x\(_7\))” element, and the “outline division style (x\(_9\))” element. All of their grey relational grade are smaller than 0.75.

The average values of the image word pair are used as the one output neuron nod. The number of neuron nods of the hidden layer used in both the NN\(_1\) and NN\(_2\) models is determined by \((\text{numbers of input nods} + \text{the numbers of output nods}) / 2\), which is the most widely used rule. The learning rule used is Delta-Rule and the transfer function is Sigmoid [9]. Table 3 lists the neuron nods of the two NN models, including the input layer, hidden layer, and output layer.

Totally 33 experimental samples were used as the learning samples. Each model learned 1,000 times at each run. When the cumulative learning times were over 30000, the root of mean square (RMS) errors was convergent, and the learning process was thus completed. The Table 4 shows the learning times of each model run and their corresponding RMS errors.
Table 3. The neuron nods of the two NN models

| The NN₁ model | Input Layer: 27 neuron nods, including 27 categories of the 9 form elements. |
|               | Hidden Layer: 14 neuron nods, (27+1)/2=14. |
|               | Output Layer: 1 neuron nods. |

| The NN₂ model | Input Layer: 18 neuron nods, including 18 categories of the 6 form elements. |
|               | Hidden Layer: 3 neuron nods, (18+1)/2=9.5 ≒ 10. |
|               | Output Layer: 1 neuron nods. |

Table 4. The RMS errors of the two NN models

<table>
<thead>
<tr>
<th>Learning Times</th>
<th>The NN₁ model</th>
<th>The NN₂ model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.1402</td>
<td>0.1355</td>
</tr>
<tr>
<td>2000</td>
<td>0.1259</td>
<td>0.1022</td>
</tr>
<tr>
<td>3000</td>
<td>0.1205</td>
<td>0.0934</td>
</tr>
<tr>
<td>4000</td>
<td>0.1176</td>
<td>0.0885</td>
</tr>
<tr>
<td>5000</td>
<td>0.1150</td>
<td>0.0806</td>
</tr>
<tr>
<td>10000</td>
<td>0.1077</td>
<td>0.0585</td>
</tr>
<tr>
<td>20000</td>
<td>0.0930</td>
<td>0.0515</td>
</tr>
<tr>
<td>30000</td>
<td>0.0717</td>
<td>0.0457</td>
</tr>
</tbody>
</table>

As shown in Table 4, the RMS errors of the NN₂ model (0.0457) is smaller than NN₁ model (0.0717). The RMS errors of the NN₂ model shows that the simple model has the higher prediction consistency on the “Simple-Complex” kansei words. This result suggests that the more the input variables, the less effective the learning process. In other words, the more complex the NN structure, the lower the prediction rate.

4. Conclusions

The purpose is to examine the design optimization on product forms. Product developers need to provide various styles of products to attract consumers. Whether consumers choose a product, depends largely on their perception of the product image. The result of this study provides useful insights in designing form of a product for enhancing product image.

The results of the case study show that the grey relational analysis can find the most important form element and can rise up Neural Networks prediction ability. We have developed two NN models to suggest the best combination of form elements in product design for a given design concept represented by a product image word pair. The RMS errors of both NN models show that the more complex the NN structure, the lower the prediction rate.

The result can help the product designers understand the consumer’s perception of product form. They can also be used to examine the effect of the corresponding product image for a given combination of product form. The product designers can use the design support information to find out the optimal combination of product form in terms of a given product image. It can help the designers do the best choice as they design new products’ form. Although the cellular phones are chosen as the object of the case study, this methodology can be used to develop other products.
References