A neural network based approach for product form design

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A neural network based approach for product design is addressed in this article. Computer modeling, fuzzy set theory and semantic difference method are applied to set up an experiment. The experimental results are analyzed by applied back-propagation neural network, which establish the relationships between product–form parameters and adjective image words. A database for the connections among the design elements, product images and shape generation rules was constructed. A computer-aided system for product–form design was then developed based on this database. With the aid of this design system, a designer can generate 3D models of any product with different images by providing basic design elements and shape generation rules. Simultaneously, a rendered 3D model of the designed product and its images are also presented by this system. Therefore, changing the configuration parameter(s) until the product shape is acceptable can modify the image of a product. In this manner, the designed product can fit more closely to the consumers' desire. Chair design is taken as a case study; but this method can be used to develop other products.

Keywords: product design, perception, industrial design, computer-aided design, neural network

In the product development process, computers have been frequently used to perform the CAD/CAM/CAE tasks. Most of them focused on configuration generation or presentation, engineering calculation or simulation, etc. A computer was only used to meet the physical requirement. As for the psychological requirement such as the image feeling a person projects on a product, this is still exclusively within human's mentality. Unfortunately, most of the tasks of an industrial designer are usually in handling the sensations, those belong to the scope of human perception, and difficult to be performed with computer technology at present.

With today's highly competitive marketplace, wasteful product develop-

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ment process or unsuitable development strategy might lead to disaster. Considerations for today's decision method is 'listen to the voice of consumers' and 'quality of the product'. Thus, how to collect design information and to design a product with systematic method are very important factors in modern product development process. Computerization is recognized as an effective method for promoting design efficiency. Although the calculating speed and accuracy of a digital computer are superior, the human's thinking can still overcome the computer in some fields, especially for cases with partially incomplete or incorrect inputs. For these cases, the human being can offer the best suggestion while the computer fails. For example, if two completely similar cups are put in different positions, lighted with different illumination and viewed from different angles, only people can identify that they are the same, not a computer. This task might be workable by using traditional artificial intelligence, however, the scale is tremendous, because the so-called 'thinking' in the artificial intelligence is based on the database and the rules constructed artificially. How to express special knowledge by using closed rules is very difficult. Moreover, the rule-based approach does not fit for changeable environment and cannot be used to handle uncertain information. Although the digital computer has striking calculation speed, problems for replacing the human's intelligence with a computer still need more attention. For the time being, the greatest contribution of a computer to human beings is in the domain of handling complicated information for prompt efficiency. Most of the information, unfortunately, that would be handled by a computer must first be quantified. Therefore, if the information of image perception could be handled with a reasonable quantification method, people's sensation behaviour could be predicted logically and the results could then be used to do emotional design, by computer, such as the evaluation of the image of a designed product, and prediction of the consuming behaviour, etc.

In the past decades, a lot of attention has been paid to the simulation of the human brain. Neural network is one of the best methods, due to its:

- Learning ability
- Storage ability
- Fault tolerance
- Inductive ability
- Parallel handling ability

It has been widely used in many disciplines[1,2]. Simon[3] initiated the pioneering job to handle design work with a logical reasoning process. This field has recently proved a very significant concept[4–15].

1 Carpenter, G A 'Neural network models for pattern recognition and associative memory' *Neural Network* Vol 2 (1989) 243–257

2 Burr, D J 'Experiments on neural net recognition of spoken and written text' *IEEE Trans. On ASSP* Vol 36 No 7 (1988) 1162–1168

3 Simon, H A *The Sciences of the Artificial* The MIT Press, Cambridge, MA (1981)

4 Nagamachi, M 'Kansei Engineering: A new ergonomic consumer-oriented technology for product development' *International Journal of Industrial Ergonomics* Vol 15 (1995) 3–11

5 Jindo, T, Hirasago, K and Nagamachi, M 'Development of a design support system for office chair using 3D graphics' *International Journal of Industrial Ergonomics* Vol 15 (1995) 49–62

6 Fukushima, K, Kawata, H, Fujiwara, Y and Genno, H 'Human sensory perception oriented image processing in a color copy system' *International Journal of Industrial Ergonomics* Vol 15 (1995) 63–74

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8 Matsubara, Y and Nagamachi, M 'Hybrid Kansei engineering system and design support' *International Journal of Industrial Ergonomics* Vol 19 (1997) 81–92

9 Nakada, K 'Kansei engineering research on the design of construction machinery' *International Journal Industrial Ergonomics* Vol 19 (1997) 129–146

10 Hsiao, S W 'Fuzzy set theory on car-color design' *Color Research and Application* Vol 19 No 3 (1994) 202–213

11 Hsiao, S W 'Fuzzy set theory applied to car style design' *International Journal of Vehicle Design* Vol 15 No 3/5 (1994) 255–278

12 Hsiao, S W 'A systematic method for color planning in product design' *Color Research and Application* Vol 20 No 3 (1995) 191–205

13 Hsiao, S W and Chang, M S 'A semantic recognition based approach for car's concept design' *International Journal of Vehicle Design* Vol 18 No 1 (1997) 53–82

14 Hsiao, S W and Chen, C H 'A semantic and shape grammar

In product form design, the most easy and effective method is to agglomerate the forms and their image feelings together to establish the relationships between form and image and then computerize the design work based on these relationships. To acquire the psychological feeling about a product for the 'emotional design', the Kansei engineering[4–9], fuzzy theory[10–13], shape grammar[14], multidimensional scaling[15] and gray theory[16] methods have been proposed. The computer-aided imaginary design systems in the above mentioned studies are mainly used to create or generate new product forms. With the aid of these systems, the designer can create new product forms by inputting an image word(s). But the generated new forms might be different from the original configuration and the designer cannot catch the images of the newly generated forms. To solve this problem, neural network theory is used in this study to construct an interactive computer aided system for product form design. With the aid of this system, a designer can generate new product forms and further catch their image perceptions during the design process and consequently grasp the image feeling a consumer projects on the designed new product after the design process completion.

1 Outline of the design model

The flow chart of this design model performance is shown in Fig. 1. It includes the following steps:

(1) Select an objective product as the subject for studying
(2) Collect the products that are already available on the market
(3) Divide the product into several elements (parts) according to their functions and construct the basic form categories (or function carriers) of each element by using a morphological chart
(4) Select the adequate image words to establish the relationships between product forms and their image perceptions
(5) Analyze the image score for each product element by using quantification method and construct a network system from input to output
(6) Construct a computer aided product form design and image evaluation system by the analyzed results
(7) Use the constructed computer-aided design system to infer the design suggestion by inputting the required image and then present a rendered 3D model and predict its image feelings.

2 Theoretical background

Back-propagation neural network (BPN) is a multi-layer network with learning ability, in which the input layer, hidden layer and output layer are included and the hidden layer might be multiple. The network used in this study is shown later on in Fig. 9, in which one hidden layer is taken. The

based approach for product design' *Design Studies* Vol 18 No 3 (1997) 275–296
15 Hsiao, S W and Wang, H P 'Applying the semantic transformation method to product form design' *Design Studies* Vol 19 No 3 (1998) 309–330
16 Hsiao, S W 'Applying grey theory and ANOVA to product's form and color design' *Submitted for publication* (2001)

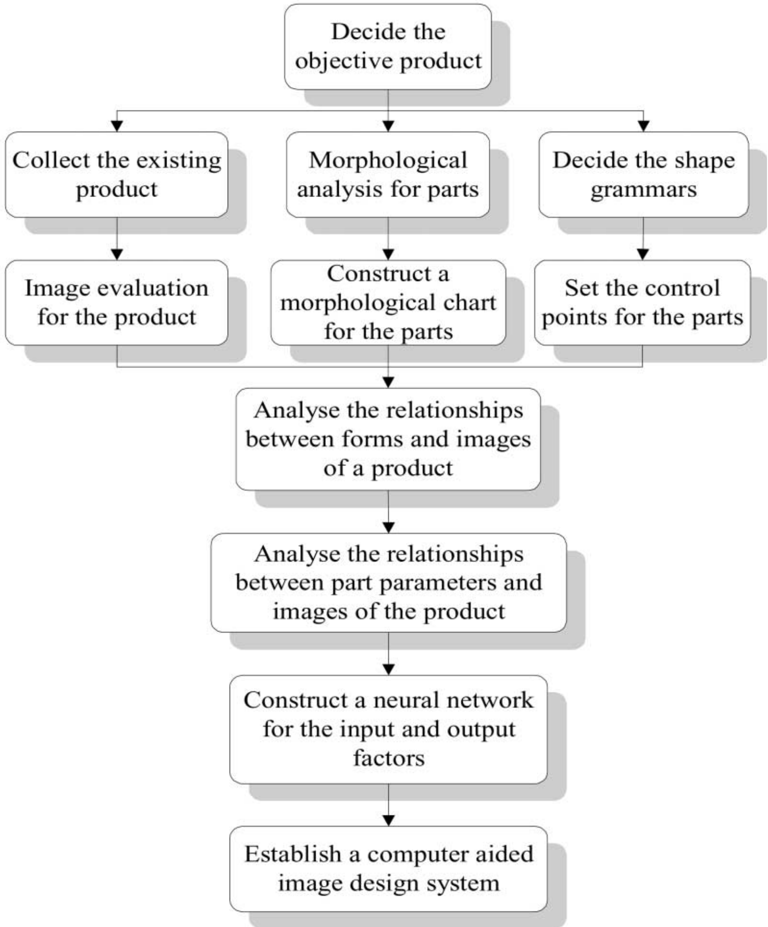

Figure 1 Flow chart of the design model

nonlinear transformation function of sigmoid function in Eq. (1) is used in this study

$$f(x) = \frac{1}{1 + e^{-x}} \tag{1}$$

There are two operation processes, the learning process and recalling process, included in a BPN. Forty training examples are input to the network to get the weights and biases between the input and the hidden layers and those between the hidden and output layers by using gradient steepest descent method. BPN is a well-developed theory and references are readily available[17,18]. Thus, the learning and the recalling algorithms for a back-propagation network used in this study are not elaborated on here.

17 Freeman, J A and Skapura, D M *Neural Networks–Algorithm, Application, and Programming Techniques* Addison-Wesley, New York, USA (1991)
18 Hertz, J, Krough, A and Palmer, R G *Introduction to the Theory of Neural Computation* Addison-Wesley, New York, USA (1991)

3 Implementation procedures

This study starts from the construction of a database for the relationships between product forms and their image sensations. This database is then used to construct a computer-aided product-image evaluation system. The procedure for establishing this system is described below.

3.1 Product elements analysis

The form parameter and the image feeling are considered as the input and the output for this system, respectively. A survey of office chairs already available on the market shows that they are generally regarded as consisting of five major components: back, seat, back support, armrest, and supporting shaft and base. Based on these five elements, the shape categories (function carriers) are developed by means of the morphological chart shown in Table 1.

3.2 Construction of the 3D model of parts

To present the product model clearly, we use Solid Works to construct 3D geometric model of a part and a whole product model for experiment. Solid Works provides an object linking and embedding (OLE) function for linking files together. Using the OLE function provided by Solid Works, we set the dimensions of parts of a product model in a command set and then modified it by using Visual Basic command(s). Based on this function, a command set for describing the configuration of a part is constructed based on needs and then used to regulate product configurations by using a Visual Basic program constructed in this study. The flow chart for constructing a 3D model of an office chair is shown in Fig. 2.

Table 1 Classification of the design elements

Design element	*Classification*		
Back	1. Square	2. Trapezoidal	3. Round
Seat	1. Square	2. Round	
Back support	1. Ellipsoidal	2. Square	3. None
Armrest	1. L-Shaped	2. T-Shaped	3. Square
Base	1. Slanted type	2. Straight type	

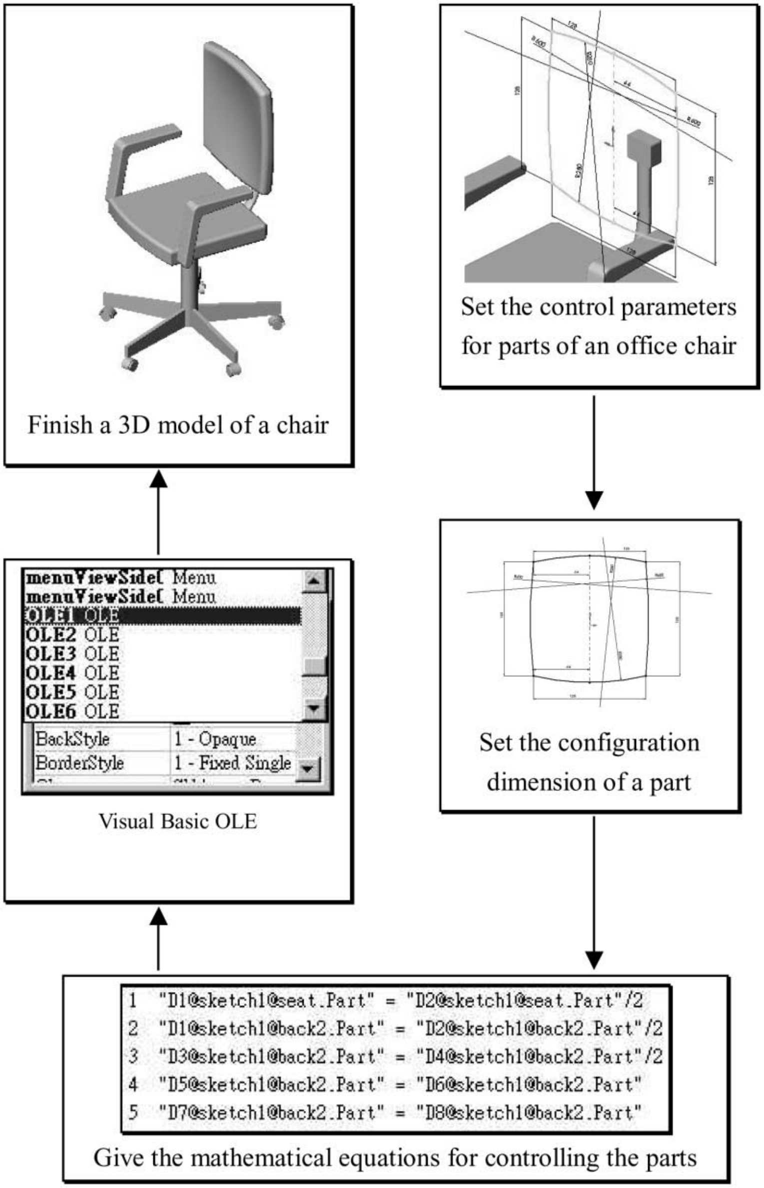

Figure 2 Flow chart for constructing a 3D model of an office chair

3.3 Shape generation rule

For diversifying the chair types, several shape generation rules are used in this study to generate more new shapes for each basic element. To simplify the problem, the shape regulation for a product is confined to changing shapes of the individual part. For example, a new chair may be obtained by changing its back form only and keeping all other parts unchanged. In this case, three back types can be presented (Table 1) with the logic shown

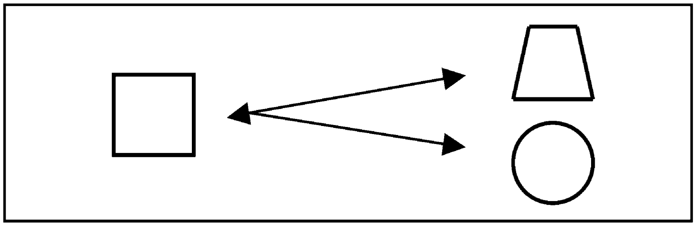

Figure 3 Shape categories generating method for a part

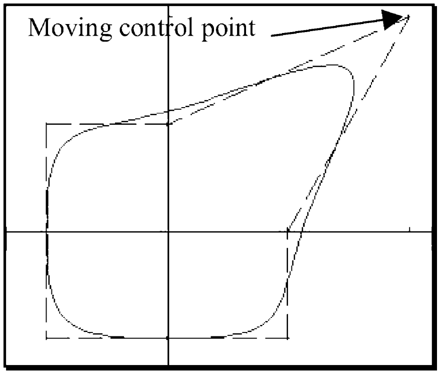

Figure 4 The method for a change of part shape

in Fig. 3 by changing the position(s) of the control point(s) for a part (Fig. 4). In this manner, the shape parameters for parts given by different subjects can be saved. For the sake of easy use, the CAD system was developed based on the object-oriented concept by using the language of Visual Basic (VB) to provide a graphical operation interface. Fig. 5 shows

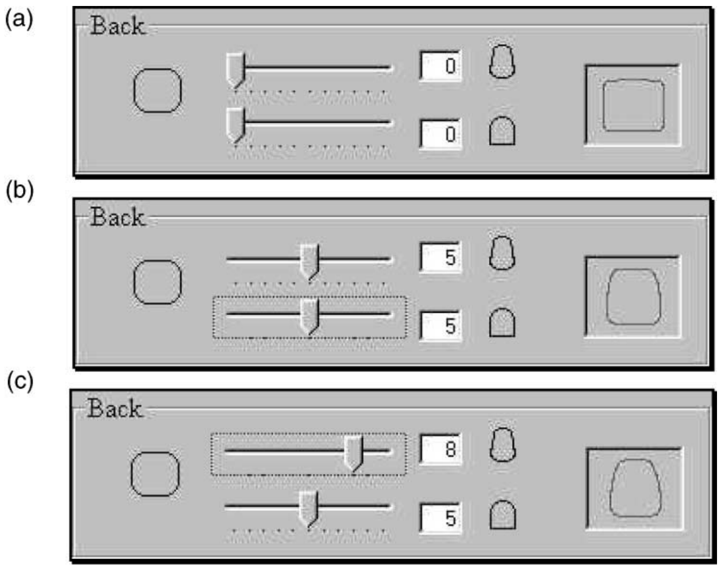

Figure 5 Examples for regulating the shape of a chair back

an example for regulating the shape of chair back. The shape of a chair back can be controlled with the regular bars. Fig. 5 shows the shape of a chair back is changed from rectangular (Fig. 5(a)) to trapezoid (Fig. 5(c)). The shape regulation for other parts such as seat, armrest, support and base etc. is also performed in the same manner. All the shapes of parts that can be changed are shown in the morphological chart (Table 1).

3.4 Selection of the image words

To specify the image perception of a product clearly, six adjective image words, which are considered as suitable for describing the image of an office chair are selected from previous investigations[10,11,14]. The selected image words are collected to form an image set as follow.

$$A = \{\text{Grand, Comfortable, Practical, Elegant, Steady, Durable}\} \qquad (2)$$

3.5 Choosing the product samples

Based on the morphological chart in Table 1, twelve basic chair samples (Fig. 6) were first obtained by combining different parts for required functions. Twenty design-related students were then asked to modify the product forms by regulating their configuration parameters for each chair and to give the image score for each product form. In this manner, 240 product samples were obtained. These samples were randomly numbered and one sample in every 5 samples was taken as the test sample. Therefore, 48 test samples were obtained to analyze the design information.

3.6 Experiment implementation

To collect the information of image perception, the above 3D geometric models of the product are given to the subjects to evaluate their image scores. The format of the experiment data is shown in Table 2. In this table, each row records the data for a sample. These data are divided into two parts. The twelve data contained in the first part are the configuration parameters which are used to set the form of the product while the six data in the second part represent the image scores for this shape fitting to the six image words shown in the image set (Eq. (2)). For the sake of simplifying the configuration parameters, a human–computer interface is designed as shown in Fig. 7. After the configuration parameters are given by a subject, they can be recorded in the data format as shown in Table 2. For example, the data shown in Fig. 7 is for sample 1 and the obtained configuration is shown in Fig. 8.

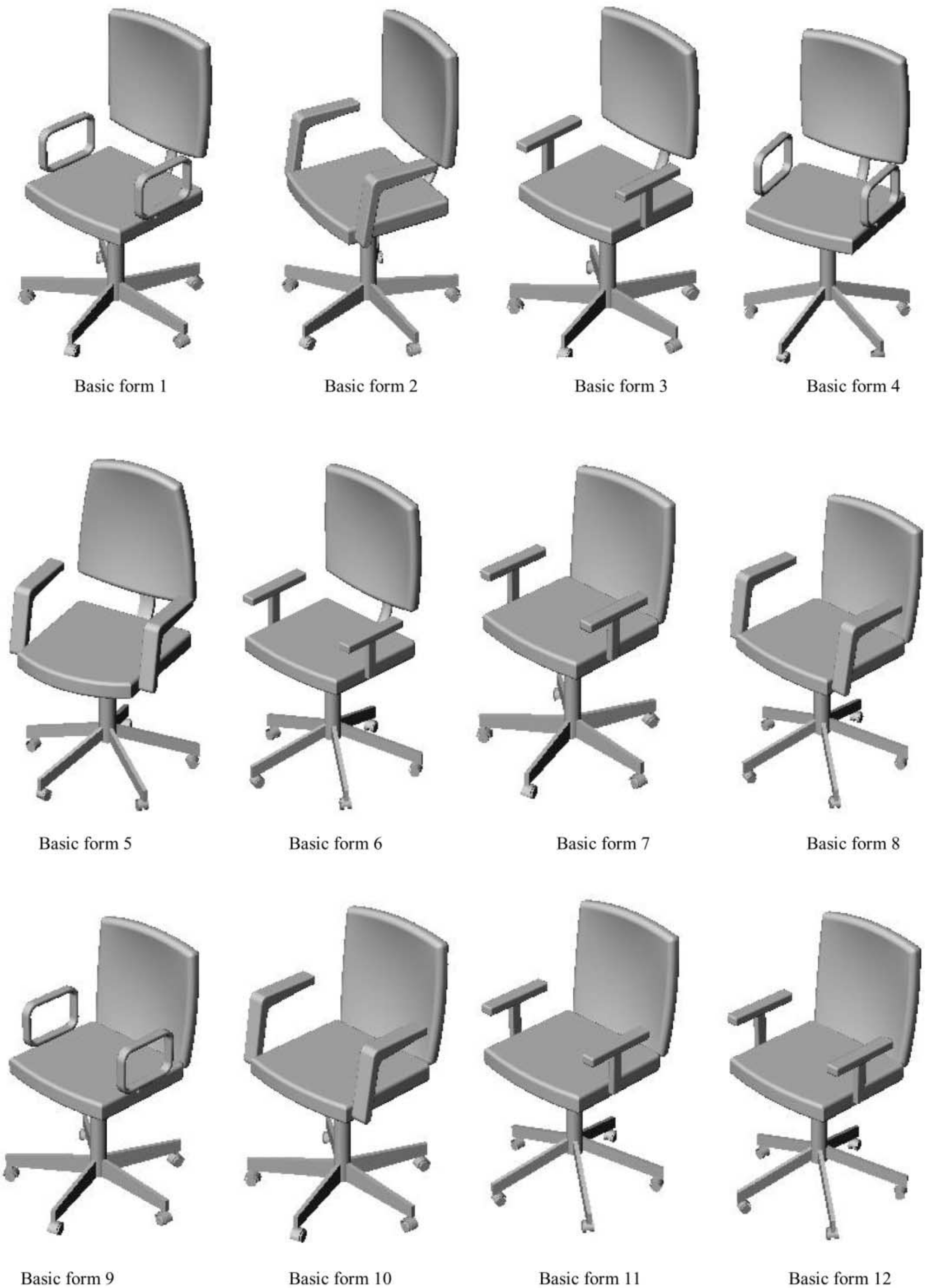

Figure 6 The selected test samples in this study

Table 2 Data format of the experimental data

	Control parameters for part configuration												*Image score for a product*					
Sample 1	0.5	0.4	0.8	0.2	0.6	0.5	−1	0	0	0	−1	1	0.7	0.6	0.7	0.6	0.5	0.5
Sample 2	0.9	0	0	0	0.2	0.2	−1	0	0	0	−1	1	0.4	0.4	0.8	0.4	0.2	0.4
…	…												…					
Sample 48	0.4	0.1	0.8	0.6	0.3	0.4	−1	0	0	−1	0	1	0.5	0.5	0.5	0.4	0.5	0.6

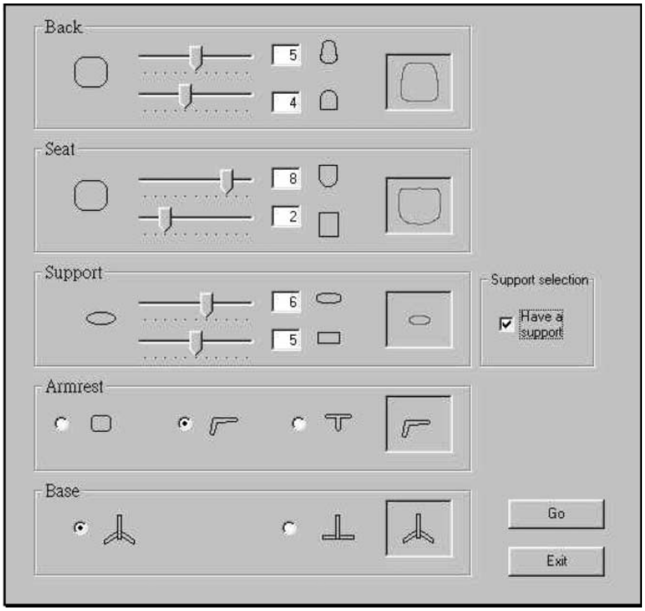

Figure 7 The method for setting configuration parameters of a whole product

3.7 Analyzing the relationship between product form and image perception

The obtained experiment data in Table 2 can be used to analyze the relationships between the form parameters and product image scores. To predict the image perceptions for different chair forms, a back-propagation neural network is used to analyze these data. In this network, 12 input parameters and 6 output parameters are set. The neuron number of the hidden layer is decided as follows

$$N_h = (N_i + N_o)/2 \quad (3)$$

where N_h, N_i and N_o are the number of neurons in hidden layer, input layer, and output layer, respectively. Thus, there are 9 neurons in the hidden layer whose arrangement is shown in Fig. 9.

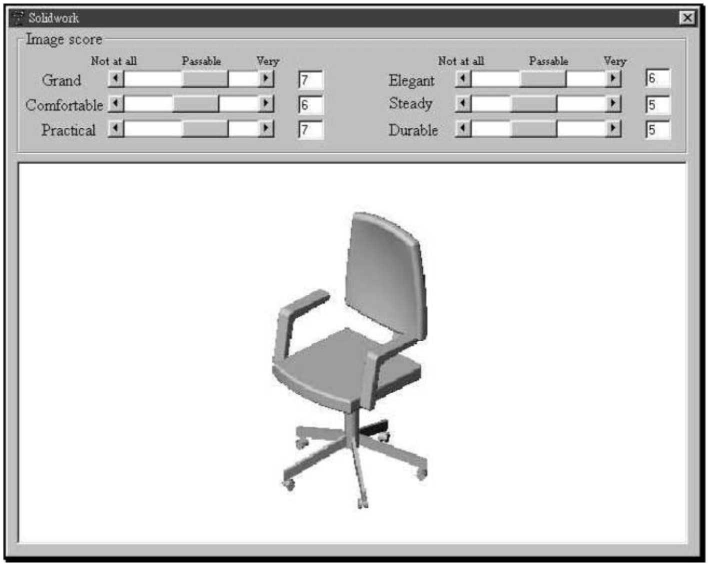

Figure 8 A complete chair presented after setting configuration parameters

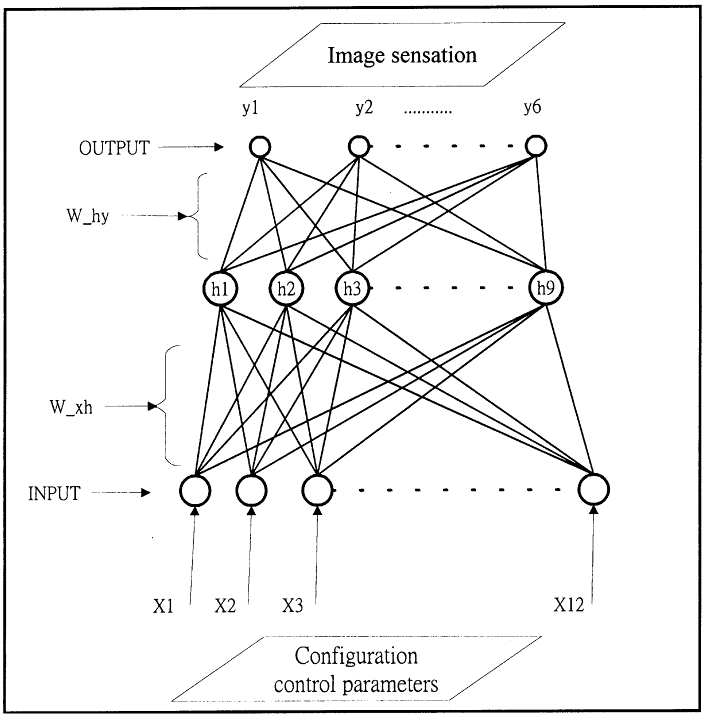

Figure 9 A construction of the back-propagation network used in this study

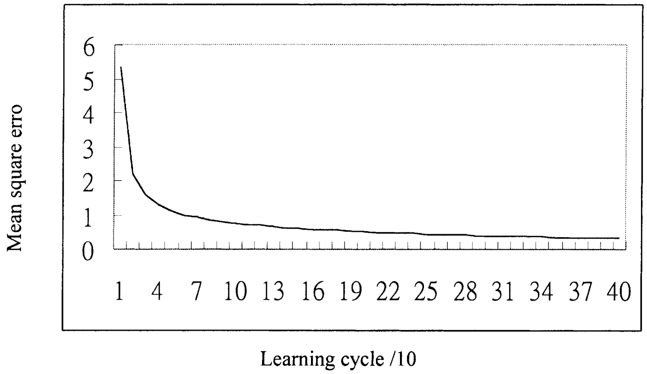

Figure 10 The convergent situation of the learning process

The first 40 experimental data of form-images in Table 2 are input to the back-propagation neural network as the training cases to train the network and the last 8 data are used as test cases. In the training stage, the inputs and outputs of the training cases are input to start the learning process, then the weights between the neurons in the input layer and the hidden layer, and those between the hidden layer and the output layer are saved until the learning process is converged. In the recalling stage, we can input the test cases, which were not learned, to check the learning effect is good or not by calculating the error between the inferred output of the neural network and the output of the test sample.

3.8 Convergence of the network

Fig. 10 shows the convergence tendency of the learning process. From this figure, we see that the learning process converges to an acceptable error after the learning process is iterated 400 cycles (Table 3). After the learning process has converged, the weights and bias among the input, hidden, and output layers are saved.

Table 3 The target values, inferred values and their mean square errors

Target values T_j						*Inferred values Y_j*						*MSE*
0.3	0.4	0.5	0.6	0.5	0.6	0.47	0.47	0.64	0.75	0.57	0.55	0.0101
0.3	0.4	0.5	0.3	0.4	0.5	0.35	0.52	0.59	0.54	0.37	0.46	0.0139
0.3	0.4	0.4	0.3	0.4	0.4	0.35	0.52	0.59	0.54	0.37	0.46	0.0188
0.3	0.4	0.5	0.3	0.4	0.4	0.35	0.46	0.6	0.49	0.45	0.52	0.0117
0.7	0.6	0.6	0.7	0.6	0.6	0.62	0.66	0.77	0.82	0.67	0.65	0.0096
0.3	0.4	0.4	0.3	0.4	0.4	0.29	0.42	0.52	0.42	0.44	0.47	0.0059
0.6	0.6	0.6	0.6	0.6	0.6	0.61	0.64	0.70	0.84	0.65	0.65	0.0123
0.5	0.5	0.5	0.4	0.5	0.6	0.37	0.45	0.61	0.53	0.55	0.59	0.0083

Table 4 The weights between the input and hidden layers

	W_{1-h}	W_{2-h}	W_{3-h}	W_{4-h}	W_{5-h}	W_{6-h}	W_{7-h}	W_{8-h}	W_{9-h}	W_{10-h}	W_{11-h}	W_{12-h}
W_{x-1}	2.33	1.54	0.99	1.46	1.20	1.48	0.47	0.81	−0.16	0.04	1.10	−0.51
W_{x-2}	−1.94	1.13	−0.56	0.99	−0.23	0.25	0.11	1.05	−0.99	0.35	−0.00	0.52
W_{x-3}	0.95	−1.46	0.80	0.38	0.10	−0.54	0.71	−0.99	1.32	0.73	0.56	−0.67
W_{x-4}	−2.69	−1.38	−0.50	2.26	−0.30	1.40	−0.57	0.38	1.79	0.78	0.58	−1.05
W_{x-5}	−0.51	1.84	−0.51	−0.63	0.64	0.79	−0.14	0.96	0.42	0.75	0.00	−0.41
W_{x-6}	0.85	−1.17	−0.46	−0.30	1.10	1.42	0.25	1.40	−0.65	0.13	−0.02	0.14
W_{x-7}	1.81	0.98	−1.06	0.59	−0.46	0.28	0.43	0.30	0.95	0.98	0.35	−0.52
W_{x-8}	2.30	1.72	1.68	1.63	0.60	1.19	−0.18	0.90	−0.19	1.01	−0.00	−0.39
W_{x-9}	0.20	−0.15	0.39	0.88	0.33	0.73	1.45	−1.27	1.81	0.38	1.16	−1.11

Table 5 The weight between the hidden and output layers

	W_{1-y}	W_{2-y}	W_{3-y}	W_{4-y}	W_{5-y}	W_{6-y}	W_{7-y}	W_{8-y}	W_{9-y}
W_{h-1}	1.18	−1.05	−0.01	−1.09	0.10	−0.40	0.84	1.32	1.27
W_{h-2}	2.10	−0.53	1.40	−1.67	0.28	−0.27	0.22	0.95	0.17
W_{h-3}	0.45	−1.50	0.81	−0.38	0.48	1.50	0.54	0.14	0.91
W_{h-4}	0.36	−1.44	1.23	−1.08	−1.95	−0.90	−0.61	1.82	0.80
W_{h-5}	2.34	0.35	−0.12	1.10	0.65	−1.73	−0.36	0.73	0.80
W_{h-6}	1.45	−0.16	−0.14	1.57	−0.88	−0.21	1.49	1.44	0.99

3.9 The recalling stage

In the recalling stage, the learned weights and biases and the inputs $X_1,\ldots,X_{ni}$, and target values T_1, $T_2,\ldots,T_{No}$ are input to the network to calculate the inferred outputs and the mean square errors (MSE) between the inferred values Y_j (j=1,2,…,N_o) and the target value T_j (j=1,2,…,N_o). Table 3 shows the result after 400 iteration cycles. The results show that the mean value of MSE is lower than 10%, which is under the threshold we previously set, suggesting the result can be used to predict the image of the designed product. Table 4 shows the learned weights between the input layer and the hidden layer. Table 5 shows the weights between hidden layer and output layer while those in Table 6 are the biases between hidden layer and output layer.

Table 6 The bias between hidden and output layers

				$\theta-h$				
0.46	−0.16	0.67	0.96	0.48	−0.02	0.82	0.50	1.18
				$\theta-y$				
2.04	2.52		0.36	0.52		2.03	2.44	

3.10 The construction of image design system

Based on the above constructed neural network for the relationship between product form and its image, the image score for a given product can be inferred by inputting their form parameters. For the user's convenience, the operation interface for the image design system is designed using Visual Basic language. With this system, the form parameter of a product can be input by regulating the rolling block for each part (Fig. 7). After the form parameters have been set, a 3D model of the suggested chair and its image score are presented based on the inferred result (Fig. 8).

4 Program development

The program constructed in this study includes 4 parts:

(1) The experiment interface for establishing the relationship between product forms and their images;
(2) The learning process for a neural network;
(3) The recalling process for the neural network; and
(4) The image system.

4.1 The experiment interface

Three parts are contained in the experimental program including setting the configuration parameters, constructing the configurations, and evaluating the image scores of the product. The parameter setting window is shown in Fig. 7 and the windows for presenting the configuration drawing and product-image scores is shown in Fig. 8.

Experimentation procedure:

(1) When the parameter-setting window is presented, the subject is asked to set the shapes for all parts of the chair by regulating the rolling block for each part to generate a whole chair.
(2) If the required shape for each part is assured then press the 'Go' button to enter the assembly drawings and image score window. The image scores for the subject gives the whole configuration of the product based on the presented configuration. The configuration can be displayed with front view, side view and isometrics in two different view angles (Fig. 11), which can be selected by the user.
(3) After the configuration of the product has been displayed, the subjects can give the image score of the product by regulating the rolling block. The image score is then saved if the function 'Save' is selected.

4.2 Image design system

The planned image design system contains three windows:

(1) The configuration-parameter setting window (Fig. 7).

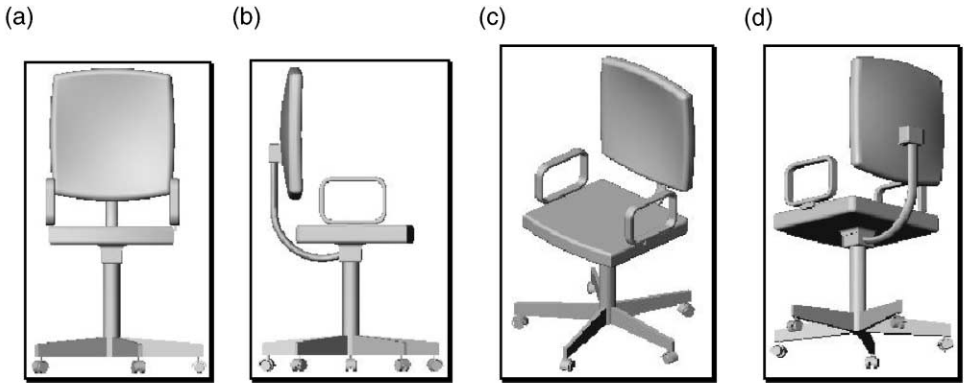

Figure 11 A product presented from different views (a) Front view, (b) Side view, (c) First isometric view, (d) second isometric view

(2) The product-rendering window (Fig. 12).
(3) The image evaluation window (Fig. 13).

The first part is used to input the configuration parameters. The second part is used to present the rendering drawing of a complete chair and the third part is used to present the imaginary score for each image, which is shown both in a digital figure and in a rectangular bar. With this value, the designer can see the image of the designed product.

5 Case study

In this case, we would like to design a chair and predict its image by starting from inputting a set of configuration parameters. The implementation procedure is described as follows.

(1) Set the 'back', 'seat' and 'support' shapes by regulating the rolling

Figure 12 A configuration-rendering window

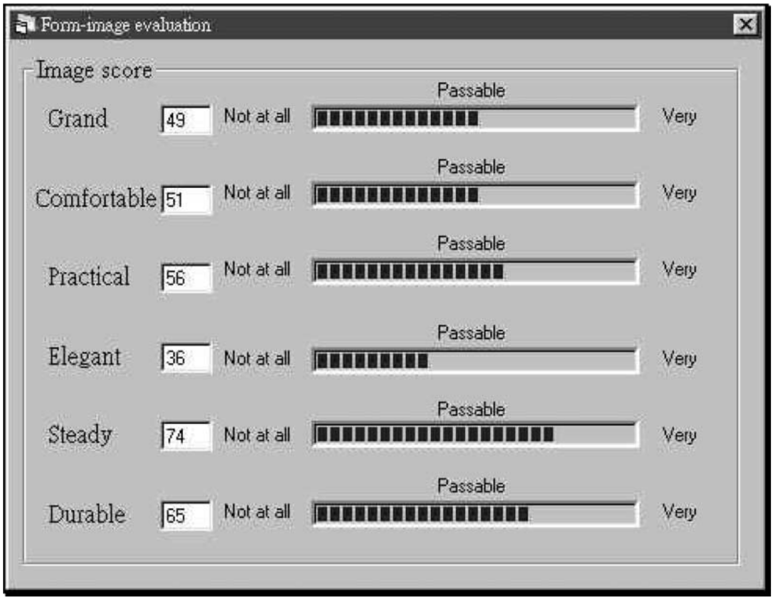

Figure 13 An image evaluation window

block (Fig. 7) to a given value for each part. Then select the shapes of the 'armrest' and 'base' by marking one of the shapes given in this Figure. The given shape parameters and assigned shapes for all parts, in this case, are shown in Fig. 14.

(2) When the shape for each part has been assured, the icon 'Go' (Fig. 7) is marked to enter the configuration-rendering window to see the assembled product from different views (Fig. 11).

(3) Check the obtained image scores for different images (Fig. 13). The result shows that the arrangement of the image scores for the obtained product is 'Steady' (0.74), 'Durable' (0.65), 'Practical' (0.56), 'Comfortable' (0.51), 'Grand' (0.49), and 'Elegant' (0.36), suggesting that the designed product has strongly 'Steady' image and somewhat 'durable'.

(4) If the designed product does not satisfy the desired image, the designer can change the form(s) of the product by repeating steps 1–3 to design a new type until the result is satisfactory.

The image variations for several different designs obtained by regulating configuration parameters are compared in Table 7. The results shown in row 2 are the six image values for the product having the configuration parameters shown in Fig. 14. When the value of the first parameter for chair back is changed from 5 to 9 and the other parameters remain unchanged, the images of the new product change to the result shown in row 3. Similarly, if the first parameter value for chair back is changed to

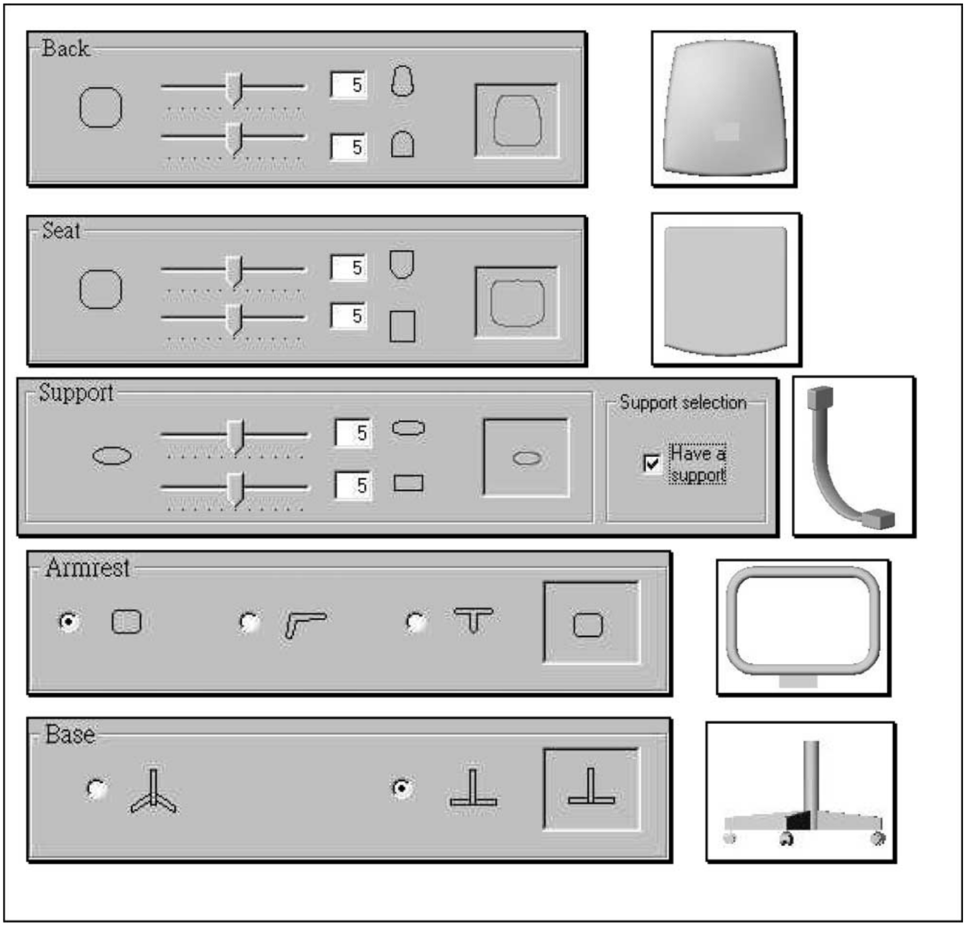

Figure 14 An example of setting configuration parameters and showing parts shape

Table 7 Image variations for regulating the configuration parameters

Change item	*Evaluation item*					
	Grand	*Comfortable*	*Practical*	*Elegant*	*Steady*	*Durable*
First item is '5'	49	51	56	36	74	65
First item is '9'	63	64	69	47	69	71
First item is '1'	31	31	42	24	76	60
First item is '1' T-shaped armrest	35	44	41	29	68	69

1, the images of the new product change to the result shown in row 4. On the other hand, if the configuration parameters in previous case remain unchanged except the armrest is changed from square to T-shape, the product images change to the values shown in row 5. The result shows that the image of a product is significantly influenced by its configuration parameter(s). Meanwhile, the image variations are not confined on a particular image, which means that a single configuration parameter or the shape of an element is changed; the image feelings for the product with respect to different images are all simultaneously changed.

Based on this design model, not only regulating the configuration parameter(s) or element shape(s) can create many different product models, but the designer can also grasp the image feeling of the whole product in the idea development stage.

6 *Conclusion*

In the design stage, how to generate creative design ideas with desired image feelings is a very important problem that the designer pays much attention to. However, the relationship between form and image is not easily obtained with one's intuitive feeling, even for an experienced designer. To solve this problem, an experiment was performed to establish the relationship between product forms and their images in this study. Then a back-propagation neural network was used to analyze the relationship between the configuration parameters and their image feelings based on the experiment results. A computer program was constructed to help the designer to create new product types by regulating the configuration parameters or the element shapes and then grasp the image feeling of the designed product with the learnt weights of the neural network. Though the development of an office chair is taken as an example in this study, this method can also be used to develop other products.

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