# Computer aided three-dimensional colour planning and visualisation system for product design

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The colour planning and visualisation system we proposed in this paper utilised automatic colour planning algorithms for colour scheme generation. The purpose of the system is to help designers efficiently colour-match their product designs. The proposed system includes four major functions: (1) the model component arrangement, (2) colour arrangement, (3) visualisation, and (4) the online evaluation functions. Through the four system functions, the designers should be able to create a preferred colour scheme faster than traditional colour planning tools/methods. The pilot study results show that the system does help design students greatly reduce the time required on the colour planning process aspect of product design when compared with using their favourite traditional colour planning software.

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## Introduction

The impact colour has on human life is extremely significant. In addition to its visual effect, colour, through the visual sense, gives people different levels of mental and physical perception [1-6]. Visual preference for colour is also engendered to affect the results of product marketing and the customers' desire to buy [7]. The application of technology to help designers design what the customer wants is very important [3,8,9]. Therefore, how to meet the product designer's demands, and complete the colour scheme for the product in an efficient and timely manner, is worthy of our attention and the focus of this paper.

## Related work

A vigorous product development process normally follows a series of steps including market analysis; establishing a design goal; product positioning; design analysis; concept development; design evaluation; proposal selection; colour planning; and developing a marketing strategy [10-12]. Following the course of the design process, the appearance, style, and colour presentation of the product will eventually be determined by the effective implementation of the colour plan and the optimization of the colour design. This helps in the decision making process and enhances acceptance of the product presentation [13]. Also, the interface used in the colour design should take into account the design principle for the product colour arrangement and the user's intended use of the product [14-18].

The product image, formed by its final shape and colour, both directly and indirectly influences the user's degree of desirability and choice. The colour image of a product obviously plays a very important role in determining product desirability. Colour preference, as a result, influences the desire to buy a product in a very significant way [19,20]. Hsiao, based on Fuzzy Logic, incorporates colour and hue for product image evaluation [21]. Tsai employs a parameter formula to establish shape and colour assessment, and utilises the neural network model to predict the outcome of design evaluation [22]. Lai utilises the concept of Kansei Engineering, in conjunction with the neural network, to analyse and predict the attractiveness of various cell phone colours via the quantitative theory. Consequently, we can see that, in addition to the shape of a product, colour is an important element in determining product desirability [23]. The final colour-design combination of the product helps finalise the design decision [13]. This study, however, employs phong shading to present a computerised colour simulation, which lacks consideration of the light and materials used. As a result, the colour generated in the product appearance simulation is not accurate enough. The actual effect of the product colour design is, consequently, only partially apparent. Therefore, we need to focus our attention on how to utilise computer simulation technology to bring simulated colour arrangement closer to reality and enhance the likelihood of a more realistic product appearance simulation. In order to help select an appropriate colour arrangement proposal, we will also need to employ automatic computing that creates a satisfactory effect and generates sufficient quantity of colour schemes. Colour scheme generation and screening helps designers enhance colour utilisation and efficiency.

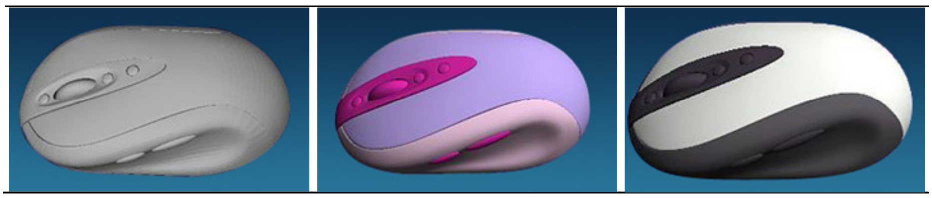

*Figure 1: Effect of geometric modelling at different stages: no colour (left), random colouring (middle) and coloured according to colour design tool (right).*

Based on the colour space system of Munsell and Moon & Spencer' Model as the theoretical foundation of colour arrangement [24-26], this study incorporates harmonisation theory's essential-colour colour design, dual-colour colour design, and multiple-colour colour design modules with the addition of optional colour selections. Using a real-time computing diagram of the illuminating effect of the environment, our system provides solutions ranging from a prototype with no colour at all to offering nearly endless colour-matching proposals to produce a more appealing effect (Figure 1). Our system generates a series of colour-matching proposals engendered via automatic computation. These proposals provide a visual colour selection reference for designers and designing teams which can be used for product proposal evaluation.

## Program design

Our product design colour-matching system includes four major functions: (1) the model component grouping function, (2) the colour arrangement function, (3) the visualisation function, and (4) the online evaluation function. Prior to utilising Moon-Spencer's harmony and Munsell's Law for colour harmonisation and matching, we grouped computer model components to determine which blocks belonged to the same colour. The second stage involved real-time computing of the visual simulation and high-resolution computer graphics. In the final step, the system suggests various colour-matching proposals and then selects an image preference evaluation through the network to be used as a reference for colour design planning. The system structure is shown in Figure 2.

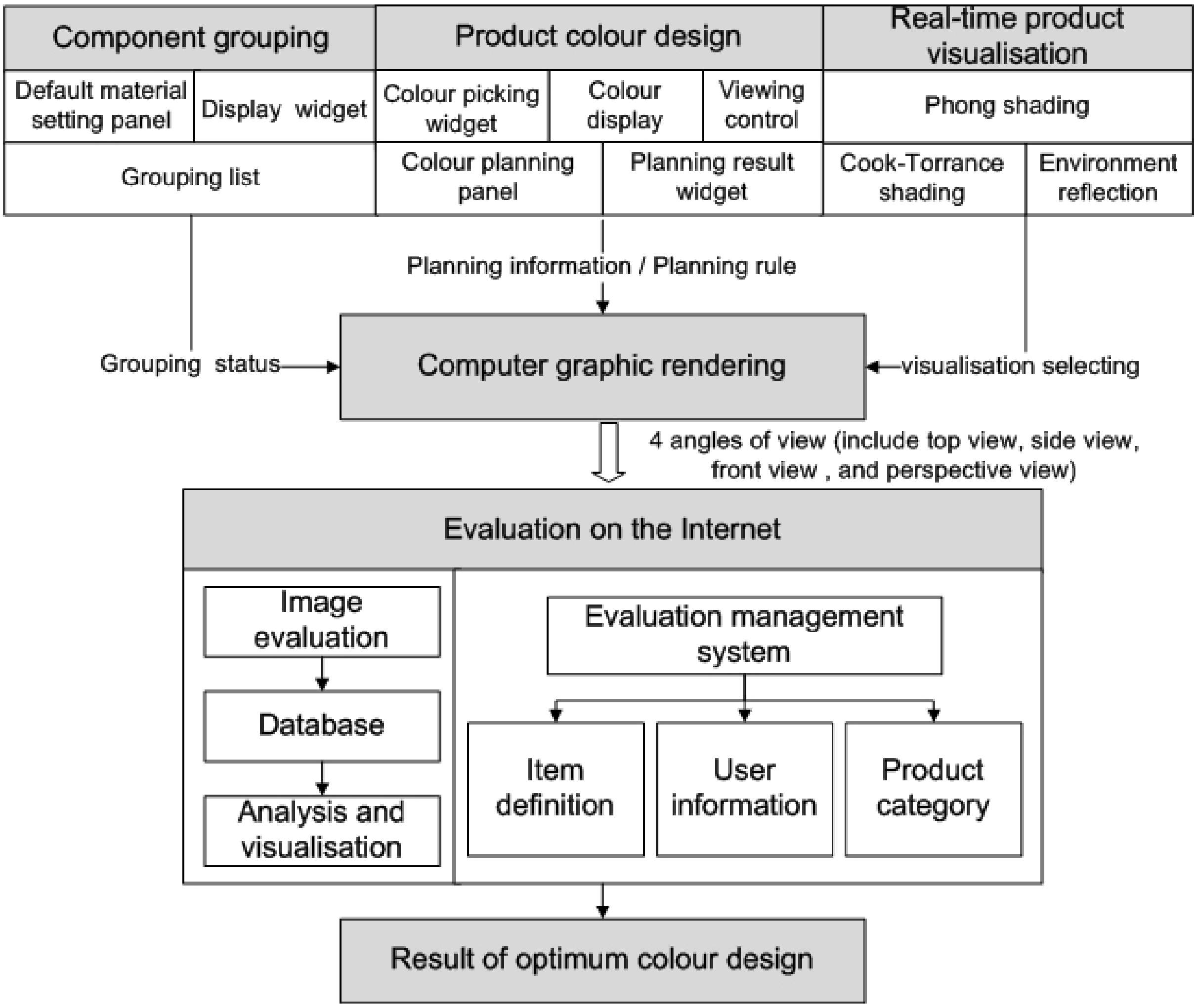


*Figure 2: System structure.*

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### *Interface design*

The user interface includes four primary functions: (1) the model component group, (2) the colour arrangement function, (3) the visualisation function, and (4) the online evaluation function. The geometric component group includes four major functions which are divided into the model component group and the cancellation group. The colour arrangement function consists of (1) a colour picking widget, (2) a colour display widget, (3) the viewing control, (4) the colour planning panel, and (5) a planning result widget. The visualisation function is made up of (1) phong shading, (2) Cook-Torrance shading, and (3) an environment reflection effect. The user-supported evaluation function includes an (1) evaluation management system, (2) an image evaluation, (3) analysis, and (4) visualisation.

In the operational process, the user must first select blocks of the geometric component group for the same colour and then choose the colour design mode. This is done for product visualization materials such as plastics and metals also. According to the colour design rule, automatic computing is then performed in the final stage and the designer, based on his professional expertise, will then select differentiated samples for evaluation. This process may be repeated and adjusted continuously as necessary until the desired effect is obtained. Following evaluation, the optimal colour design is then chosen by the organisation or design team (Figure 3). The detailed operation of the system design process is shown in Figure 4.

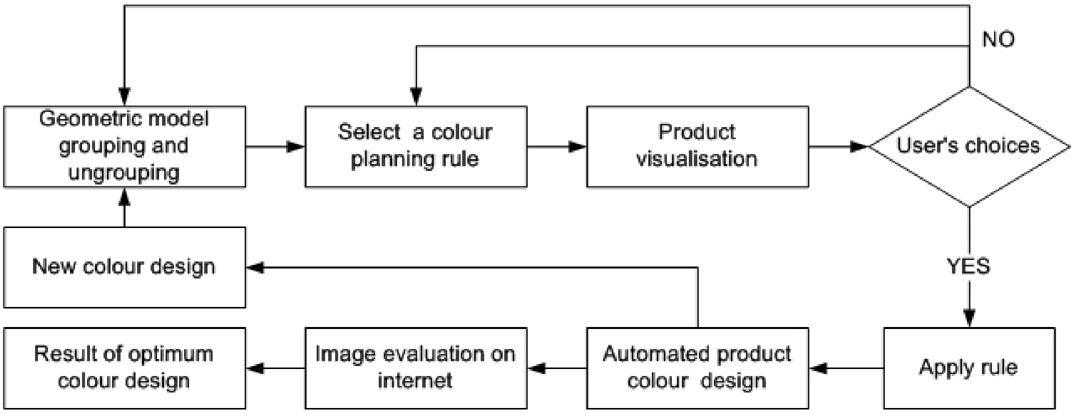


*Figure 3: User interaction procedure model.*

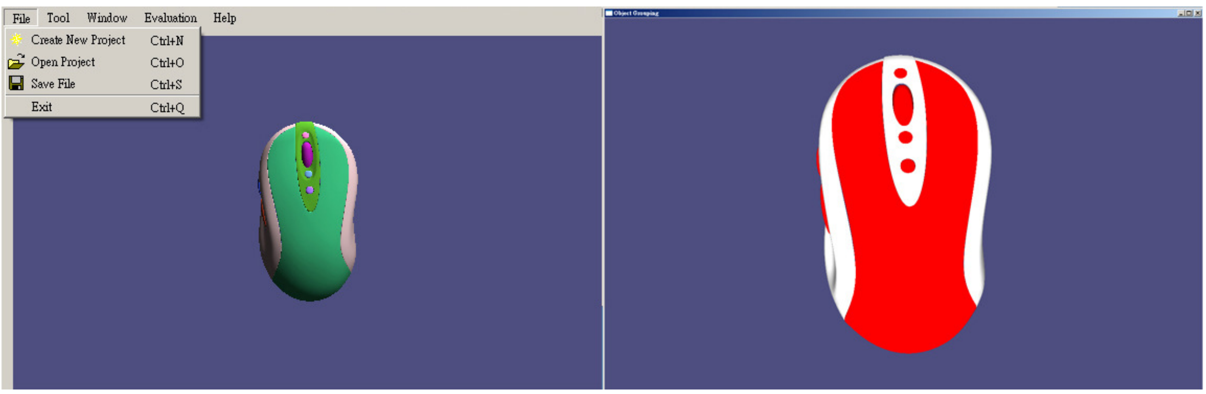


*Figure 4 (a): Illustration of the design system operation: import 3D model (left) and group the elements that are required to have the same colour (right).*

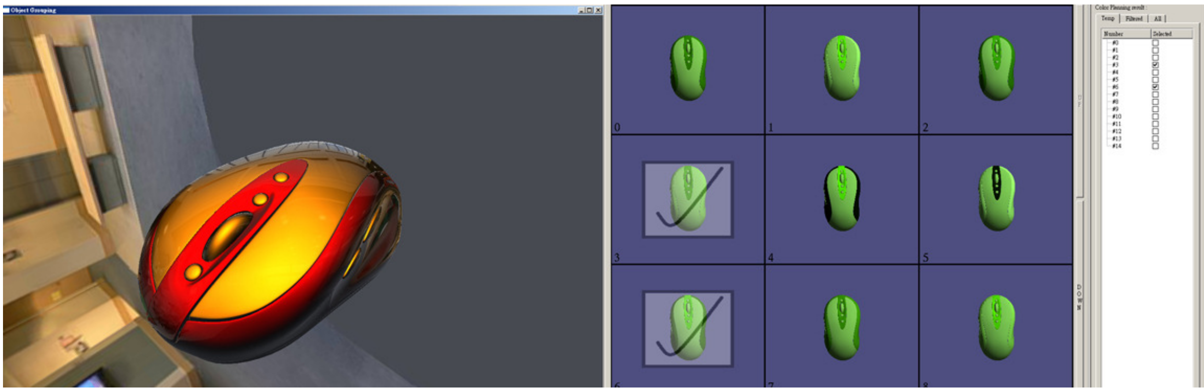

*Figure 4 (b): Illustration of the design system operation: optional setting for materials such as gold, silver copper, aluminium and plastic (left) and colour-picker interface with colour scheme options (right).*

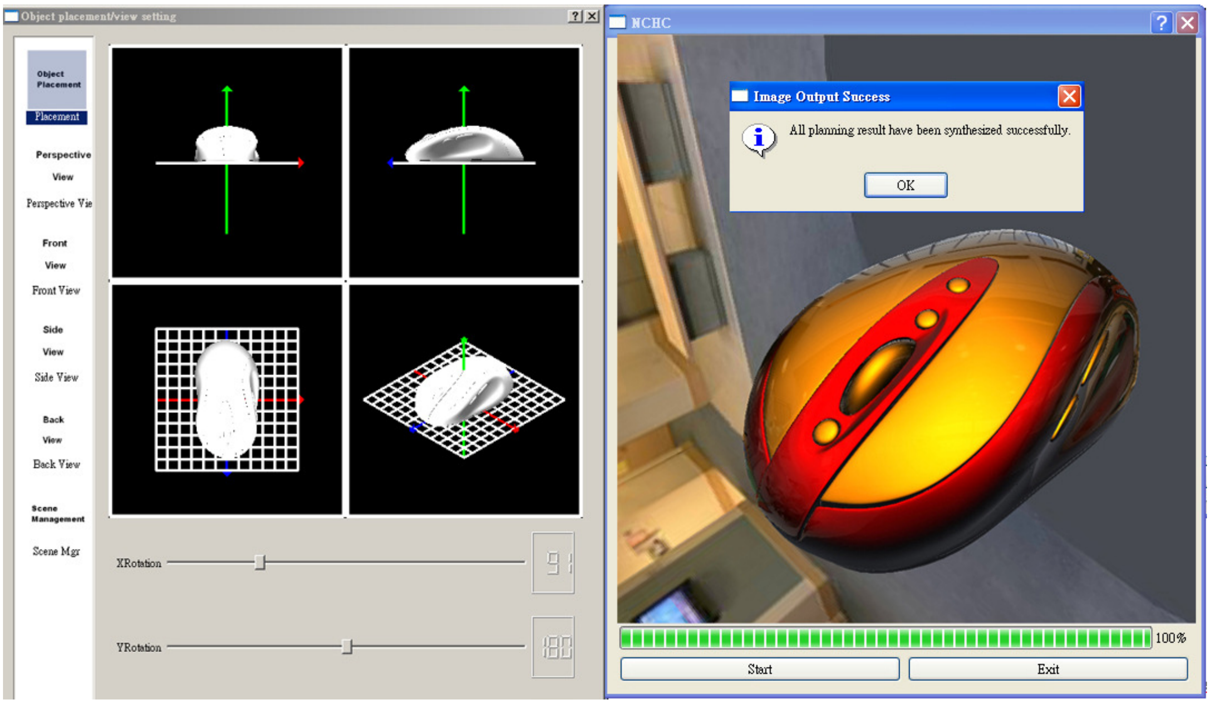


*Figure 4 (c): Illustration of the design system operation: setup model view point such as elevation, side, top and perspective views (left) and render colour scheme according to the setup specifications (right).*

### *Choice of language*

This system employs a network-structured evaluation mode and uses PHP in tandem with MySQL database management. The 3D product visualization program is written in the OpenGL API 2.0 programming language. The GUI interfaces are designed via Qt GUI Designer (version 4.0.1). The system integration and development environment is Visual Studio .Net 2003 and the programming language is C++.

### *Product colour design and computing*

In general, the purpose of colour design is to create a visual order of two or more colours and to harmonize the overall presentation between the two contrasting elements, order and diversity. Prior to automatic colour design, this study employs the HSV colour selecting system which is frequently used by designers. In order to ensure data integrity during colour design computing, HSV must first be converted to the RGB colour mode. This study employs the two colour modes of colour design for development, Munsell's Law and Moon & Spencer's Model.

Munsell's Law:

$$A_1V_1C_1 = A_2V_2C_2 = A_nV_nC_n \qquad \text{eqn. 1}$$

where $A$ is area, $V$ *is* colour value, $C$ is chromaticity, and $n$ can be any number specified.

Moon & Spencer's Model:

$$A_1[C_1{}^2 + 64(V_1 - 5)^2]^{1/2} = A_2[C_2{}^2 + 64(V_2 - 5)^2]^{1/2} = A_n[C_n{}^2 + 64(V_n - 5)^2]^{1/2} \qquad \text{eqn. 2}$$

where $A$ is area, $V$ *is* colour value, $C$ is chromaticity, and $n$ can be any number specified.

According to the two aforementioned colour designs, there are some frequently used methods such as monochromatic, analogous, complementary, and special colour designs, all of which will be explained in detail as below.

*Dual-colour colour design*

Dual-Colour Colour Design is colour design based on hue. According to the angle of a colour formed in the hue circle, it can be divided into monochromatic colour design and analogous colour design. A greater angle formed by two colours equates to the two having less colour in common whereas a smaller angle equates to the two having more colour in common.

- Monochromatic: In monochromatic colour design, an essential colour is chosen and the value and chromaticity of the other is changed to match the essential colour.
- Analogous: In analogous colour design, after one colour is chosen, the other colour is chosen varying 15° to the right or to the left.
- Complementary: the principle of complementary colour design is that the two colours vary by 180°.

*Colour design involving three colours or more*

- Split-complementary: After one colour is selected, the other two are analogous to its complementary colours.
- Triad: Three-colour colour design with the angle between each colour is 120°.
- Tetrad: Two sets of complementary colours. The included angle between the two essential colours is 5-60°.

*High-contrast metal colour design*

Based on the colour design formula, the metal tint is seen as a colour of high value and low chromaticity. The angle is determined by the metal tint itself. As an example, the complementary colour of sapphire blue is yellow. There are exceptions also, though, such as the colour gold should not be matched with the colour yellow or the colour silver with the colour light gray to avoid confusing similar colours.

### *Rendering effect*

The computer graphics of this system are primarily performed using (1) the phong shading model, (2) the Cook-Torrance shading model, and (3) the environment reflection effect.

*Phong shading model*

The current technology employed for image development commonly divides colour development into three components: scattering ($I_d$), reflection ($I_s$), and environment ($I_a$). The environment component, ($I_a$) takes into account absorption of environmental light by the material and indirect illumination of the environmental light. ($I_d$) focuses on the relation between the incident angle of the light and the surface normal vector of the object. Thereby, we know that the scattering intensity is adjusted proportionally in relation to Cos$\theta$. ($I_s$) tells us that the rougher the material ($Ns \approx 0$), the more the reflection will be scattered and, as a result, highlights will be less prominent. Conversely, the smoother the material, the more the light will be concentrated at angle $\Phi$ and produce a highlight. When the object image is finally developed, the colour seen from the point on the plane can be determined via $I = I_d + I_s + I_a$.

The components of the light are divided into three major modes: ($L_a$): environmental light (used to simulate indirect lighting), ($L_d$): scattering light (the primary colour of direct lighting), and ($L_s$): reflection light (the colour of reflected light). The surface materials of the object are also divided into several corresponding components: ($K_a$): the material component that absorbs environmental light, ($K_d$): the material component that absorbs scattering light, ($K_s$): the material component that absorbs reflection light, and ($N_s$): the material surface roughness (in general, the greater the value, the smoother the surface).

The colour of the light shown on the material can be approximated by three elements: (1) environment, (2) scattering, (3) and reflection.

$$I_d = K_d L_d \mathrm{Cos}\theta \qquad \text{(scattering)} \qquad \text{eqn 3}$$

$$I_L = K_L L_L (\mathrm{Cos}\Phi)^{Ns} \qquad \text{(reflection)} \qquad \text{eqn 4}$$

$$I_a = K_a L_a \qquad \text{(environment)} \qquad \text{eqn 5}$$

$$I = I_d + I_s + I_a \qquad \text{eqn 6}$$

where L is the direction of the light, N is the normal vector at the point, R is the direction of reflection of the light, V is the direction of the observer. Figure 5 shows the phong shading model with the circled area indicating the scope of highlight.

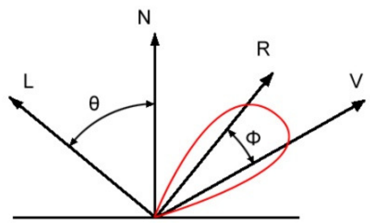


*Figure 5: Phong shading model.*

*Cook-Torrance shading model*

We consider the roughness of the object's surface material. From a microscopic perspective, we utilise the probability model to compute the outcome of lighting the object's surface. The possible outcomes are divided into three effects: (1) a scattering effect, (2) a geometric item effect, and (3) a reflection effect. The scattering effect takes into account the reflection of the light off the object's facet slope which results in the showing of the primary colour. The geometric effect takes into account the situation where the reflection of the light from the object's surface is blocked by the surface itself. For the refection effect, according to the average normal vector on the object surface's (i.e. Gaussian distribution), the positions of both the light and the observer, in conjunction with the probability model, are used to compute the reflection [27].

*Environment reflection effect*

Six environment photos taken and stored beforehand are pieced together as a picture block. According to the relationship of the normal vector between the observer and the object's surface, the direction of the reflection is computed during real-time development. The colour of the picture block *in that direction* is then identified and incorporated to generate the effect of the reflection.

### *Design evaluation*

This study is joined by two different groups of participants. The two different groups are a group of designers and an anonymous user group. Concerned scholars believe personal decision, based on personal character and perception is susceptible to subjective bias. The advantage of a group decision is that the members of the group incorporate views from various backgrounds which result in more comprehensive information. Also, group decisions enhance the acceptance of different problem-solving approaches [28,29]. Therefore, in order to effectively provide professional assistance for colour design planning, our system employs two different approaches. Backend planning of the evaluation both adds and reduces evaluation items. The group evaluation information includes three items: (1) view drawing, (2) perspective, and (3) both the RGB and HSV values. The evaluation items include "Strongly Agree," "Agree," "Somewhat Agree," "No Comment," "Somewhat Disagree," "Disagree," and "Strongly Disagree." The information presented can be selected by the designer and automatically included in the evaluation system during diagram computing for group members' comments. The final result is selected via cooperation and discussion.

## Case computing outcome

### *Case study of the mouse models*

First, the mouse digital file format is converted into OBJ format. Next, the digital model is read into the system. After that, the mouse model components are grouped and the blocks sharing the same colour are assigned to the same group (Figure 6). In the colour selection mode, different colour matching patterns are available such as monochromatic, analogous, and complementary colour designs. Different colour matching patterns include their own parameters, for example, the setup of the angle of the colour. With the monochromatic colour design pattern, an essential colour is chosen and then the value and saturation of the other colours are changed to generate monochromatic colour scheme. With the analogous colour design pattern, after one colour is chosen, the other colour is chosen from 15° either to the right or to the left. With the complementary colour design pattern, the idea is that the two colours be 180° apart.

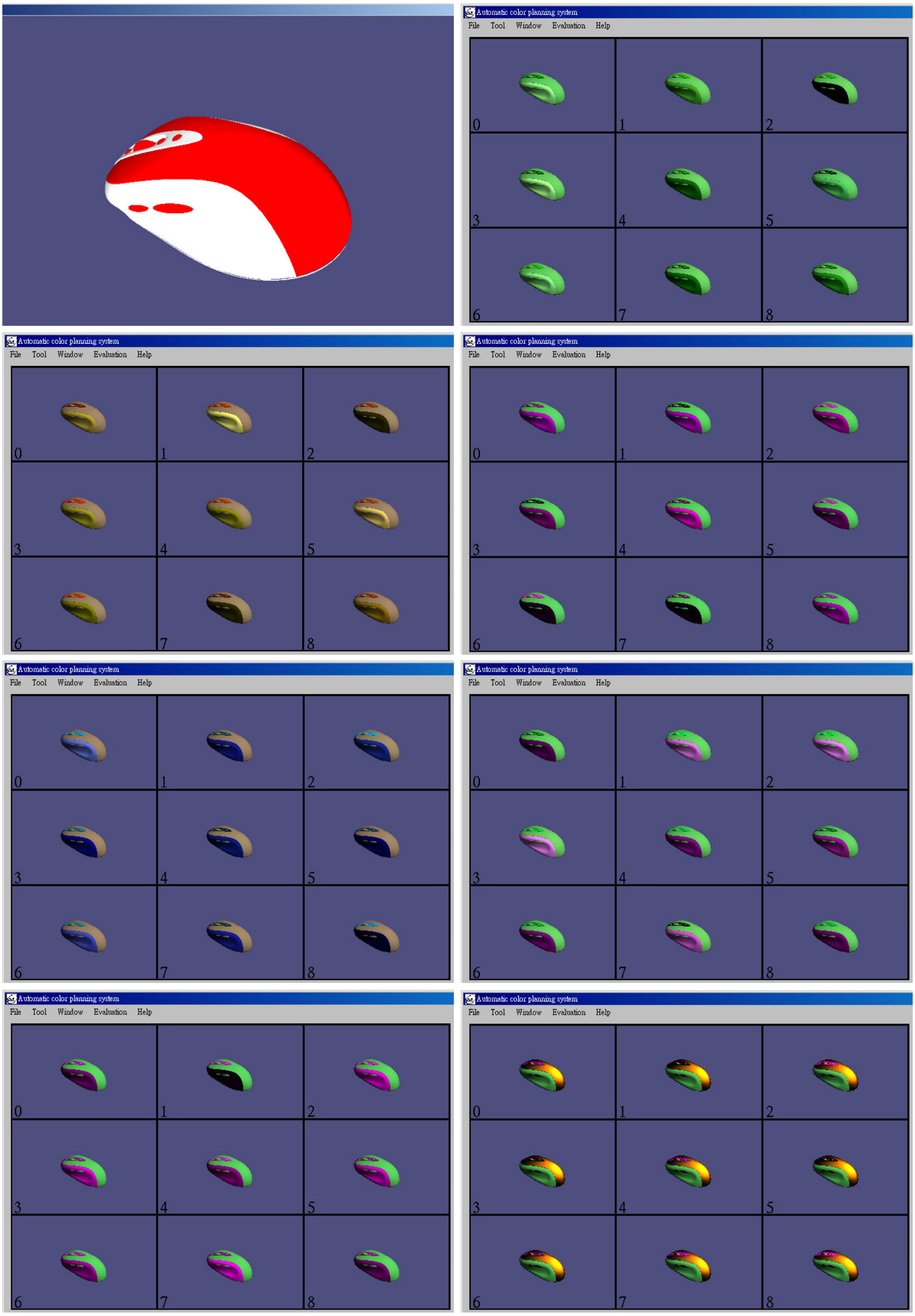


*Figure 6: Example outcomes of the colour planning and visualisation system: (a) distribution of colour block; (b) monochromatic colour design; (c) analogous colour design; (d) split-complementary colour design; (e) triad colour design; (f) tetrad colour design; (g) complementary colour design; (h) high-contrast metal colour design.*

Initial colour design computing is able to generate a nearly limitless number of match possibilities which, as a result, makes available more colour design options for the designer to choose from.

### *Network evaluation*

In the example using the mouse, there are hundreds, even thousands, of possible colour matching combinations and outcomes. During the proposal screening process, designers can utilize the system's network evaluation function to finalize both the colour design proposal and the product series planning. The system's network-based collaboration evaluation mechanism facilitates the generation of the final proposal (See Figure 7).


*Figure 7: Evaluation screen of the colour planning and visualisation system.*

## Experimental

There were 17 male and 22 female participants in our experiment. All of the participants were industrial design students between 19 and 23 years old. The 3D model used in the experiment was a 3D computer mouse. The experiment was divided into two phases: (1) the system (a.k.a.) computer-aided colour planning phase and (2) the manual colour planning phase. The students were also divided into two groups. One of the groups worked on the computer-aided colour planning experiment while the other group worked on the manual colour planning experiment.

In the computer-aided colour planning experiment, the participants were asked to use two different colour theories (i.e. Moon and Spencer and Munsell colour theories) to generate five different colour schemes respectively. The colour matching theories were provided by the system. After ten colour schemes were selected using the computer-aided system, the participants were asked to complete a questionnaire regarding their user experience with the computer-aided colour planning system.

During the manual colour planning process, the participants were allowed to use commercial software (e.g. Photoshop, CorelDraw, or Illustrator) to manually design a colour scheme for the mouse. After the participants agreed on the best colour scheme, they were asked to complete a questionnaire regarding their user experience with the manual colour planning process.

The two Likert scale method-based questionnaires were designed to help us better understand the participants' user experience with the two colour planning tools (i.e. computer-aided and manual). Each questionnaire consisted of four questions and five choices per question: "Strongly Agree," "Agree," "No Opinion," "Disagree," and "Strongly Disagree." The questions were as follows:

1. The colour planning method satisfied my personal colour planning needs.
2. The colour planning method helped me obtain my preferred/favourite colour schemes.
3. The colour planning method effectively helped me reduce the time I spent on colour planning.
4. Overall, the colour planning system helped me with my colour planning.

In order to get additional feedback on the system, the participants were also asked to write two short essays regarding their user experience with the colour planning system. Also, the time the participants spent designing their colour schemes using the system was recorded.

To ensure colour consistency and accuracy, the same laptop was used throughout all of the experiments. Also, the LCD screen was colour calibrated using a SPIDER2 PRO colorimeter. The experiment results are shown in Tables 1 and 2.

| Question number | Question | SA | A | NO | D | SD |
|---|---|---|---|---|---|---|
| 1 | The colour planning method satisfied my personal colour planning needs. | 0% | 64.1% | 23% | 10.3% | 2.6% |
| 2 | The colour planning method helped me obtain my preferred/favourite colour schemes. | 0% | 79.5% | 12.8% | 5.1% | 2.6% |
| 3 | The colour planning method effectively helped me reduce the time I spent on colour planning. | 5.1% | 23.1% | 38.5% | 28.2% | 5.1% |
| 4 | Overall, the colour planning system helped me with my colour planning. | 12.8% | 59% | 20.5% | 5.1% | 2.6% |

*Table 1: Results using manual colour planning system (SA: Strong Agree; A: Agree; NO: No Opinion; D: Disagree; SD: Strongly Disagree).*

| Question number | Question | SA | A | NO | D | SD |
|---|---|---|---|---|---|---|
| 1 | The colour planning method satisfied my personal colour planning needs. | 0% | 64% | 23.1% | 10.3% | 2.6% |
| 2 | The colour planning method helped me obtain my preferred/favourite colour schemes. | 10.3% | 53.8% | 15.4% | 17.9% | 2.6% |
| 3 | The colour planning method effectively helped me reduce the time I spent on colour planning. | 17.9% | 61.5% | 10.3% | 10.3% | 0% |
| 4 | Overall, the colour planning system helped me with my colour planning. | 15.4% | 69.2% | 10.3% | 5.1% | 0% |

*Table 2: Results using computer-aided colour planning system (SA: Strong Agree; A: Agree; NO: No Opinion; D: Disagree; SD: Strongly Disagree).*

In order to better understand the participants' opinions regarding the two methods, we scored answers given from 4 to 0, from "Strongly Agree" to "Strongly Disagree," respectively. According to Tables 1 and 2, the average scores of the four questions from both systems are shown in Figure 8.

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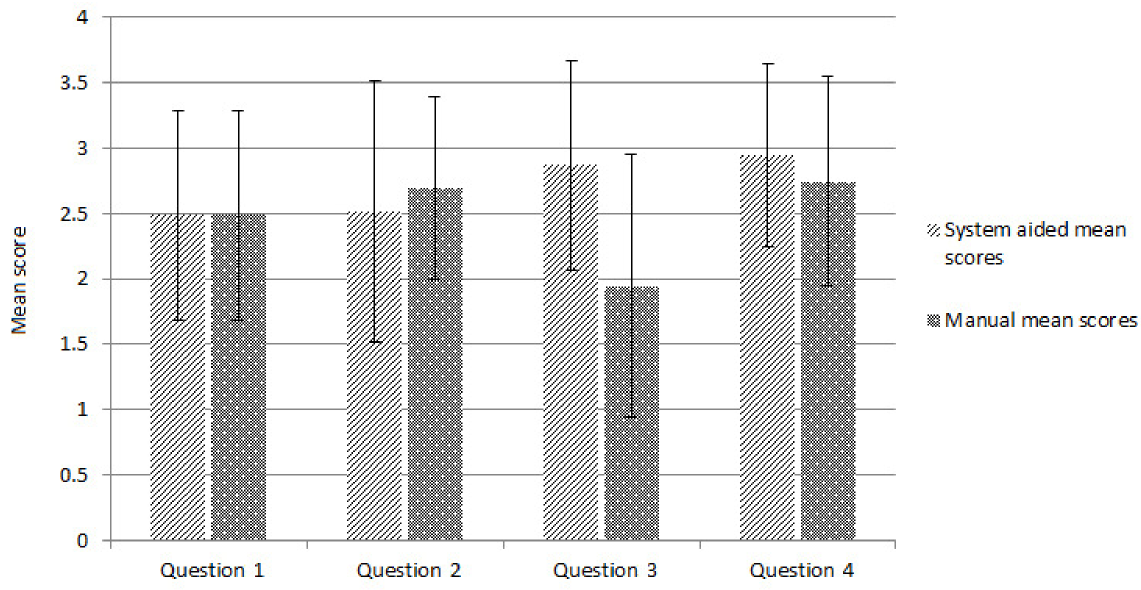


*Figure 8: Comparisons of the average scores/deviations using the different colour planning systems.*

According to Figure 8, the most obvious difference between the two systems is that the computer-aided colour planning system scored much higher than the manual colour planning system on Question 3. This means that the participants felt that the computer-aided colour planning system helped them shorten the time spent on colour planning. Also, the *actual* time it took the participants to complete their colour planning using the computer-aided colour planning system supports this conclusion as well. On average, it took the participants 11 minutes to create a preferred colour scheme using the manual colour planning system whereas the participants were able to create 10 preferred colour schemes within 21 minutes using the computer-aided colour planning system. We also noticed that the computer-aided system was less successful at obtaining the users' preferred/favourite colour schemes than the manual system.

Additionally, we also found that 30 out of the 39 participants choose the colour schemes generated using the Munsell colour harmony theory as their preferred colour scheme. In the essay questions, the participants also gave positive feedback on the computer-aided colour planning system in terms of time efficiency. However, they also suggested that if the system offered a function which would allow them to slightly adjust the computer-generated colour scheme, it would be more useful than it is currently.

## Discussion

This study attempts to employ computer graphic technology to generate colour design proposals. Using automatic colour design and a series of colours selected by professional designers, the system helps designers finalise their colour design proposal more efficiently. Using the system's built-in network-based evaluation feature, the colour preference and final colour design proposal can be easily confirmed. The system developed for this study can be used for the colour designing of any product.

In the pilot study, most of the participants agreed that the new colour planning system did help them reduce the time they spent on the colour planning process. The results of the pilot study also showed that the time required to produce a satisfactory colour scheme using the new colour planning system is much less than it would be using traditional manual colour planning processes. However, the result also showed that the computer-aided system was less successful at obtaining users' preferred colour schemes than manual system. Some participants did voice criticism that the new system would not allow them to modify the computer-generated colour schemes and that such a function would be highly desirable in a future version.

Limited by current colour design pattern theories, this study primarily focuses on 2D image colour design. Further experimentation is, therefore, required to verify whether using the surface area of the 3D object in 3D colour design computing might involve slight errors. Thereby we will be able to determine if there is a significant discrepancy between the two. Also, collecting information (e.g. colour preferences) from the product user groups for different product categories could be helpful when used as a reference during product development and marketing planning.

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