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A quantitative aesthetic measurement method for product appearance design

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ABSTRACT

Product appearance is one of the crucial factors that influence consumers' purchase decisions. The attractiveness of product appearance is mainly determined by the inherent aesthetics of the design composition related to the arrangement of visual design elements. Hence, it is critical to study and improve the arrangement of visual design elements for product appearance design. Strategies that apply aesthetic design principles to assist designers in effectively arranging visual design elements are widely acknowledged in both academia and industry. However, applying aesthetic design principles relies heavily on the designer's perception and experience, while it is rather challenging for novice designers. Meanwhile, it is hard to measure and quantify design aesthetics in designing artefacts when designers refer to existing successful designs. In this regard, this study aims to introduce a method that assists designers in applying aesthetic design principles to improve the attractiveness of product appearance. Furthermore, formulas for aesthetic measurement based on aesthetic design principles are also developed, and it makes an early attempt to provide quantified aesthetic measurements of design artefacts. A case study on camera design was conducted to demonstrate the merits of the proposed method where the improved strategies for the camera appearance design offer insights for concept generation in product appearance design based on aesthetic design principles.

1. Introduction

Product appearance remains one of the most vital factors in the purchase decisions of consumers [1-4]. In recent years, many companies have made much effort to improve their product appearance to create a competitive advantage in the market. This is especially true in nowadays consumer products (e.g., smartphones, digital cameras, personal computers, etc.). Focusing on improving the attractiveness of product appearance, a plurality of factors is required to address. These factors can be classified into subjective and objective aspects (Table 1). The subjective aspect concerns the expression of design information in product appearance. This aspect affects the way people understand and interpret the product forms and is closely related to the background and life experience of a person (e.g., age, social status, gender, personality, culture, etc.) [5-11]. For example, a product in pink colour communicates more feelings of 'feminine' and is usually designed for female consumers. The objective aspect, on the other hand, reflects the considerations of the constitution and arrangement of visual design elements (i.e., form, colour, texture, etc.) that result in universal appealing product appearances. This aspect reflects the inherent attractiveness perceived by the human senses. It suggests that certain lines, proportions and colour combinations are deemed aesthetically pleasing according to human cognition. Regarding the objective aspect of product appearance, designers generally apply aesthetic design principles to compose and place visual design elements. In product appearance design, visual design elements are viewed as the vocabularies of visual language. They constitute physical product forms containing visual design messages. During the design communication process, the design message will be delivered to people and affect their aesthetic appraisals to the forms. Principles of Aesthetic design are universally acknowledged compositional strategies for visual appearance design [12-15]. They are key in effectively constituting and arranging visual design elements [16,17]. They contain organisational theories of how to compose visual design elements to create aesthetic features (e.g., balance, contrast, unity, etc.)

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Table 1
Subjective and objective aspects of product appearance design.

Product appearance design	
Subjective aspect	Objective aspect
Emotional features	Aesthetic features
• Cute	• Balance
Retro	Contrast
Luxurious	Proportion
…	…

for forming an aesthetically pleasing design. As aesthetic design principles are very important in product appearance design, they are widely applied by product designers and industrial designers. Aesthetic design principles are found implemented in a lot of popular product design artefacts [18-20]. For example, in the famous lemon squeezer designed by Philippe Starck, aesthetic design principles of 'symmetry' and 'uniformity' were applied [19]. Kang [18] proposed a method for aesthetic product design by combining the rough set theory and fuzzy quality function deployment design matrix.

Applying aesthetic design principles involves the considerations on choices of forming the right aesthetic features. As this process relies heavily on designers' perceptions and experiences, it would be challenging for novice designers in product appearance design. Further, the application of aesthetic design principles is also hardly measured and quantified by designers when they refer to existing design artefacts. In addition, little attention has been paid to support the application of aesthetic design principles for product appearance design.

Hence, this study aims to propose a method that assists designers in applying aesthetic design principles for product appearance design with quantification of design aesthetics. To achieve the objective, a framework for improving the attractiveness of product appearance is proposed. In this framework, aesthetic measurement formulas for investigating the application of design principles to form product appearance are developed. Each applied design principle of a product appearance is defined as an 'aesthetic indicator'. With design samples and their aesthetic measurement, the scale of each 'aesthetic indicator' of the design samples is calculated. The scale of an 'aesthetic indicator' reflects how much a corresponding design principle is applied to a design sample. A mapping model between aesthetic indicators and the user aesthetic preference acquired through user assessment is constructed. Based on the mapping model, design optimization is then performed. From the design optimization, enhanced aesthetic indicators that indicate how to use aesthetic design principles to generate improved appearance designs are obtained. This study makes an early attempt in quantifying product aesthetics based on aesthetic design principles. It also facilitates designers, especially novice designers, to evaluate existing design artefacts and generate quality design concepts.

2. Related works

2.1. Product appearance design

Studies on supporting the product appearance design based on their evaluation criteria can be classified into (1) the group that focuses on emotional responses and (2) the group emphasizing the aesthetic constitution rules for organizing design elements.

To access users' emotional responses, Kansei Engineering is one representative methodology [21,22]. Kansei Engineering is defined as 'translating technology of a consumer's feeling (Kansei) of the product to the design elements' [23-26]. Three important issues are addressed in this method: (1) how to capture user affective needs of the product, (2) how to analyze user affective needs and build relations between products and affective needs, (3) how to interpret user affective needs and improve the design of products in subsequent design processes. To acquire users' emotional needs, Semantic Differential (SD) is used as a fundamental method to evaluate the design based on the collected Kansei words through surveys or experiments. A model is constructed to generate the mappings between physical design elements and Kansei words. Various kinds of attempts have been made to extend the Kansei Engineering approach. Chen and Chuang [27] proposed a method that integrates the robust design method and Kano model into Kansei Engineering to enhance the subjective quality of aesthetics and user satisfaction. Smith and Smith [28] combined the Latent Semantic Engineering approach with Kansei Engineering to create a semantic space model that improves the matching accuracy between users' Kansei requirements and product designs. To adjust the inconsistency in the understanding of Kansei tags among different users, Huang, Chen, and Khoo [29] proposed a basic-emotion based SD method to obtain data for establishing the mapping between products and Kansei tags. Yang and Shieh [30] implemented Support Vector Regression to map the relationship between user affective responses and product form features. To identify the crucial design attributes and reduce the data dimension for the neural network, Shieh and Yeh [31] compared Principal Component Analysis (PCA) and Partial Least Squares (PLS) for modelling between design attributes and four sets of Kansei adjectives. They found that PLS had a better performance in the pre-processing of data for training the neural network model. To precisely predict the satisfaction of customers, Dou et al., [32] proposed a satisfaction modelling approach by evaluating customers' satisfaction with products based on Kansei requirements. Then, the satisfaction model for the customers of different clusters were constructed for purchase willingness prediction. Hsiao and Tsai [33] employed Fuzzy Neural Networks to build up relationships between product form parameters and image adjectives and used Genetic Algorithm (GA) for searching near-optimal design solutions. Although Kansei Engineering is successfully in identifying user-preferred design elements, it might not be capable of supporting the placement and arranging design elements [34,35]. The way of arranging and placing design elements has been already decided and would be the same as the way in the original design samples. Moreover, few studies considered the integration of functional design and aesthetic designs.

Only a few studies implemented the aesthetic design theories regarding compositional rules for aesthetic design. Bauerly and Liu [36] proposed several simple algorithms in an attempt to construct human cognitive representations of compositional attributes in terms of 'symmetry', 'balance', and 'number of groups'. Nonetheless, their algorithms were mainly used in the scenario of interface layout design. Lo, Ko and Hsiao [37] defined a set of equations for measuring the aesthetics of product form regarding six aesthetic design principles. Besides, they applied GA to perform product form optimization based on the defined equations. However, colour and texture were not considered in aesthetic measurement as well as in product form optimization.

2.2. Aesthetic design theory

In aesthetic design, design elements are identified as the vocabulary that constitutes the design form [12]. Common recognized design elements were line, shape, colour, and texture [38]. To constitute design elements, many researchers have contributed to tracing rules for designing the psychological appealing form. The appealing form is considered to be a form that maintains the correct aesthetic balance between concinnity order and complex arousal [6]. Towards both arousal-reducing and arousal-driving design directions, aesthetic design principles were adopted to support heuristic guidance for visual composition in design [12,13]. Aesthetic design principles represent how to bring design elements together in a way that creates and conveys beauty. Common applied aesthetic design principles are balance, proportion, simplicity, unity, symmetry, contrast, harmony, etc. and are reviewed as follows.

(1) Balance: Balance relates to our physical sense of balance that our eyes prefer the visual weight to be equal on the two sides of an

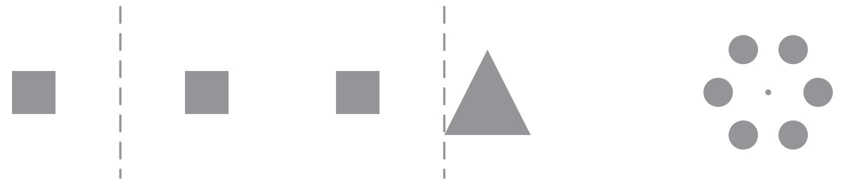


Fig. 1. Types of balance.

axis. Balance occurs in a design composition when visual elements are equally distributed to deliver a sense of visual stability [39,40]. In general, there are three types of visual balance: the formal balance (symmetry balance), the dynamic balance (asymmetry balance), and the radial balance (Fig. 1). The formal balance and dynamic balance are commonly observed in product design, and we mainly focus on the measurement of these two aspects.

(2) Proportion: Proportion considers the comparison between the sizes and scales of the body and the elements. It is an important principle related to styling design. Proportions are generally expressed in the matter of constant ratios, which are the basis of the proportional system. Many classic proportional systems have been preserved from ancient times until now. There are ratios constructed by root rectangles ($1:\sqrt{2}, \sqrt{3}, \sqrt{4}, \sqrt{5}$) [41]. The golden ratio originally used by Greeks as a means of achieving beauty forms has been one of the most widely used proportional systems [16].

(3) Simplicity: Human tends to perceive and interpret simple forms more than those ambiguous or complex forms [42-44]. The aesthetic of simplicity is one crucial element and is being heavily applied. Simplicity is about making design easier to understand, subtracting the core and removing all unnecessary elements in design composition.

(4) Unity: Unity is the fundamental aesthetic design principle that helps to gather design elements together and create connections between elements to form the design as a whole. Unity is based on the gestalt grouping laws of gestalt theory. Gestalt theory indicates that our mind tends to perceive things that are viewed as a unified whole rather than a sum of individual parts [45,46]. Commonly used Gestalt grouping laws are similarity, proximity, alignment, closure, continuation, figure and ground, etc.

(5) Symmetry: Symmetry means the design compositions are formed in the same way on both sides of an axis. It is a state of visual balance, the formal balance. It can be achieved by repeating the reverse of a design layout on the opposite side of a defined axis, either horizontal, vertical or angled. The aesthetic design principle of symmetry has long been associated with physical concinnity, natural, or man-made and has been commonly found in classical architectures [47,48]. There are three types of symmetry (reflective, rotative, and translative) [39].

(6) Contrast: Contrast refers to the arrangement of design elements with noticeable differences in a piece to draw and direct attention, generate emotions, and create emphasis on information. Contrast consists of strategies that are opposite of visual harmony.

(7) Harmony: Harmony in our aesthetic measurement model mainly refers to colour harmony. Colour harmony helps to select and combine colours in a fashion that is harmonious to human eyes, which is related to hue configuration. There are primarily several kinds of hue harmonious: complementary harmonious, split complements, triad harmony, tetrad harmony, analogous harmony, etc. [16,49].

However, aesthetic design principles are generally formulated in qualitative descriptions [50]. The application of aesthetic design principles varies with designers' perceptions and experiences. Without extensive experience, it may be hard to decide the use of aesthetic design principles for generating design concepts [51] successfully.

2.3. Aesthetic measurement

Studies on the measurement of product aesthetics can be classified into the groups of (1) understanding the form preferences, (2) quantifying human feelings or emotions, and (3) assessing aesthetic design theory.

Studies on the first group were focused on identifying the relationships between shape dimensions and preferences of users and measuring the product form aesthetics based on the form preferences. For example, Kelly et al. [52] incorporated the form preference to measure the aesthetic appealing forms in the given context and combine the form preference with engineering performance under a design optimization paradigm. Orsborn, Cagan, and Boatwright [53] implemented a utility function that incorporates several defined form parameters to quantify the aesthetic form preference. Based on the utility function, product form designs that match the form preference are created. However, this way of measuring product aesthetics cannot capture the implied meanings behind the product form.

Studies on the second group translate product aesthetics into semantic labels representing certain emotional meanings. For example, Hsiao, Chiu, and Chen [54] used the semantic word 'female' and 'male' to analyze the hue, value and chroma of colour and proposed an aesthetic measurement formula for evaluating the aesthetic degree of colour matching. The most typical research of this group is the Kansei Engineering, which has been reviewed in Section 2.1. Nonetheless, this group does not include the aesthetic analysis based on the aesthetic theory for creating universal appealing forms.

Studies on the third group analyze product aesthetics based on classic aesthetic theories and aesthetic design principles. Birkhoff [55] first proposed a measured approach that divides aesthetic design principles into two groups: orderliness and complexity, as indexes for evaluating aesthetics. According to Birkhoff, aesthetic measure M is defined as,

$$\mathrm{M} = O/C$$

where O represents the number of elements of the order and C denotes the number of elements of complexity. In this equation, the aesthetics is based on 'Unity in Variety', which consists of the argument on aesthetic balance. This equation reflects the degree of beauty between the design of unity and variety. Some studies focus on aesthetic measurement in terms of aesthetic design principles. Bauerly and Liu [36] proposed algorithms to quantify the value of three principle attributes, which are symmetry, balance, and number of groups, to mimic the human cognitive representation of the aesthetic design principle attributes. They discovered the relationship between principle attributes (symmetry) and the overall aesthetic appeal. However, the aesthetic design principles and algorithms used are only for interface design, so fewer aesthetic design principles are used and the algorithms are relatively simple and limited. Lo, et al. [37] created six aesthetic measure equations for evaluating balance, equilibrium, symmetry, proportion,

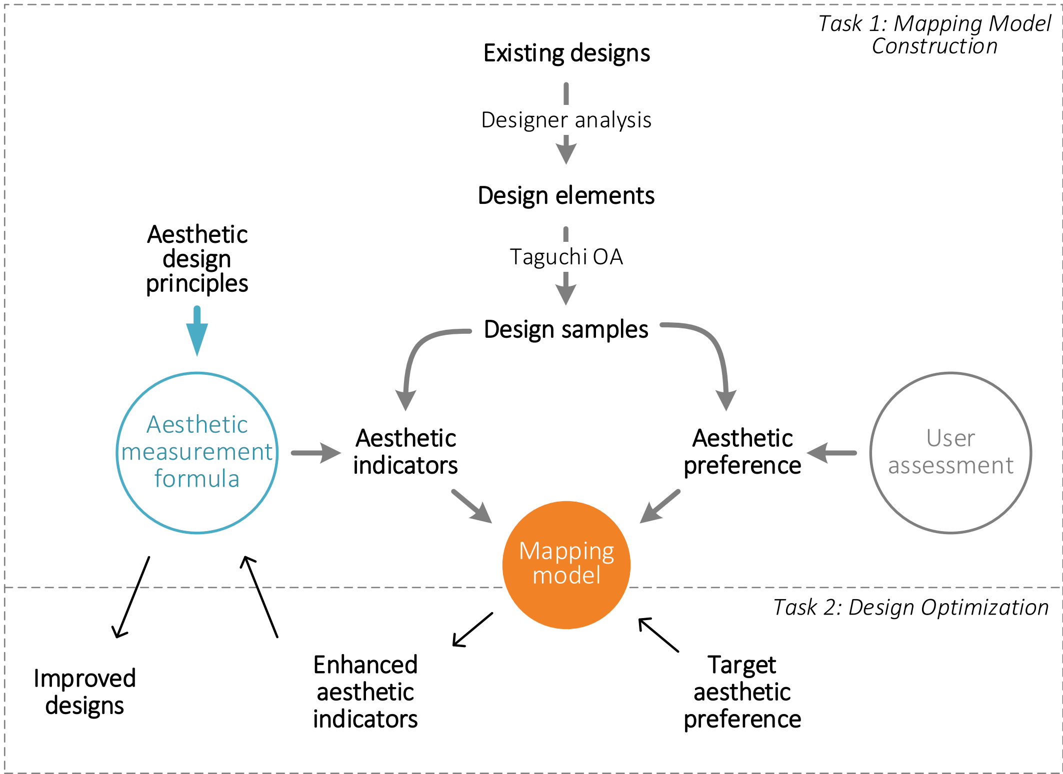


Fig. 2. Framework of product appearance design based on aesthetic design principles.

unity, and minimalist of 3D shape objects, and applied Genetic Algorithm (GA) to optimize the shape. The equations are only applicable to investigate the styling of product shape from the perspective of its overall 3D vision. The chosen aesthetic design principles do not take colour design into account and the aesthetic evaluation of a product's 2D views (e.g., views of front, back, left, etc.) are not included. Combining eye-tracking technologies, Liu et al., [56] developed an aesthetic measurement method to evaluate the design of product appearance. In this study, the International Affective Picture System (IAPS) was employed to select the participants who could represent the public's emotional and aesthetic experience. Thus, based on the aesthetic theory, the index system for evaluating aesthetics was constructed where the relationship between aesthetic evaluation indexes and physiological eye movement indexes was determined. The customer's emotion about each design alternative was evaluated by using eye-tracking techniques to obtain the optimal design. However, aesthetic design elements that are less easily captured visually were not considered in the study.

In summary, most studies of aesthetic, conceptual design emphasize mapping users' emotional responses to product forms for generating aesthetic product forms [57-59]. Only a smaller group of publications discusses the aesthetic design theories regarding compositional strategies for aesthetic form creation. Further, few studies investigate the application of aesthetic design theories in both shape and colour design.

To implement aesthetic design principles for product appearance design, the key challenge is to investigate the use of aesthetic design principles to arrange design elements and provide quantitative analysis. Further, how to employ the analysis results of the use of aesthetic design principles for generating attractive product appearance is another challenge.

3. Framework

The framework of the proposed method is presented in this section. The proposed method aims to systematically support designers to select and apply aesthetic design principles for improving product appearance design. Fig. 2 illustrates the framework. Two tasks are included in the framework: mapping model construction and design optimization. To explore the way of applying aesthetic design principles, the use of aesthetic design principles in existing designs is investigated and quantified in terms of aesthetic indicators. The task of mapping model construction aims to capture the relationships between aesthetic indicators of existing designs and the corresponding user aesthetic preferences that are acquired through user assessment of existing designs. This task contains steps of determining design samples, acquiring aesthetic indicators and aesthetic preference, and constructing mappings. In the first step, design samples are defined by designers with selected design combinations of certain design elements. Design elements are generally extracted from existing designs and contain essential design features and values. To effectively determine design samples, Taguchi Orthogonal Array (OA) is implemented to assign design elements and generate design combinations. The use of Taguchi OA helps to reduce the number of necessary design combinations and allows to select the partial design combinations as design samples with design elements are relative equally considered. In the second step, based on the design samples and their design elements, aesthetic indicators are calculated based on the aesthetic measurement formulas that are proposed to indicate the use of aesthetic design principles of design samples. To be more specific, aesthetic measurement formulas help to quantify the scale of each aesthetic indicator that reflects how much a corresponding aesthetic design principle is found implemented in the product appearance of a design sample through equations. From the aesthetic measurement formula, the value of each aesthetic indicator is obtained. Aesthetic indicators are measured from different design aspects of the product appearance, such as design styling, colour combination, and surface texture. A design aesthetic ontology model is presented in Section 4 to further explain the proposed aesthetic indicators and the relationships between design samples and aesthetic measurement formulas. The equations of aesthetic measurement formulas are also discussed in Section 4. In this step, the corresponding aesthetic preference of design samples is acquired through user

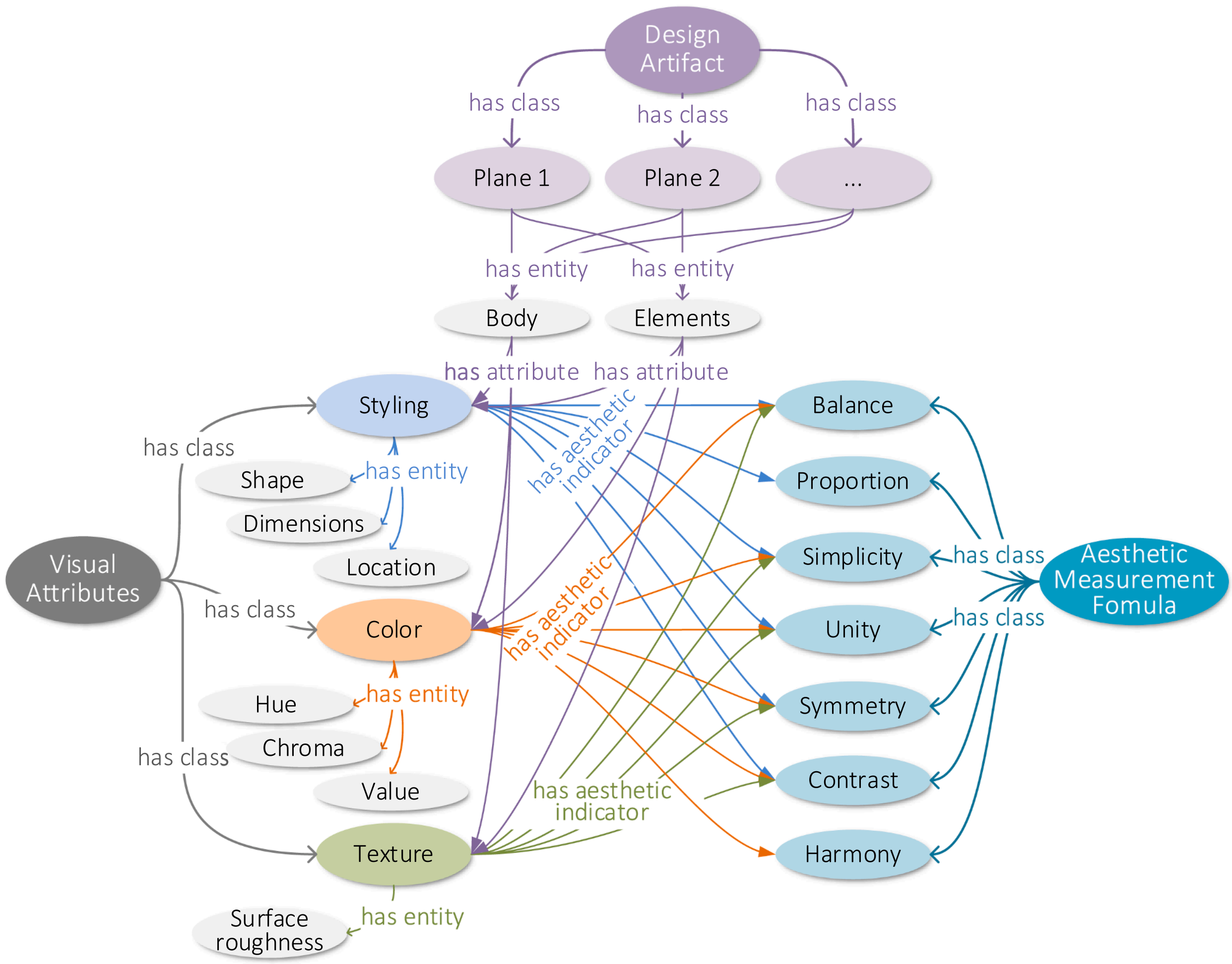


Fig. 3. The proposed design aesthetics ontology.

assessment. In the third step, considering the number of defined aesthetic indicators is larger than aesthetic preference features, a mapping model is built to capture the relationships between aesthetic indicators and aesthetic preference with the input of aesthetic indicators and the output of aesthetic preference.

The mapping model is constructed for the design optimization task that searches for the value of optimal aesthetic indicators that resulted in the highest aesthetic preference. Many existing optimization tools such as the Genetic Algorithm (GA) for dealing with non-linear mappings can be considered for this task. The task aims to optimize aesthetic preference and obtain enhanced aesthetic indicators that suggest the way of applying aesthetic design principles. According to the aesthetic measurement formula, improved designs are discovered to match the values of the enhanced aesthetic indicators. An example of using GA to generate enhanced aesthetic indicators of the digital camera design is illustrated in Section 5.4.

To summarize, the tasks and steps of the proposed framework of product appearance design based on aesthetic design principles are listed as follows:

(1) Task 1: Mapping model construction.
  - Step 1: Determining design samples
  - Step 2: Acquiring aesthetic indicators and aesthetic preference
  - Step 3: Constructing mappings
(2) Task 2: Design optimization.
  - Step 1: Searching for aesthetic indicator values that result in optimal user preference
  - Step 2: Generating improved design concepts based on enhanced aesthetic indicators

4. Aesthetic measurement

This section illustrates the aesthetic measurement of the proposed method based on aesthetic design principles. A design aesthetic ontology is created to clearly represent the relationships between a tangible design artefact with body and elements, its visual attributes (i.e., styling, colour, and texture), and the aesthetic indicators that are derived from the aesthetic measurement formulas. The contents and equations of the proposed aesthetic measurement formulas are also provided in this section.

4.1. Design aesthetic ontology

Fig. 3 illustrates the proposed design aesthetic ontology. A tangible design artefact based on its form is decomposed into different planes. A plane is defined as a two-dimensional design space. For example, an iPhone 6 can be decomposed into three planes (front, back, and side views). The plane is an important part of form generation that is utilized to create both two-dimensional configurations and three-dimensional configurations. Therefore, the proposed method of aesthetic measurement starts from the assessment of each plane of a design artefact. There are identifying design entities in each plane and are classified into a body and elements. A body is defined as the overall physical shape and is determined by the boundary contour of a design artefact in a plane. Elements are major physical shapes of a design artefact and are usually

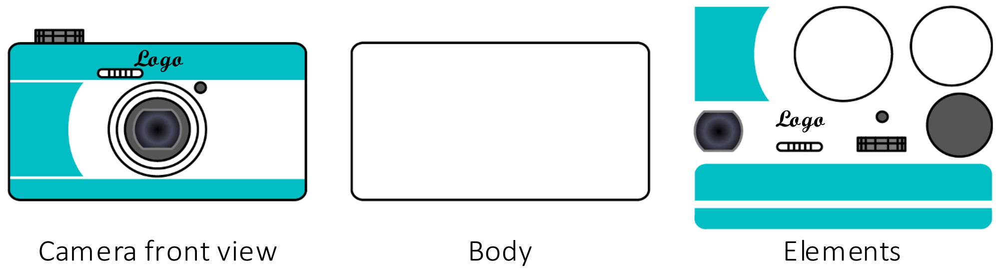


Fig. 4. The body and elements of a camera design.

placed within the body in a plane. They are used to create and represent various forms. An example of the body and elements in a camera design is presented in Fig. 4.

Both a body and the elements have visual attributes, including styling, colour, and texture containing visual messages that help to identify and interpret design forms. Styling contains form related design characteristics and describes the outline composition of a body or the elements. It has design features such as shape, dimension and location. The shape is a representation or symbolic illustration using an edge contour line. Dimension refers to the actual measured or relative size of the shape of a body or elements. Location is the specific place where elements are arranged in a plane regarding the relative position of the body or other elements.

Colour is the visual property that derives from the spectrum of light. In general, there are three dimensions of colour: hue, value (or brightness), and chroma (saturation). Hue is the basic feature of a colour dominated by its visible wavelength. Chroma measures the relative purity of a specific colour on a scale from a hue to grey. Value refers to the relative lightness or darkness appearing in a black and white figure. There are several types of colour notion systems. Among them, the Munsell colour system [60,61] is well-recognized as the most visually uniform colour space to date. It is an asymmetrical colour solid where hue is displayed around the perimeter of its horizontal slices, chroma radiate outward from the centre vertical axis, and value is measured vertically from 0 (black) to 10 (white). Munsell colour system is implemented to define the features of colour as hue, chroma, and value.

Texture is defined as the surface characteristics of a body or elements that are sensed through sight and touch. It is a compound of surface pattern, tactile physical grains, and surface reflectance. Surface patterns are usually variegated in different colours and physical grains, which are depicted with lines or shapes. Thus, to define the features of texture, we only consider the surface reflectance that is associated with the roughness of surface material as the feature of texture. A rough surface reflects light in a more diffuse way than a polished smooth surface creating a distinct surface vision from the smooth surface.

The three visual attributes have close relationships with the proposed aesthetic measurement formulas regarding different design elements. The detailed descriptions and equations of each aesthetic measurement formula regarding each visual attribute of the design artefact are provided in the following section.

4.2. Aesthetic measurement formulas

Aesthetic measurement formulas emphasize the quantitative evaluation in organizing visual design elements according to the definitions of aesthetic design principles. Seven formulas regarding the commonly employed aesthetic design principles (i.e., balance, proportion, simplicity, unity, symmetry, contrast, and harmony) were proposed for aesthetic measurement. The detailed explanations of the formula creation are presented as follows.

4.2.1. Balance

Balance suggests that the elements of a design artefact are equally distributed in vision. To achieve the state of visual balance, designers arrange design elements to address the styling, colour, and texture design. Considering the styling design, design elements with larger areas provide heavier feelings to people. On the other hand, design elements with small areas communicate a lighter feeling of weight. In addition, the distance between the location and central axis of the design element also affects the perception of balance. The farther a design element is away from the central axis, the stronger sense of weight it will create. To quantify the degree of balance in the styling design, a coordinate system is set up where the x-axis and the y-axis are located in the middle of the body length and body width, respectively (Fig. 5). The degree of balance in styling design can be represented by Eq. (1).

$$Balance_{styling} = 1 - \left| \frac{\sum C_{i_x} S_i + C_{b_x} S_b}{\sum S_i + S_b} * \frac{2}{x} \right| \tag{1}$$

Here C_{i_x} and C_{b_x} are the centroids of element i and body in x-coordinator, and S_i and S_b are the areas of element i and body; $Balance_{styling}$ represents the degree of balance in the styling design.

To create the visual balance of the colour design, the effect of colour chroma and value is considered. [57]In general, bright and intense colours carry more visual weight than those dark and mild colours. In the Munsell colour system, colour chromas are determined by the limited strength of particular hues. For example, the chroma of red pigment is considered twice as intense as the blue-green pigment. Based on the above information, Eq. (2)-(4) are defined to calculate the degree of balance in the colour design.

$$Balance_{Chr} = \begin{cases} 1 & for\ Chr_i = Chr_b = 0 \\ 1 - \left| \frac{\sum Chr_i * C_{i_x} * S_i) + Chr_b * (C_{b_x} S_b - \sum C_{i_x} S_i)}{\sum (Chr_i * S_i) + (Chr_b) * \left(S_b - \sum S_i\right)} * \frac{2}{x} \right| & others \end{cases} \tag{2}$$

$$Balance_V = 1 - \left| \frac{\sum[(10 - V_i)^* C_{i_x}{}^* S_i] + (10 - V_b)^*(C_{b_x} S_b - \sum C_{i_x} S_i)}{\sum[(10 - V_i)^* S_i) + (10 - V_b)^*(S_b - \sum S_i)} {}^* \frac{2}{x} \right| \quad (3)$$

$$Balance_{color} = w_{Chr}{}^* Balance_{Chr} + w_V{}^* Blance_V,$$

Where.

$$w_{Chr} + w_V = 1 \quad (4)$$

In Eq. (2)-(4), $Balance_{Chr}$ and $Balance_V$ represent the degree of balance regarding the colour chroma and value, respectively; Chr_i and Chr_b represent the chromas of element i and body in the Munsell colour system. Here w_{Chr} and w_V are the weights of chroma and value in the colour balance calculation. The weights in Eq(4) are determined by the design team. The default value of w_{Chr} and w_V is $\frac{1}{2}$ respectively. $Balance_{color}$ represents the degree of balance in styling design.

In consideration of the texture design, design elements with a rough and complex surface texture carry a heavier visual feeling than elements with a simple and smooth texture. Eq. (5) represents the calculation of balance in texture design.

$$Balance_{texture} = 1 - \left| \frac{\sum(Rou_i{}^* C_{i_x}{}^* S_i) + Rou_b{}^*(C_{b_x} S_b - \sum C_{i_x} S_i)}{\sum(Rou_i{}^* S_i) + Rou_b{}^*(S_b - \sum S_i)} {}^* \frac{2}{x} \right| \quad (5)$$

Here Rou_i and Rou_b represent the surface roughness of element i and body, respectively. $Balance_{texture}$ represents the degree of balance in texture design.

4.2.2. Proportion

Proportion addresses the relative sizes and scales between the body and the elements. To apply proportion in styling design, three ratios of the body and the elements are considered. Our strategy is to compare the three ratios with the specific ratio of classic proportional systems that are selected by the design team. The more the ratios approach the selected classic ratio, the more the degree of proportion is applied in the design. The first ratio is the width-length ratio of the body and elements. Eq. (6) and (7) present the width-length ratio of the body and elements respectively. Here R_{WL_i} and R_{WL_b} are width-length ratios of element i and body; x_i and x is the width of element i and body respectively; y_i and y is the length of element i and body respectively. Eq. (8) is to calculate the degree of proportion in terms of the width-length ratio (P_{WL}). R_c is the constant ratio which is selected from the classic proportional system.

$$R_{WL_i} = \begin{cases} \frac{x_i}{y_i}, & if \quad x_i \le y_i \\ \frac{y_i}{x_i}, & if \quad x_i > y_i \end{cases} \quad (6)$$

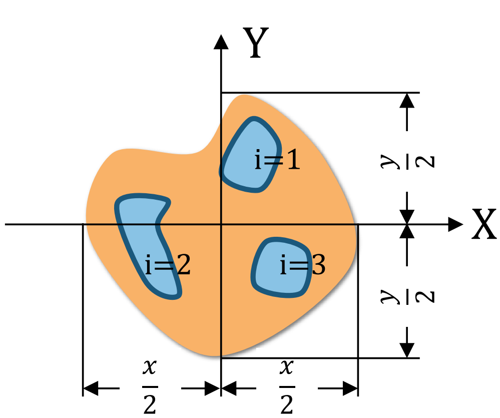


Fig. 5. Coordinator system for measuring the degree of balance.

$$R_{WL_b} = \begin{cases} \frac{x}{y}, & if \quad x \le y \\ \frac{y}{x}, & if \quad x > y \end{cases} \quad (7)$$

$$P_{WL} = 1 - \frac{\sum(|R_{WL_i} - R_c|^* S_i) + |R_{WL_b} - R_c|^* S_b}{(\sum S_i + S_b)^* R_c} \quad (8)$$

The second ratio concerns the relative location ratio of elements. Eq. (9)-(11) represents the calculation of the degree of proportion in terms of element location ratio. Here C_{i_x} and C_{i_y} are the centroid values of element i in x-coordinate and y-coordinate, respectively. $\frac{2|C_{i_x}|+x}{2x}$ and $\frac{2|C_{i_y}|+y}{2y}$ represent the relative location ratio between element relative location and body length or width. P_{L_x} and P_{L_y} indicate the degrees of proportion regarding element location ratio in the directions of the x-coordinator and y-coordinator. P_L denotes the degree of the proportion of element location ratio.w_{L_x} and w_{L_y} are the weights of P_L. The default values of both weights are $\frac{1}{2}$.

$$P_{L_x} = 1 - \frac{1}{R_c}{}^* \sum(\left| \frac{2|C_{i_x}| + x}{2x} - R_c \right| {}^* \frac{S_i}{\sum S_i}) \quad (9)$$

$$P_{L_y} = 1 - \frac{1}{R_c}{}^* \sum(\left| \frac{2|C_{i_y}| + y}{2y} - R_c \right| {}^* \frac{S_i}{\sum S_i}) \quad (10)$$

$$P_L = w_{L_x}{}^* P_{L_x} + w_{L_y}{}^* P_{L_y},$$

Where.

$$w_{L_x} + w_{L_y} = 1 \quad (11)$$

The third ratio is the relative scale ratio between elements and the body. Eq. (12)-(14) shows the degree of proportion measurement regarding this ratio (P_S). P_{S_x} and P_{S_y} are the degree of proportion in x-coordinate and y-coordinate, respectively. w_{S_x} and w_{S_y} are the weights of P_S, with the default weight of $\frac{1}{2}$ respectively. Eq. (15) calculates the total degree of proportion P. w_{WL}, w_L and w_S are the weights of P_{WL}, P_L, and P_S in total proportion degree calculation. The default value of w_{Chr} and w_V is $\frac{1}{3}$ respectively.

$$P_{S_x} = 1 - \frac{1}{R_c}{}^* \sum(\left| \frac{x_i}{x} - R_c \right| {}^* \frac{S_i}{\sum S_i}) \quad (12)$$

$$P_{S_y} = 1 - \frac{1}{R_c}{}^* \sum(\left| \frac{y_i}{y} - R_c \right| {}^* \frac{S_i}{\sum S_i})] \quad (13)$$

$$P_S = w_{S_x}{}^* P_{S_x} + w_{S_y}{}^* P_{S_y},$$

Where.

$$w_{S_x} + w_{S_y} = 1 \quad (14)$$

$$P = w_{WL}{}^* P_{WL} + w_L{}^* P_L + w_S{}^* P_S,$$

Where.

$$w_{WL} + w_L + w_{RS} = 1 \quad (15)$$

4.2.3. Simplicity

Simplicity is to use the core and fewer elements that to make design easier to be perceived by humans. Two aspects which include the number of attributes and the degree of simplicity are taken into consideration to discover how simplicity is applied in a design. A reference design needs to be created in its simplest form by the design team for comparison with designs to be evaluated. The reference design should contain only necessary elements. For example, a front layout of the camera reference design comprises elements of only a body and a lens. In addition, the reference design should have simple shape(s),

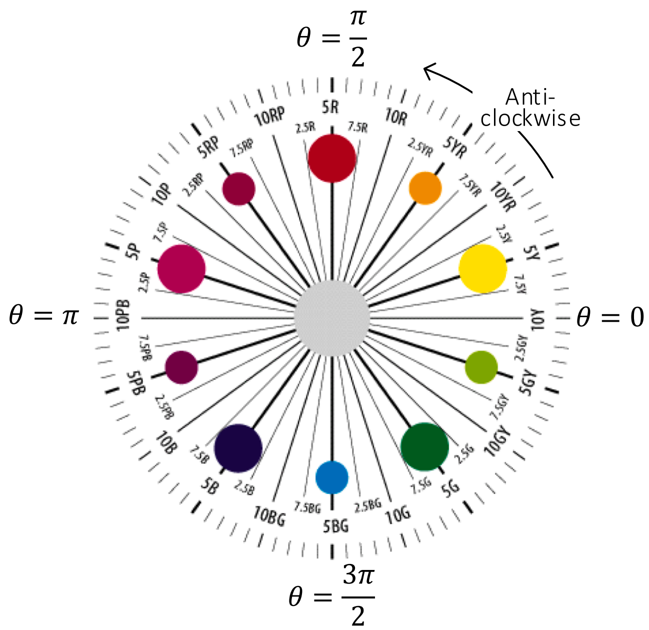


Fig. 6. illustration of defined hue angle..θ

colour(s) and texture(s). A simple shape usually has a regular outline and is with fewer line segments. A simple colour can be a colour with a higher value and a lower chroma, i.e., white colour. Additionally, a smoother texture with a pure colour looks simpler than those rough or variegated textures. Eq. (16) shows the calculation of simplicity regarding the number of attributes ($Simplicity_N$) compared with the reference design. N_r is the number of attributes in styling, colour or texture design (N_r can be the shape number in styling design, the colour number in colour design or the texture number in texture design). N is the number of attributes in styling, colour or texture design.

$$Simplicity_N = 1 - \frac{N_r}{N} \quad (16)$$

Eq. (17) calculates the degree of simplicity of attribute ($Simplicity_D$) in terms of shape, colour, or texture compared with the reference design. A rating scale for indicating the degree of simplicity of attribute needs to be proposed by the design team. D_{max} and D_{min} are defined as the highest and lowest scores on the rating scale. D_{max} is also the score of the degree of simplicity of the reference design. D_i and D_b are the scores indicating the degree of simplicity of element i and body, respectively. They are rated by the design team in comparison to the reference design. Eq. (18) is the calculation of the total degree of simplicity. w_N and w_D are the weights of $Simplicity_N$ and $Simplicity_D$. Their default values are all $\frac{1}{2}$.

$$Simplicity_D = \frac{1}{\sum S_i + S_b} * [\sum(\frac{D_{max} - D_i}{D_{max} - D_{min}} * S_i) + \frac{D_{max} - D_b}{D_{max} - D_{min}} * S_b] \quad (17)$$

$$Simplicity = w_N * Simplicity_N + w_D * Simplicity_D,$$

where.

$$w_N + w_D = 1 \quad (18)$$

4.2.4. Unity

Unity aims to group design elements and create the visual connections between design elements based on the Gestalt grouping laws. The employment of Gestalt grouping laws involves the arrangement of different visual attributes. For example, similarity suggests the selection of similar visual attributes of design elements that people would perceive as a group. This grouping law is related to the use of similar shapes, colours, and textures. Proximity indicates that elements closer to each other appear more related to each other and is achieved by reducing the space between elements being grouped. Alignment occurs when design elements share a common axis, conveying a more connected feeling to each other. The implementation of alignment is associated with the location of design elements. The proposed method of evaluating the degree of unity relies on the identification of the groups of design elements according to each Gestalt grouping law by the design team. Eq. (19) and Eq. (20) represent the calculation of the degree of unity ($Unity$). U_j stands for the degree of unity in terms of the Gestalt grouping law j. N_j is the number of the groups of design elements identified by the design team concerning the Gestalt grouping law j. The

Table 2
Design parameters for camera front face design.

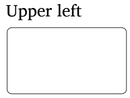
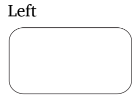
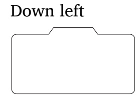
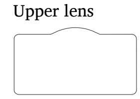
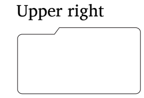
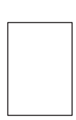
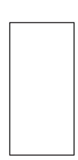
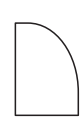
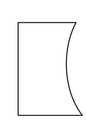
	Level 1	Level 2	Level 3	Level 4	Level 5
A. Logo font	Medium	Small			
B. Logo location	Upper left	Left	Down left	Upper lens	Upper right
C. Body shape					
D. Body colour	5R 5/16 (RGB 232, 47, 68)	7.5GY 8/12 (RGB 146, 224, 63)	7.5 PB 5/16 (RGB 83, 113, 232)	White N10 (RGB 255, 255, 255)	Black N0 (RGB 0, 0, 0)
E. Body dimensions	100:60	110:60	110:70	110:80	120:70
F. Grip shape					
G. Grip colour	5Y 9/12 (RGB 255, 229, 29)	2.5P 5/18 (RGB 158, 87, 222)	5 GB 8/8 (RGB 75, 224, 208)	White N10 (RGB 255, 255, 255)	Black N0 (RGB 0, 0, 0)
H. Decorating lines shape	Topline	Top small area	Top and bottom small area	Top large area	Top and bottom large area
I. Decorating lines colour	5Y 9/12 (RGB 255, 229, 29)	2.5P 5/18 (RGB 158, 87, 222)	5 GB 8/8 (RGB 75, 224, 208)	White N10 (RGB 255, 255, 255)	Black N0 RGB 0, 0, 0)
J. Lens shape and location	Centre	Centre right	Centre right (large)	Right	Right (large)
K. Lens frame colour	5Y 9/12 (RGB 255, 229, 29)	2.5P 5/18 (RGB 158, 87, 222)	5 GB 8/8 (RGB 75, 224, 208)	White N10 (RGB 255, 255, 255)	Black N0 (RGB 0, 0, 0)
L. Button, flash and light	With button, with flash, left light	With button, with flash, the right light	With button, without flash, the right light	Without the button, with flash, the right light	Without the button, without flash, the right light

Table 3
Taguchi Orthogonal Arrays L50 ($2^1 \times 5^{11}$) for partial factorial combinations of design parameters.

	A	B	C	D	E	F	G	H	I	J	K	L
Sample 1	1	1	1	1	1	1	1	1	1	1	1	1
Sample 2	1	1	2	2	2	2	2	2	2	2	2	2
Sample 3	1	1	3	3	3	3	3	3	3	3	3	3
Sample 4	1	1	4	4	4	4	4	4	4	4	4	4
Sample 5	1	1	5	5	5	5	5	5	5	5	5	5
Sample 6	1	2	1	2	3	4	5	1	2	3	4	5
Sample 7	1	2	2	3	4	5	1	2	3	4	5	1
Sample 8	1	2	3	4	5	1	2	3	4	5	1	2
Sample 9	1	2	4	5	1	2	3	4	5	1	2	3
Sample 10	1	2	5	1	2	3	4	5	1	2	3	4
Sample 11	1	3	1	3	5	2	4	4	1	3	5	2
Sample 12	1	3	2	4	1	3	5	5	2	4	1	3
Sample 13	1	3	3	5	2	4	1	1	3	5	2	4
Sample 14	1	3	4	1	3	5	2	2	4	1	3	5
Sample 15	1	3	5	2	4	1	3	3	5	2	4	1
Sample 16	1	4	1	4	2	5	3	5	3	1	4	2
Sample 17	1	4	2	5	3	1	4	1	4	2	5	3
Sample 18	1	4	3	1	4	2	5	2	5	3	1	4
Sample 19	1	4	4	2	5	3	1	3	1	4	2	5
Sample 20	1	4	5	3	1	4	2	4	2	5	3	1
Sample 21	1	5	1	5	4	3	2	4	3	2	1	5
Sample 22	1	5	2	1	5	4	3	5	4	3	2	1
Sample 23	1	5	3	2	1	5	4	1	5	4	3	2
Sample 24	1	5	4	3	2	1	5	2	1	5	4	3
Sample 25	1	5	5	4	3	2	1	3	2	1	5	4
Sample 26	2	1	1	1	4	5	4	3	2	5	2	3
Sample 27	2	1	2	2	5	1	5	4	3	1	3	4
Sample 28	2	1	3	3	1	2	1	5	4	2	4	5
Sample 29	2	1	4	4	2	3	2	1	5	3	5	1
Sample 30	2	1	5	5	3	4	3	2	1	4	1	2
Sample 31	2	2	1	2	1	3	3	2	4	5	5	4
Sample 32	2	2	2	3	2	4	4	3	5	1	1	5
Sample 33	2	2	3	4	3	5	5	4	1	2	2	1
Sample 34	2	2	4	5	4	1	1	5	2	3	3	2
Sample 35	2	2	5	1	5	2	2	1	3	4	4	3
Sample 36	2	3	1	3	3	1	2	5	5	4	2	4
Sample 37	2	3	2	4	4	2	3	1	1	5	3	5
Sample 38	2	3	3	5	5	3	4	2	2	1	4	1
Sample 39	2	3	4	1	1	4	5	3	3	2	5	2
Sample 40	2	3	5	2	2	5	1	4	4	3	1	3
Sample 41	2	4	1	4	5	4	1	2	5	2	3	3
Sample 42	2	4	2	5	1	5	2	3	1	3	4	4
Sample 43	2	4	3	1	2	1	3	4	2	4	5	5
Sample 44	2	4	4	2	3	2	4	5	3	5	1	1
Sample 45	2	4	5	3	4	3	5	1	4	1	2	2
Sample 46	2	5	1	5	2	2	5	3	4	4	3	1
Sample 47	2	5	2	1	3	3	1	4	5	5	4	2
Sample 48	2	5	3	2	4	4	2	5	1	1	5	3
Sample 49	2	5	4	3	5	5	3	1	2	2	1	4
Sample 50	2	5	5	4	1	1	4	2	3	3	2	5

smaller N_j with the larger N_E indicates the larger degree of unity of Gestalt grouping law j, and vice versa. N_E is the total number of elements in the visual plane. w_j denotes the weights of each Gestalt grouping law j. To calculate unity, designers also need to determine w_j, which is assigned based on the importance of each Gestalt grouping law.

$$U_j = 1 - \frac{N_j - 1}{N_E} \tag{19}$$

$$Unity = \sum (w_j {*} U_j)$$

Where.

$$\sum w_j = 1 \tag{20}$$

4.2.5. Symmetry

Symmetry indicates that design elements are placed in the same way on both sides of an axis and are divided into reflective, rotative, and translative symmetry. In our proposed aesthetic measurement formula, we mainly focus on reflective symmetry as they are more widely applied in product design. To investigate the degree of symmetry in a two-dimensional plane, the design team needs to firstly select an appropriate axis for calculating the degree of symmetry. The axis should be divided the design into two parts that are as symmetric as possible. The axis can be the symmetry axis of a major design element, the axis that is across the centroid of the body, or the central axis of a body's length or width. The degree of symmetry (*Symmetry*) is expressed in Eq. (21). Here S_d is the different area between the two sides of a symmetry axis. S_{large} is the larger area of the divided two sides of the body parts.

$$Symmetry = 1 - \frac{S_d}{S_{large}} \tag{21}$$

4.2.6. Contrast

Contrast reflects that the arrangement of design elements is presented in opposite ways to gain attractiveness. Generating contrast elaboration design can be accomplished by emphasizing the differences in size, shape, colour, and texture between different elements. Different from the cases in graphic layout design, the shape of elements in product design is mostly decided by the related functional components. The use of contrast in the styling design of product design is usually limited by product functions. Thus, we mainly focus on the measurement of colour contrast. The following equations calculate the colour difference between the colours of the body and the elements. Because the ontology model uses the Munsell colours system to describe the colours, the colour values should be converted to the RGB colour values first for the calculation of contrast. Euclidean distance is adopted to quantify the colour difference with different RGB values. Eq. (22)-(23) represents the calculation of the degree of colour contrast (*Contrast*). ΔE_i represents the colour difference between body and element i. R_i, G_i, B_i and R_b, G_b, B_b are the RGB values of element i and the body, respectively.

$$\Delta E_i = \sqrt{(R_i - R_b)^2 + (G_i - G_b)^2 + (B_i - B_b)^2} \tag{22}$$

$$Contrast = \sum_{i=1}^{n} \Delta E_i \bullet \frac{S_i}{S_b} \tag{23}$$

4.2.7. Harmony

Based on the same reason for applying contrast, the use of harmony in the styling is affected by the functional components of the product. Therefore, we mainly address the colour design to achieve harmony. Colour harmony can be classified into two directions: complementary directed harmony and analogous directed harmony. Complementary directed harmony is composed of hues with complementary sets. Analogous directed harmony includes two or more similar hues positioned next to one another. To describe the distance between different hues, hue angles are defined based on the colour circle of the Munsell colour system, as illustrated in Fig. 6. The value of hue angles is defined from 0 to 2π (2π is not included) anti-clockwise corresponding to the segments of the colour circle. If the hue value of one colour is N (colours from the value axis between black to white), there is no colour angle for this colour. Elements or bodies filled with this colour are not considered for the measurement of harmony. S_g indicates the area of the element colours without hue angles. Eq. (24) is defined to calculate the degree of complementary directed colour harmony ($Harmony_C$). θ_i and θ_b are defined as hue angles of element i and body, respectively. Eq. (25) represents the calculation of the degree of analogous directed colour harmony ($Harmony_A$).

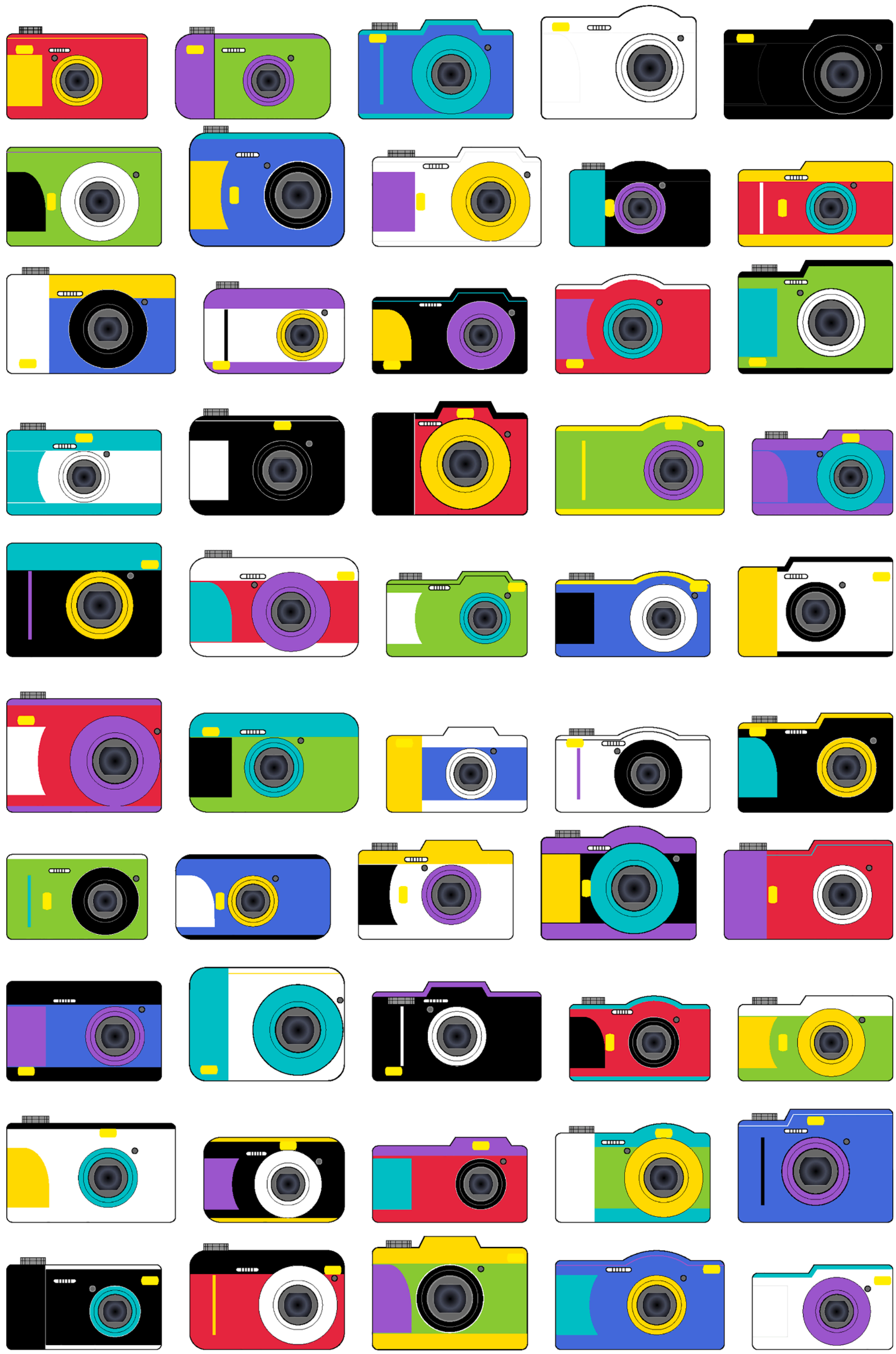


Fig. 7. Design samples for camera front face design.

$$Harmony_C = 1 - \frac{|\sum(S_i{*}\sin\theta_i) + (S_b - \sum S_i){*}\sin\theta_b| + |\sum(S_i{*}\cos\theta_i) + (S_b - \sum S_i){*}\cos\theta_b|}{2(S_b - S_g)} \quad (24)$$

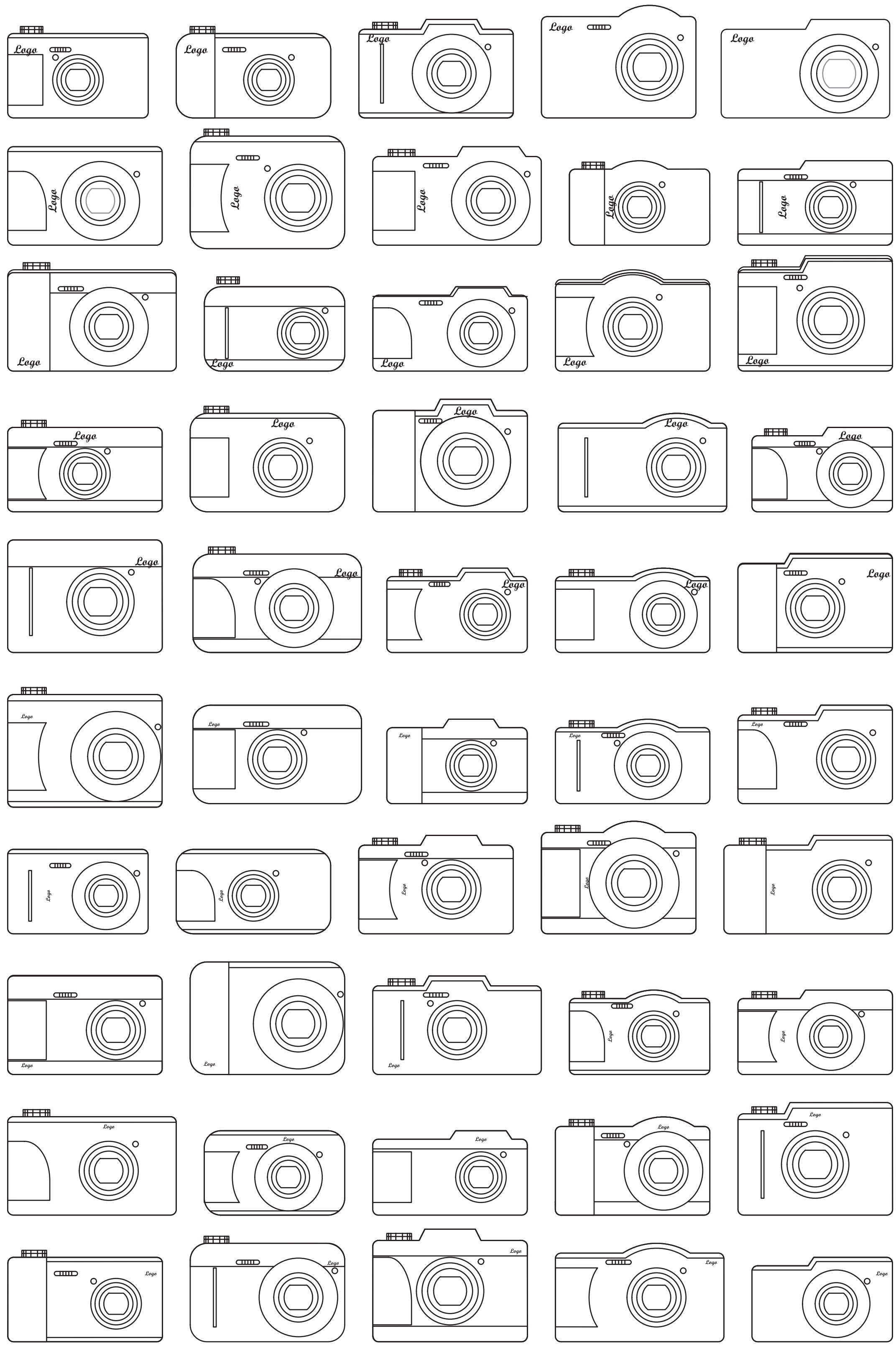


Fig. 8. Design samples for camera front face design (styling).

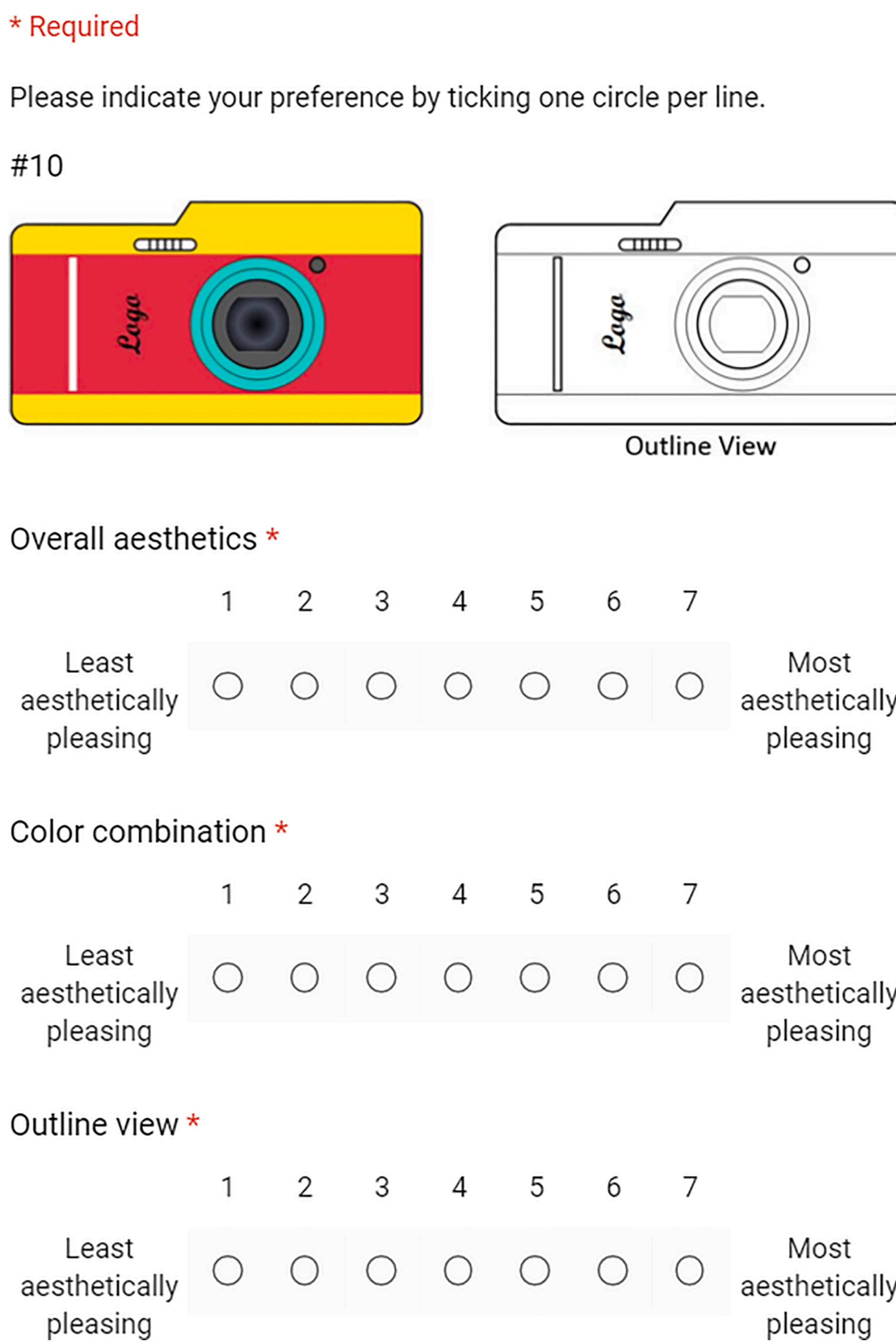


Fig. 9. An example of the survey questions for evaluating camera front face design.

$$Harmony_A = 1 - Harmony_C \tag{25}$$

5. Case study

This section illustrates how the proposed framework and the aesthetic measurement formulas are applied in design scenarios through a case study of camera design. The objective of the case study was to generate concepts for the front face design of compact digital cameras. The detailed steps are listed in the following sections.

5.1. Determining camera design samples

To obtain camera design samples, the visual attributes for compact cameras were firstly determined. In this case study, only the design of styling and colour were considered. Based on the design features of the existing cameras in the market, design parameters for the camera front view design were defined (Table 2). Eight styling design attributes (logo font, logo location, body shape, body dimensions, grip shape, decorating line shape, lens styling, and button, flash and light styling) and four-colour design attributes (body colour, grip colour, decorating line colour, and lens frame colour) were selected to indicate the camera design parameters. This included one attribute with two levels and 11 attributes with five levels. There are 8 colours used in the case study. The

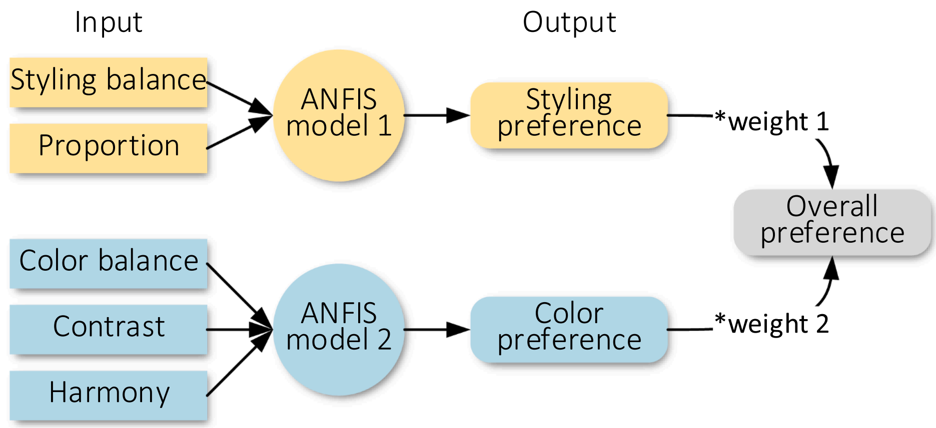


Fig. 10. the structure of input-output of 2 sub-models in ANFIS training.

Table 4
Modelling errors of ANFIS model and Neural Network model.

		Training error (MSE)	Testing error (MSE)
ANFIS	Sub-model 1 (styling)	0.6290	0.6708
	Sub-model 2 (colour)	0.7136	0.7224
Neural Network	Sub-model 1 (styling)	0.5677	0.8002
	Sub-model 2 (colour)	0.7900	0.7986

values of these colours for the colour design attributes are presented in Table 2. The colours are represented by the Munsell colour system, and their RGB values are annotated in parentheses. To cover a wider range of colours, the colours representing the hues in the Munsell colour circle are selected to meet the demands of evaluating complementary directed harmony and analogous directed harmony. The full factorial of the combinations of defined design parameters would be up to 97,656,250 ($2^1 \times 5^{11}$) design samples. To effectively determine the design samples, Taguchi Orthogonal Arrays L50 ($2^1 \times 5^{11}$) was implemented to generate partial factorial combinations of design parameters, shown in Table 3. In Table 3, the columns represent the design parameters with corresponding levels. Based on Table 3, fifty design samples were then created and are presented in Fig. 7 and Fig. 8. Fig. 7 presents the design samples for the camera front face design, and different styling combinations are presented in Fig. 8.

5.2. Acquiring camera aesthetic indicators and aesthetic preferences

Four aesthetic indicators, including balance, proportion, contrast, and harmony were determined for evaluating the aesthetics of the camera front face design. Based on the proposed aesthetic measurement formula, the values of styling balance, colour balance, proportion, contrast, and harmony of each design sample were calculated. The constant ratio R_c for calculating 'proportion' was determined as the golden ratio (≈0.6180). The weights w_{WL}, w_L, and w_S were determined as 0.8, 0.05, and 0.15 respectively.

The aesthetic preferences were collected in terms of preferences in styling design, colour design, and overall aesthetics of the camera design samples. The data were collected through online surveys, which were published in Amazon Mechanical Turk. To assess the aesthetic preferences for digital cameras, online survey participants were shown the colour and the outline view of the camera front face of camera design samples. They were asked to indicate their aesthetic ratings in three questions reflecting three design aspects (styling design, colour design, and overall aesthetics) of each camera design sample. The preferences of the overall aesthetics were used to find the weight of the styling design preference and the colour design preference for optimizing overall aesthetic preference in the optimization step. Fig. 9 shows an example of the survey questions for evaluating one camera design sample. Attention checks on whether the participants have skipped questions were added to validate the survey data. A total of 30 surveys were received as valid data and were consolidated for modelling.

5.3. Constructing mapping model

In consideration of the number of aesthetic indicators and aesthetic preference features, a mapping model was constructed with the input of aesthetic indicators and the output of aesthetic preference. The adaptive neuro-fuzzy modelling approach [62] was implemented to capture the relationships between these relationships. It builds an adaptive network-based fuzzy inference system (ANFIS). The ANFIS integrates both neural networks and fuzzy logic principles, having good learning and adaptive capability to capture non-linear relationships between inputs and outputs. The fuzzy inference system mainly consists of a series of if-then rules representing models or knowledge, with membership functions and fuzzification and de-fuzzification operations. Five layers where each layer consists of several nodes described by node functions are used to construct a typical ANFIS to learn and tune parameters in a fuzzy inference system based on a hybrid learning mode. The inputs of the present layer are obtained from the nodes in the previous layers. The membership function parameters are trained from input and output data using either backpropagation or a combination of backpropagation and least-squares estimation. Two ANFIS models were built for styling and colour design and are illustrated in Fig. 10.

An initial Sugeno-type fuzzy inference system structure was generated for ANFIS training in terms of styling, colour, and overall preference using subtractive clustering. The structure was constructed in MATLAB. The cluster centre's range of influence was set as 0.62 for sub-model 1 (styling) and 0.72 for sub-model 2 (colour). The input and output membership function types are Gaussian curve membership function and linear type, respectively.

Eighty per cent of the total data was randomly selected as training data, and the rest was selected as testing data. The data were normalized to a zero mean and unit variance for modelling. The ANFIS structure was trained by learning from the training data using the backpropagation method. The testing data was used to test the performance of the ANFIS model. To further test the modelling performance, the neural network with two hidden layers with Levenberg-Marquardt backpropagation was also implemented to construct the two sub-models. The neurons were determined as [3,10] for sub-model 1 (styling) and [3,18] for sub-model 2 (colour). The mean squared errors (MSE) between the predicted

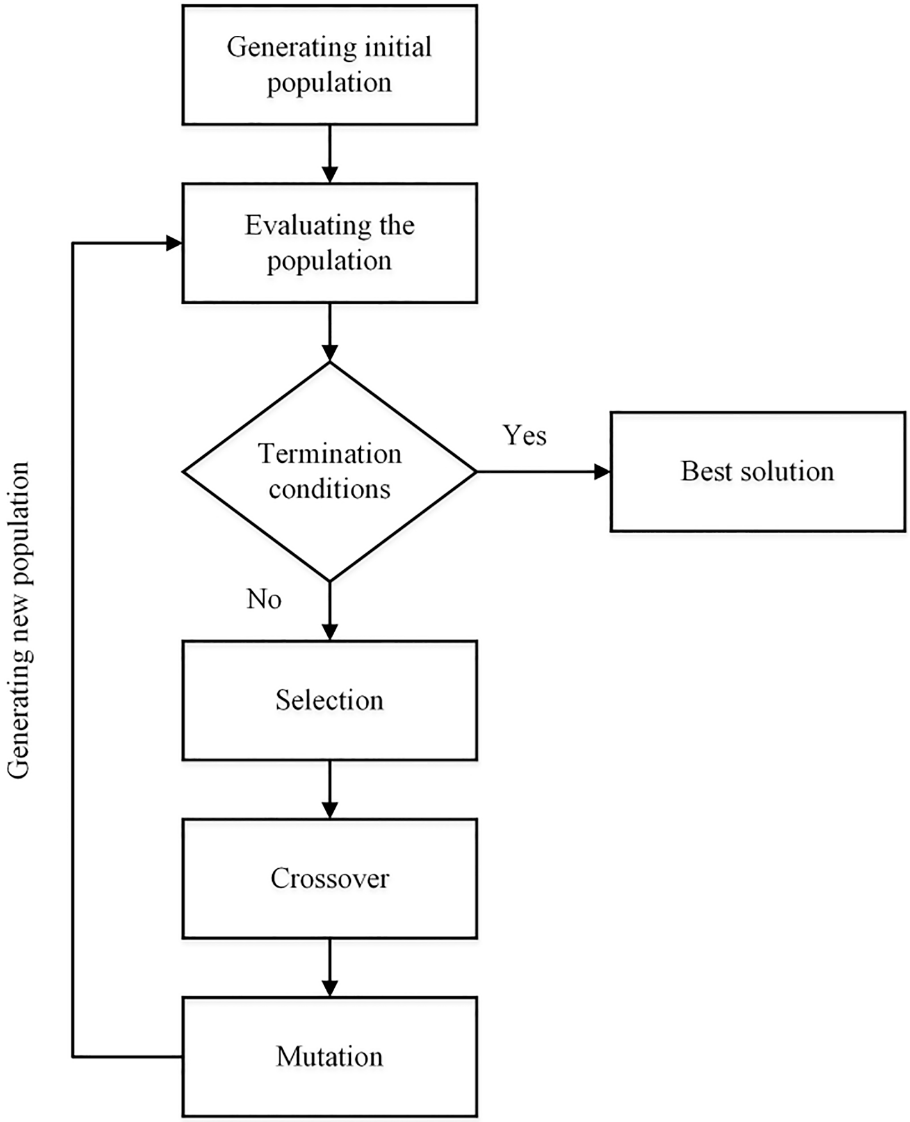


Fig. 11. The scheme of implementing the classic GA.

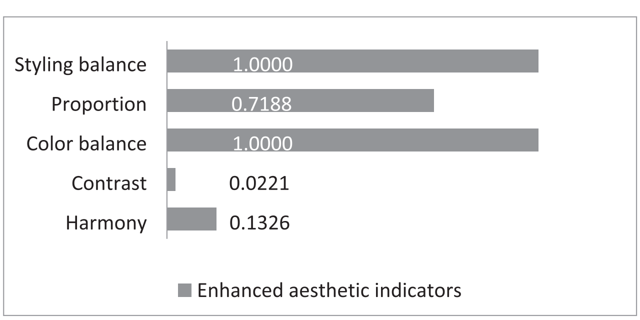


Fig. 12. GA results of enhanced aesthetic indicators.

output and the original output of training data and testing data for the ANFIS and Neural Network model have been compared accordingly and listed in Table 4.

According to the results, both the testing MSE of two ANFIS sub-models was smaller than the testing MSE of the Neural Network model. In addition, the differences between training MSE and testing MSE for the two ANFIS sub-models were not significant. However, the

Table 5
Design parameters for concept generation of digital camera front face design.

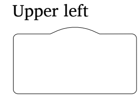
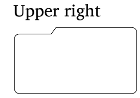
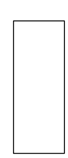
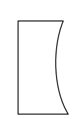
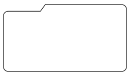
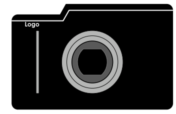
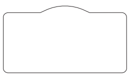
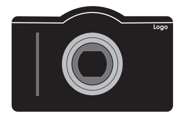
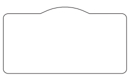
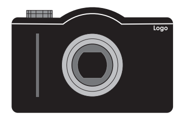
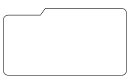
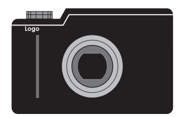
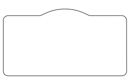
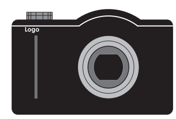
	Level 1	Level 2	Level 3
A. Logo location	Upper left	Upper right	
B. Body shape			
C. Body colour	7.5RP 8/8 (RGB 255, 177, 198)	White N10 (RGB 255, 255, 255)	Black N0 (RGB 0, 0, 0)
D. Body dimensions	110:70	110:80	
E. Grip shape			
F. Decorating lines	Topline white	Top large area white	
G. Lens	Centre	Centre-right	Right
H. Button	Button	No button	

Table 6
Selected design parameters and generated design concepts.

A	B	C	D	E	F	G	H	Improved concept	Estimated overall aesthetic preferences
Upper left		Black N0 (rgb 0, 0, 0)	110:70		Topline white	Centre	No button		0.8471
Upper right		Black N0 (rgb 0, 0, 0)	110:70		Topline white	Centre	No button		0.8511
Upper right		Black N0 (rgb 0, 0, 0)	110:70		Topline white	Centre	Button		0.8875
Upper left		Black N0 (rgb 0, 0, 0)	110:70		Topline white	Centre	Button		0.8014
Upper left		Black N0 (rgb 0, 0, 0)	110:70		Topline white	Centre-right	Button		0.7665

difference between training MSE and testing MSE for the first Neural Network sub-model was slightly larger than the training MSE. Both of the differences were considered within the acceptable range.

5.4. Design optimization

The ANFIS model was selected for design optimization. The objective of the optimization was to search for the combination of aesthetic indicators that would result in optimal user preference and generate optimal design concepts from selected design parameters. Genetic Algorithms (GAs) are known to be one of the most popular methods for searching and optimization. In GAs, each solution is called individual, and a fitness function is used for selecting the best individual. The best value of the fitness function was searched by using genetic operators (reproduction, crossover, and mutation) in a population of individuals. As a result, GAs converge on the optimal solution by evolving the best individual in each generation. In this study, the classic GA was implemented to search for the enhanced values of aesthetic indicators. The scheme of applying the classic GA is shown in Fig. 11. Based on survey results of the aesthetic preference for styling design, colour design and overall aesthetics, the weights of styling design preference and colour design preference for determining overall aesthetic preference were estimated as 0.4777 and 0.6075 respectively. The overall aesthetic preference was set as the optimization target. Fig. 12 presents the value of each aesthetic indicator when the optimal overall aesthetic preference is obtained by applying GA optimization. These results suggested that users preferred the camera design to have a highly balanced arrangement in styling and colour combinations, a proportion slightly closer to the golden ratio, and a lowly contrasted design and slightly lowly harmonized design in colour selection.

Based on enhanced aesthetic indicators, the improved concepts that contribute to the enhanced aesthetic indicators were automatically generated based on selected design parameters defined by designers. Table 5 illustrates selected design parameters for generating camera front face design concepts. The possible design combinations were constructed based on these design parameters. There were 864 possible design combinations in total in this case study. The values of aesthetic indicators for each possible design combination were calculated. By comparing aesthetic indicator values of possible design combinations with enhanced aesthetic indicator values, design combinations with values closer to the enhanced aesthetic indicator values were selected. Based on the parameters of these design combinations, the improved concepts were generated. Table 6 shows the selected top five design combinations and their corresponding design concepts with their estimated overall aesthetic preferences. The mean value of the overall aesthetic preferences of the original 50 camera samples was 0.4396. Compared with this value, the estimated overall aesthetic preferences of the top five design combinations were improved to 0.8471, 0.8511, 0.8875, 0.8014 and 0.7665, respectively. In addition, the estimated overall aesthetic preferences of all the top five design combinations were ranked within the top eight of the overall aesthetic preferences of the 50 camera samples. The comparison shows that the design optimization step is effective in selecting design parameters and achieving improved user aesthetic preference. The improved design concepts were considered as design concept candidates for the design team to make the further selection for concept development.

6. Conclusions

Aesthetic design principles are universally recognized design strategies and are frequently applied in product appearance design. However, the implementation of aesthetic design principles depends largely on designers' subjective intuitions and experiences and is especially challenging for novice designers. In this paper, a method to support product appearance design based on applying aesthetic design principles was proposed. The method includes two main tasks, which are mapping model construction and design optimization. Aesthetic measurement formulas supported by a design aesthetic ontology were developed to calculate the aesthetic indicators, which realize the implementation of aesthetic design principles. A case study based on camera design was reported to demonstrate the feasibility and effectiveness of the proposed framework for supporting product appearance design. An ANFIS model was constructed to map the relationships between design aesthetics and aesthetic preferences. The aesthetic preferences were optimized through GA and the corresponding aesthetic indicator values were determined. Based on the obtained aesthetic indicators, the enhanced design concepts were generated with improved aesthetic preferences.

This study introduced a method for quantitative aesthetic measurements of design artefacts that facilitates concept generation in product appearance design. A new concept, the aesthetic indicator, was proposed to provide quantitative evaluations of how aesthetic design principles are applied. It made an early attempt to systematically quantify product aesthetics based on aesthetic design principles. The mapping model construction task was conducted that captures the relationships between the aesthetic indicators of products and the aesthetic preferences of users. Based on the mapping model, design optimization was performed to suggest more improved design concepts with enhanced aesthetic indicators and aesthetic preferences. What's more, the developed mapping model also helps to predict user aesthetic preferences on existing or the generated design concepts. However, limited by the number of design samples, this study only included 2 aesthetic indicators of the styling design and 3 aesthetic indicators of the colour design for demonstration. For future work, more aesthetic indicators and design samples should be considered to offer more insights into the proposed method.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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