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A creativity-based design process for innovative product design

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Abstract

In today's highly competitive and uncertain market environment with short product life cycles, product development must not only satisfy the quality and speed of production, but it must ensure that products themselves have included innovative values. As creativity plays an important role in new product development (NPD), it can be utilized in search of novel ideas for innovative product design, and also can be regarded as a helpful tool in advancing NPD output.

In this paper, we developed a creativity method based on the naturally sensuous ability of human beings. We also proposed a creativity-based design process integrating some systematic design methodologies with a developed creativity tool. The essence of this proposed design process is not the sole performance of the creativity tool but the coherent efforts among each involved process technique.

To prove the practicability of this design process, a case study was conducted according to various procedures that were followed. By applying evolutionary thinking, the sensuous association method, and other systematic approaches to the design process, a number of concept solutions were produced. An optimal solution was then determined by using an operative decision-making model based on the weighted generalized mean method.

Relevance to industry

Rebuilding a product design process (PDP) with creativity techniques can effectively assist designers in encouraging design creativity, further improving the overall performance of innovative product design. Accordingly, this research provides a new approach to the design process for industries by taking advantage of a creativity-based design process to achieve the goals of innovative product design.

Keywords: Creativity; Design process; Product design; Decision-making model; Systematic approach

1. Introduction

New product development (NPD) is a complex area of ideas and innovations, involving strategy, management, research and development, production, marketing, and decision-making, and requires linking science and technology/invention or innovation with the marketplace. The success of new products mostly depends on new product development process and management (Chaturvedi and Rajan, 2000), including effective attainment

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of knowledge and using it as part of the product design process (Poolton et al., 2000). Cooper (1996) indicated that new product development is a vital endeavor for modern industries. Companies must learn how to innovate effectively, overhauling their new product processes—from idea to launch—and incorporating winning ideas for successful new products. However, Griffin (1997) reported that, despite widespread acceptance in the literature, almost 40% of firms surveyed still use no formalized product development process.

Product design is a goal-directed problem-solving activity that relies heavily on human experience, creative thinking, and related knowledge; it should be done by integrating creativity and innovation tools with axiomatic design methodology for durable product development (Goel and Singh, 1998). Villa (1998) indicated that continuing innovation in industries is defined as: promoting a frequent redesign of offered products as well as of the production processes required. Also, he proposed an "innovation loop" concept and introduced a conceptual model of multi-resolution design process. Majaro (1988) suggested the first step in the innovation process is the generation of ideas or 'creativity', but an important minority of pioneering design theorists has implied that the most valuable part of the design process is that which occurs inside the designer's head and partly out of reach of his conscious control (Jones, 1992, pp. 46–47). Unfortunately, the "black-box view" of designing can not be clearly expressed in contemporary design theories based on rational analytics. In fact, design work not only consists of logical rules dealing with distinct procedures but also innovative thinking producing intricate creativity.

Product design process (PDP) is an essential factor during the early phase of new product development, which can be considered a complex set of integrated efforts, including generating ideas, developing concepts, modifying details, and evaluating proper solutions. An inappropriate product design process not only affects product life-cycle phases but also increases the possibility of failure in new product development. Since the 1960s, some design scholars, such as Hall (1968), Archer (1971), French (1971), Pahl and Beitz (1984), Hubka (1989), etc. have successively developed many design processes, taking advantage of definite methodology to eliminate the illusion of "Designer as black boxes". The conventional design process can offer designers a helpful tool to product design and thus increases NPD output. However, Stevens and Burley (1997) indicated that about 3000 raw ideas are required to produce one substantially new commercially successful industrial product. They also found that NPD requires breakthrough creativity because the first ideas for commercialization are almost never commercially viable until they have been substantially revised through a thought process involving branching (Stevens et al., 1999).

Bullinger et al. (2000) once stated: the new millennium has fostered a look towards the future, accompanied by both hopes and fears. Facing today's global information society, companies must focus on the task of meeting competition and challenges. A high level of complexity, dynamism and uncertainty characterizes the economic situation for industry and its production facilities. In today's highly competitive and uncertain market environment with short product life cycles, product design must not only satisfy the 'quality' and 'speed' of production, but it must ensure that products themselves have included innovative values. Stevens et al. (1999) demonstrated that positive correlations were found between profits resulting from NPD project analyses and the degree of creativity of the analysts evaluating those projects. McAdam and McClelland (2002) also documented the performance results using new product ideas and creativity practices in the UK textile industry. Therefore, this research focuses on the integration of a creativity method and systematic design approaches, and proposes a creativity-based design process for innovative product design. The proposed process can effectively assist designers in encouraging design creativity, further improving the overall performance of innovative product design.

2. Theoretical background

2.1. The use of creativity techniques

Creativity is still one of the most mysterious elements in human thinking. Behavior involves two different levels of creativity, namely personal and social-cultural (Liu, 2000). Heap (1989) explained that creativity is the synthesis of new ideas and concepts through the radical restructuring and re-association of existing ones', whereas innovation is the implementation of the results of creativity. Although creativity in the design process is regarded as a powerful tool, it is often characterized by the occurrence of a 'creative leap', which is not easy to be described in logical rules of conventional design theory. Research in creativity techniques has been done in the past. For example, Geschka (1996) reviewed three creativity techniques: brainstorming, visual confrontation, and morphological techniques, which were developed and have been used in Germany or German-speaking countries since the 1960s. Krohe (1996) presented a view on managing creativity as well as a summary of 22 creativity stimulating techniques, such as bug listing, goal/wish, manipulative verbs, nominal group technique, wildest idea, wishful thinking, etc. Cross (1997) constructed a procedure based on a 'creative-leap' example and generic descriptive models of creative design to provide further insight into the example. Lugt (2000) described four creative problem solving experiments involving meetings in which graphic variations on brainstorming technique were explored. Dorst and Cross (2001) proposed refinements to the co-evolution model, and also suggested that creativity in the design process can validly be compared to "burst of development". These techniques are universally employed for encouraging creativity and assisting people in producing a wide variety of novel ideas.

2.2. Sensuous association method

Referring to the applicably existing creativity techniques, we developed a creativity method based on the naturally sensuous ability of human beings. This method is what we call the "Sensuous Association Method (SAM)", whose main aim is to produce creative ideas by both a designer's individual association and surrounding stimulation. As shown in Fig. 1, the method contains four personal behaviors of human sensuousness and one extrinsic influence of the environment. They are expressed as follows:

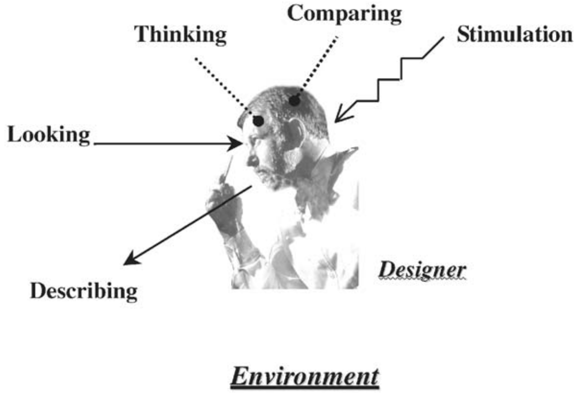


Fig. 1. Diagram of the sensuous association method (SAM).

(1) Looking: look at the involved things—information input course.
(2) Thinking: think about their origins and evolutionary trends—inference and re-association course.
(3) Comparing: compare what you look at and what you think about—extraction and restructuring course.
(4) Describing: describe your mental image formed after extraction and restructuring—creativity output course.
(5) Stimulation: furthermore, the designer's creative inspiration is increased through team interaction and surrounding atmosphere, which are also considered an input source of listening and feeling—catalysis and outburst course.

The SAM is used for refreshment of sensuousness and association of inspiration, and it can be regarded as a creativity tool for encouraging designers' potential to produce innovative ideas quickly. The operation of the SAM is described below:

(1) Put together a design team from a group of carefully selected people for a product design project.
(2) Before the SAM is performed, team members must be gathered into a discussion room, so arranged that a large number of categorized

information/pictures are stuck on the wall-board to make a very creative environment.

(3) When discussion begins, one member should be assigned as a recorder, the other members should look quietly at a section of product photos on the wall-board. The sensuous associating can be done by the design team members to help them think logically about the origins and evolutionary trends of the target product.
(4) During the SAM operation, the participant has to compare his/her associations with information/pictures observation and contemplation, extracting novel ideas regarding creative concepts.
(5) While creative images appear in one's mind after the comparison and extraction, they must be described in a sensuous phrase (e.g., lovely and pliant like a little bird, slender waist of a beauty, as sharp-sighted as an eagle, etc.), and written down by the recorder.
(6) Consequently, members' interactions will stimulate each other's creative inspirations in a highly conducive environment. The environment is conducive to opening up the creative potential hidden in each member's mind.

Since the SAM includes four natural behaviors of human beings: looking, thinking, comparing and describing, as well as advantageous surrounding stimulation, design creativity can be easily aroused. In such a natural and interactive atmosphere, not only team members' creative abilities can be enhanced, but a great deal of practical and quality ideas can be produced as well.

3. Outline of the creativity-based design process

Since creativity plays an important role in new product development, it has to be integrated into the product design process. Hence, we propose a creativity-based design process integrating some systematic design methodologies with the SAM. The essence of this design process is not the sole performance of the creativity tool but the coherence among involved stages of the process.

The proposed design process includes three essential stages: (1) divergence, (2) transformation, and (3) convergence (Jones, 1992, pp. 63–69). The divergent stage is an analytic process for searching the problem space, which can be described as "breaking the design problem into pieces". The transformation stage is a synthetic process for generating the solution space, characterized as "putting the pieces together in new ways". The convergent stage is an integration and evaluation process for finding applicable sub-solutions and optimal design solutions, described as "testing to discover the results of putting the new arrangement into practice".

There are many design methods and techniques employed in the overall design process: evolutionary thinking, systematic structure analysis, correlation matrix, interaction matrix/net, SAM in the divergent stage, morphological analysis, analysis of interconnected decision areas (AIDA) in the transforming stage, and then a decision-making model based on the weighted generalized mean method used to evaluate an optimal design solution in the convergent stage. The framework of this creativity-based design process is shown in Fig. 2, and the detailed procedural method of implementation is illustrated step by step in Section 4.

4. Implementation methods

To illustrate the detailed procedure and to prove the practicability of the proposed design process, methods of implementation were used and a case study of appearance design for an electric scooter was conducted in this section. According to the three essential stages and framework of this creativity-based design process shown in Fig. 2, the procedures of implementation are described in the following subsections.

4.1. Description of the target product

Electric scooters are considered a new green technology for the 21st century. They are also regarded as a viable niche market and a potential

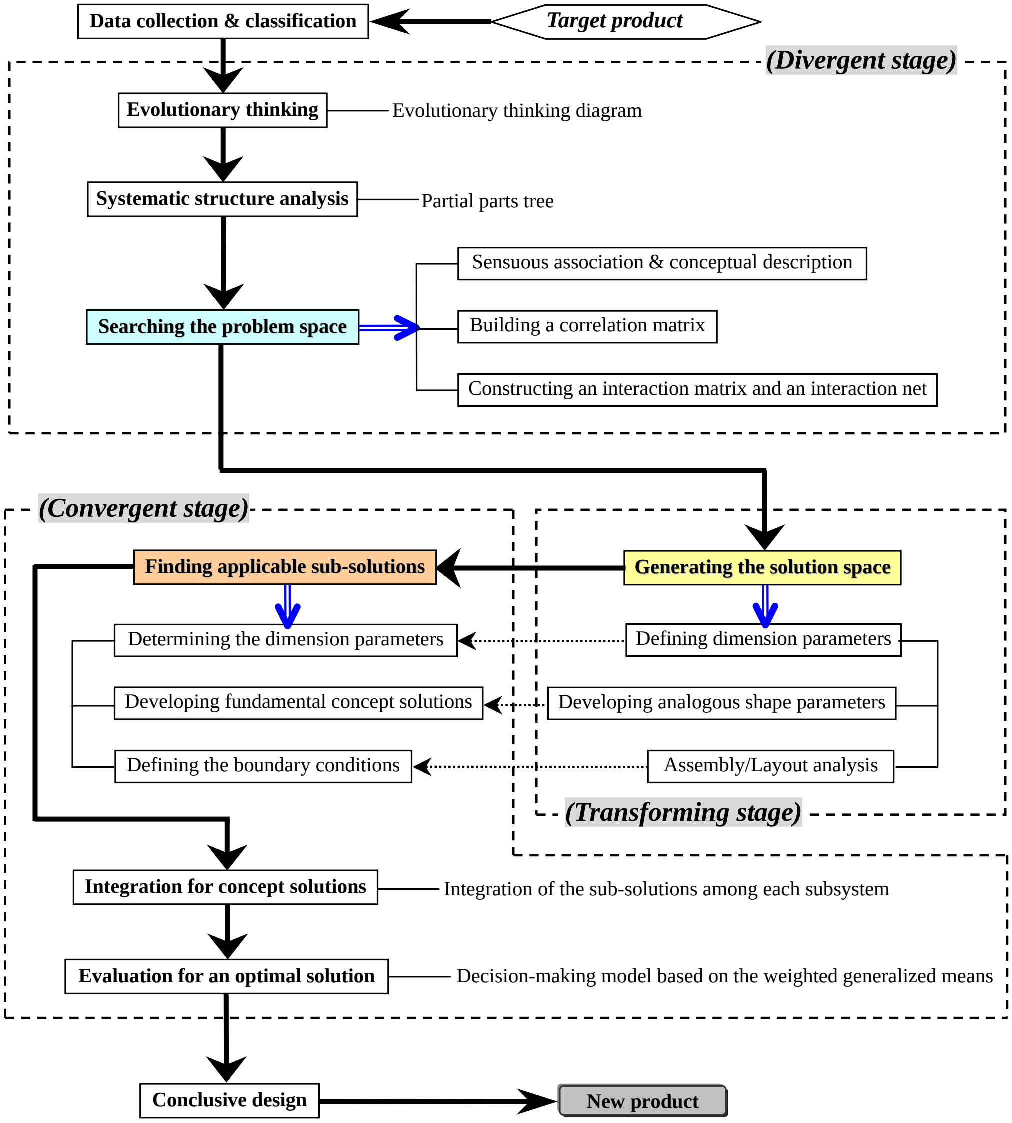


Fig. 2. Framework of the creativity-based design process.

industry for many countries, especially in Asian areas (Colella, 2000; Tso and Chang, 2003).

In order to formulate product development policy and establish intended goals of designing, related product information (e.g., product specifications, design regulations, technical documents, photos, patterns, etc.) should be collected first, and then categorized based on its characteristics and attributes.

4.2. Divergent stage of the design process

As product design is considered a problem-solving activity, the problem space—the locus in which problem solving activities take place (Goldschmidt, 1997), should be defined by expanding the boundary of design criteria so as to have a large and fruitful search space in which to look for problem solutions.

4.2.1. Evolutionary thinking of the target product

Basically, the 'wheel' was a vital invention for human civilization that changed the way of moving on land and expanded the domain of human activity. To understand the developmental history and evolutionary pathway toward the target product, as well as anticipating its possible development in the future, we collected a large number of related product photos and arranged them in an evolutionary thinking diagram as shown in Fig. 3. By contemplating the diagram, various kinds of two-wheel vehicles were distinguished, including the bicycle, motorcycle, motor bike, electric bike, scooter, and electric scooter. We subsequently assumed the position of electric scooters is different from traditional fuel scooters.

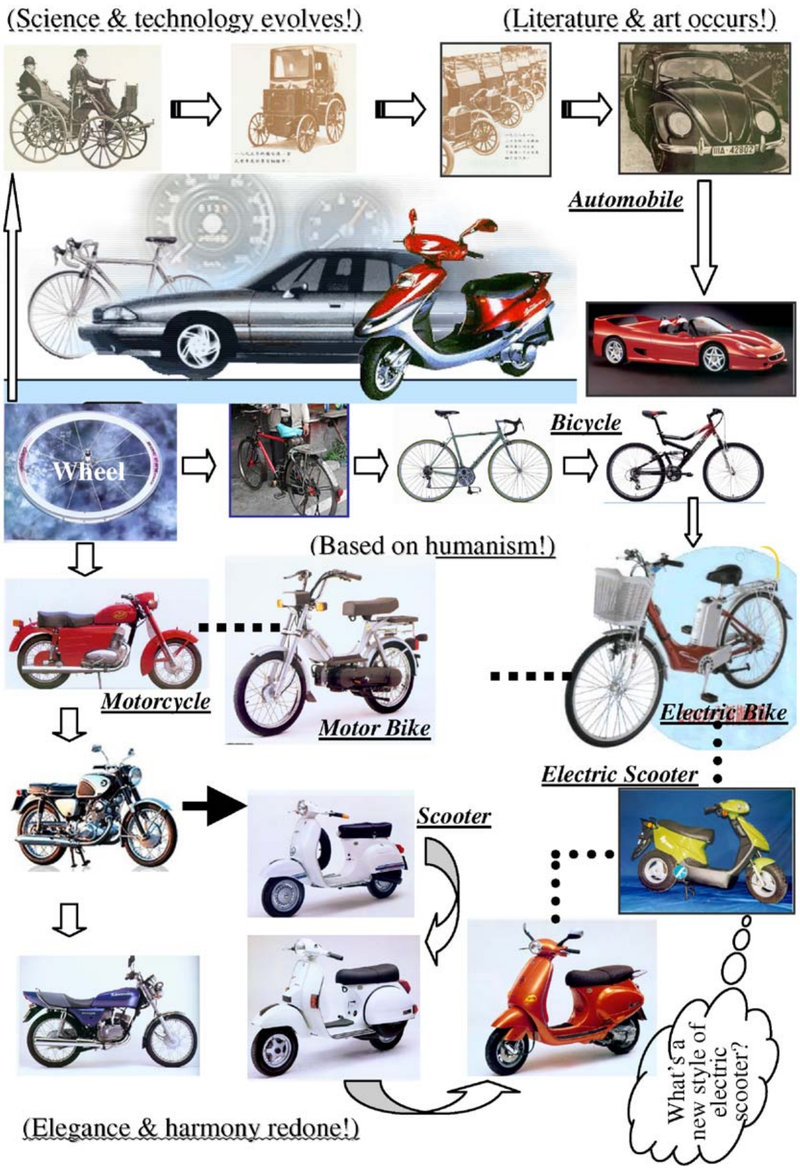


Fig. 3. Evolutionary thinking diagram for the target product.

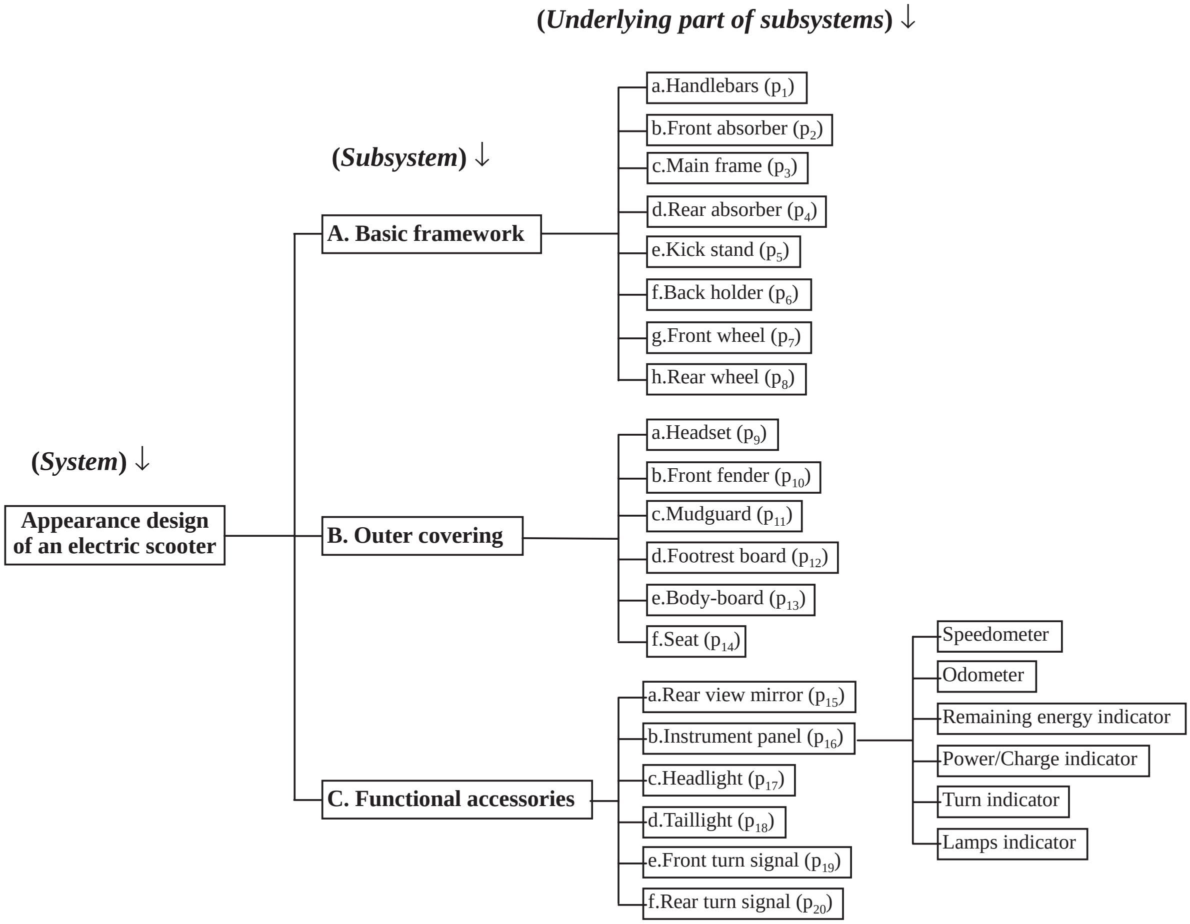


Fig. 4. Partial parts tree for appearance design of an electric scooter.

Electrically powered two-wheel scooters however will become a significant means of transportation for many urban areas. Moreover, we also identified some design objectives for developing an elegant, harmonious, and humanistically designed electric scooter.

4.2.2. Systematic structure analysis of the product's components

For reducing complex processes of design activity and simplifying design objects, the target product should be analyzed based on a systematic structure. In this appearance design case, an electric scooter was separated into three subsystems: the basic framework, the outer covering, and functional accessories, and their involved components were grouped into a partial parts tree as shown in Fig. 4. Due to the underlying parts of subsystems being more subject to appearance designing, they should be considered major units in the partial parts tree of this case. The subsystem component set can be expressed as below:

$$P = \{p_1, p_2, p_3, \ldots, p_n\}, \quad (1)$$

where p_j is an underlying part of subsystems, $j = 1, 2, 3, \ldots, n$.

4.2.3. Searching the problem space

Following procedures of evolutionary thinking and systematic structure analysis, critical problems such as product evolution, design objectives, and

Table 1
List of the conceptual description phrases

Item no.	Conceptual description phrase	Item no.	Conceptual description phrase
s_1	Bulging front and raised rear	s_{12}	A fly with a huge head
s_2	Round rear end, like a semi-sphere	s_{13}	A drop of tears
s_3	Incline at 45°	s_{14}	To promote step by step
s_4	A flat plate—real level	s_{15}	To treat another as one's equal
s_5	A bald-headed guy	s_{16}	An unemployed locksmith
s_6	To obstruct or hinder in the middle	s_{17}	To have edges and corners of view
s_7	To be deeply attached to each other	s_{18}	A drooping buttock
s_8	To turn upward	s_{19}	A partial lunar eclipse
s_9	Flimsy wings, stacked up	s_{20}	A guy with big feet
s_{10}	Looking for a needle in a haystack	s_{21}	Round as pearls and smooth as jade
s_{11}	No need to cover with	s_{22}	Slender waist of a beauty

parts analysis and grouping were identified. Based on initial identification, the problem space can be searched as follows.

(1) Sensuous association and conceptual description.
Using the SAM described in Section 2.2 to expand the boundary of design creativity, a large number of conceptual description phrases can be produced. By deleting the similar, preposterous, or indeterminate phrases, the selected conceptual description phrases can be arranged into a set as below:

$$S = \{s_1, s_2, s_3, \ldots, s_q\}, \quad (2)$$

where s_i is a single phrase, $i = 1, 2, 3, \ldots, q$.

In this case study, nearly 100 photos relevant to the scooters were classified and stuck on the wall-board. Through the use of the SAM, we chose the 22 conceptual description phrases characterized as creative ideas of the problem space. They are itemized as shown in Table 1.

(2) Building a correlation matrix between conceptual description phrases and underlying parts.
In order to properly apply the creative ideas to the development of subsystem components, a practicable correlation between conceptual description phrases and each subsystem part should be identified.

Based on Eqs. (1) and (2), the correlation matrix, R, can be represented as

$$R = S^{\mathrm{T}} \cdot P = (s_1, s_2, s_3, \ldots, s_q)^{\mathrm{T}} \cdot (p_1, p_2, p_3, \ldots, p_n) = (r_{ij})_{q\times n}, \quad (3)$$

where $i = 1,2,3,\ldots,q$; $j = 1,2,3,\ldots,n$.

The entries r_{ij} are defined by the following entry rules:

Rule 1: If s_i correlates with p_j, then $r_{ij} = 1$; i.e., the conceptual description phrase is able to apply to the subsystem part(s).

Rule 2: If s_i does not correlate with p_j, then $r_{ij} = 0$; i.e., the conceptual description phrase and the subsystem part(s) are icompatible with each other.

Using Eq. (3), a correlation matrix for the case study was constructed as shown in Table 2, which helps us to clarify which pairs of parts and phrases are compatible with each other. The question of how to turn the conceptual description phrases into real design elements for the subsystem parts was the problem space in this design case.

(3) Constructing an interaction matrix and an interaction net.
An interaction matrix is similar to that of a correlation matrix, which helps us to analyze the interaction between any two parts within the underlying parts. The interaction

Table 2
The correlation matrix between conceptual description phrases and underlying parts for the design

Description phrases	Basic frameworks								Outer covering						Functional accessories						Others
	Handle-bars	Front absorber	Main frame	Rear absorber	Kick stand	Back holder	Front wheel	Rear wheel	Headset	Front fender	Mudguard	Footrest board	Body-board	Seat	Rear view mirror	Instrument panel	Headlight	Taillight	Front turn signal	Rear turn signal	
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	p_{19}	p_{20}	
s_1	0	0	0	0	0	0	0	0	0	**1**	0	0	**1**	0	0	0	0	0	0	0	
s_2	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	**1**	0	0	
s_3	0	0	0	0	0	0	0	0	0	**1**	0	0	**1**	0	0	0	0	0	0	0	
s_4	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	
s_5	**1**	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	**1**	0	0	0	
s_6	0	0	0	0	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0	0	0	0	
s_7	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	
s_8	**1**	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
s_9	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	
s_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	
s_{11}	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	
s_{12}	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	**1**	0	**1**	0	0	0	
s_{13}	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	**1**	**1**	
s_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	
s_{15}	0	0	0	0	0	0	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0	0	
s_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
s_{17}	0	0	0	0	0	0	0	0	0	**1**	**1**	0	**1**	0	0	0	0	0	0	0	
s_{18}	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	
s_{19}	0	0	0	0	0	0	0	0	0	0	**1**	0	**1**	0	0	0	0	0	0	0	
s_{20}	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	
s_{21}	0	0	0	0	0	0	0	0	**1**	**1**	0	0	**1**	0	0	0	**1**	**1**	0	**1**	
s_{22}	0	0	0	0	0	0	0	0	0	**1**	**1**	0	**1**	0	0	0	0	0	0	0	

Table 3
The interaction matrix between any two parts within the underlying parts

	Aa	Ab	Ac	Ad	Ae	Af	Ag	Ah	Ba	Bb	Bc	Bd	Be	Bf	Ca	Cb	Cc	Cd	Ce	Cf
Aa		1*	1	0	0	0	1	0	1*	1	0	0	0	0	1*	0	0	0	0	0
Ab			1*	1	0	0	1*	0	0	1	1*	0	0	0	0	0	0	0	0	0
Ac				1*	1*	1*	1	1	0	0	0	1*	1*	1	0	0	0	0	0	0
Ad					0	0	1	1*	0	0	0	0	1	0	0	0	0	0	0	0
Ae						0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Af							0	0	0	0	0	0	1*	1	0	0	0	0	0	0
Ag								1	0	1	1	0	0	0	0	0	0	0	0	0
Ah									0	0	0	0	1	0	0	0	0	0	0	0
Ba										1	0	0	0	0	1*	1*	1*	0	1*	0
Bb											1*	1*	1	0	0	0	1*	0	1*	0
Bc												0	0	0	0	0	0	0	0	0
Bd													1*	1	0	0	0	0	0	0
Be														1*	0	0	0	1*	0	1*
Bf															0	0	0	0	0	0
Ca																0	0	0	0	0
Cb																	1	0	0	0
Cc																		0	1	0
Cd																			0	1
Ce																				1
Cf																				

matrix, B, can also be presented as

$$B = P^{\mathrm{T}} \cdot P = (p_1, p_2, p_3, \ldots, p_n)^{\mathrm{T}} \cdot (p_1, p_2, p_3, \ldots, p_n) = (b_{ij})_{n \times n} \quad (4)$$

where $i = 1, 2, 3, \ldots, n$; $j = 1, 2, 3, \ldots, n$

The entry rules of entries b_{ij} are defined as below:

Rule 1: If p_i directly interacts with p_j, then $b_{ij} = 1*$.

Rule 2: If p_i indirectly interacts with p_j, then $b_{ij} = 1$.

Rule 3: If p_i has no interaction with p_j, then $b_{ij} = 0$.

Rule 4: p_i and p_i itself (i.e. $i = j$) no need to be compared.

Using Eq. (4), an interaction matrix for the scooter design was carried out as shown in Table 3.

For extending the use of interaction matrix and searching the problem space concerning the interactions of underlying parts, an interaction net should be constructed based on the result of the interaction matrix operation. As shown in Fig. 5, the constructed network shows not only which pairs of parts are connected, but also distinctly illustrates the relative importance or interdependence among the underlying parts.

Analyzing Fig. 5, we found that interaction was closer between the basic framework and the outer covering, whereas the functional accessories were more independent than the other subsystems. Considering all parts, the main frame of the scooter ($Ac_{(6+4)}$) interacted with 10 parts, including six direct interactions and four indirect interactions. The body-board ($Be_{(6+3)}$) interacted with nine parts, including six direct interactions and three indirect interactions. The front fender ($Bb_{(4+5)}$) interacted with nine parts, including four direct interactions and five indirect interactions. The analysis demonstrates the appearance design of an electric scooter should focus on the main frame for the basic framework design, and the body-board and the front fender for the outer cover design. Most of the functional accessories directly interacted with the headset ($Ba_{(5+1)}$), including the rear view mirror ($Ca_{(2+0)}$), the instrument panel ($Cb_{(1+1)}$), the headlight ($Cc_{(2+2)}$), and the front turn signal ($Ce_{(2+2)}$); hence, they could be considered for collocation with the headset in the design.

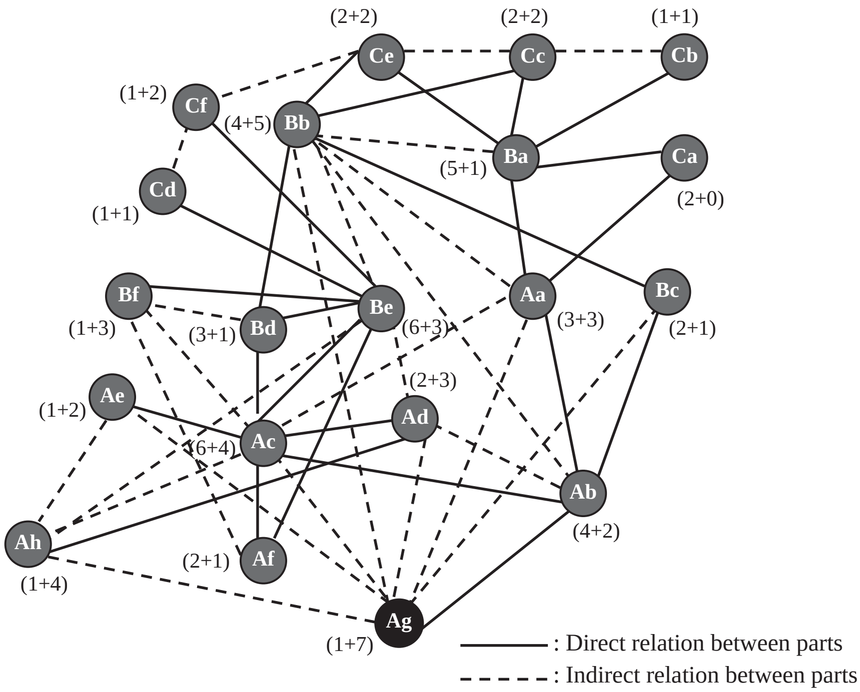


Fig. 5. Interaction net among the underlying parts.

4.3. Transforming stage of the design process

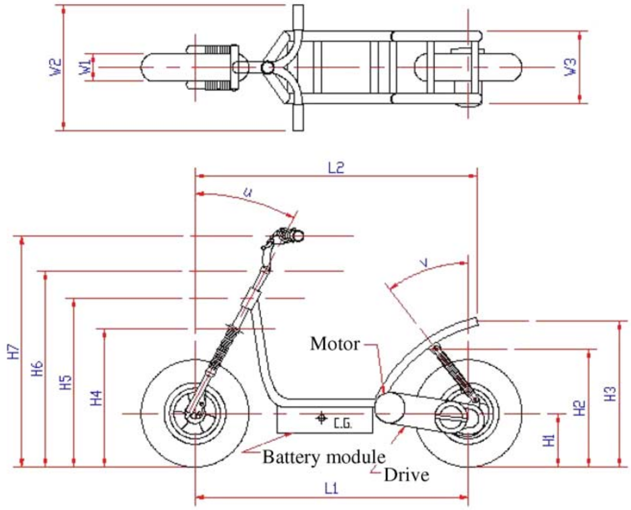
Many design concepts were created from the problem space through the divergent process. The design concepts regarded as radical problem solutions are not concrete enough. They should be transformed into a definite solution space, taking advantage of positive design elements to make the concepts a reality.

4.3.1. Generating the solution space

For converting the design concepts into practical design elements, the definite solution space must be generated corresponding to the three subsystems we designated before.

(1) Defining dimension parameters for the basic framework design.
According to the analysis of Fig. 5, the basic framework design should be based on the main frame, whose key points are not only to ensure the structural strength but also to meet the dimensional parameters, such as center-of-gravity position (CG), wheelbase, overall length, overall width, overall height, etc. Since the CG position of an electric scooter is different from that of a conventional fuel scooter (Lai et al., 2003), it must be precisely determined. In this design, over-sized and no-inner-tube tires with front-disc and rear-drum type of brakes were used. The significant dimension parameters of the basic framework design are shown in Fig. 6, and they can be considered a solution space in teams of the basic framework subsystem.

(2) Developing analogous shape parameters for the outer cover design.
Since outer covering is the most important factor in appearance design of an electric scooter, it must be considerably well-thought-out. Based on the result of Table 2, if a conceptual description phrase correlates with any underlying part (i.e. $r_{ij} = 1$), it should be turned into an analogous shape parameter by image outlining of the phrase and part's feature, and the image outlines also should be represented in a morphological chart.



Where:

✧ L1: Wheelbase
✧ L2: Overall length
✧ H1: The height between the wheel axle and ground
✧ H2: The height between the pivot of the rear absorber and ground
✧ H3: The height between the rear end of the main frame and ground
✧ H4: The height between the absorber head of the front forks and ground
✧ H5: The height between the steering bearing and ground
✧ H6: The height between the joint of the handlebar and ground
✧ H7: The height between the outer sides of the handlebar and ground
✧ W1: Wheel width
✧ W2: Handlebar width
✧ W3: Main frame width
✧ u: The included angle between the axle center line of the front absorber and the perpendicular
✧ v: The included angle between the axle center line of the rear absorber and the perpendicular

Fig. 6. The significant dimension parameters of the basic framework design.

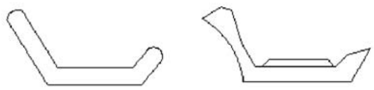
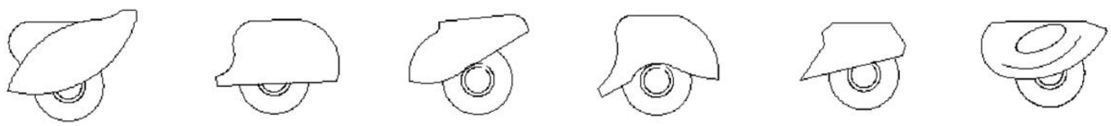
As shown in Table 4, the morphological chart contains some concrete design elements of creative ideas originating from the SAM operation. The chart can be considered a solution space in teams of the outer covering subsystem. In the morphological chart, we have four pieces of shape parameters for the headset (Ba), six for the front fender (Bb), four for the mudguard (Bc), two for the footrest board (Bd), six for the body-board (Be), and three for the seat (Bf). Theoretically, there are 3456 sets of conceptual design possibilities in the solution space by permuting and composing these pieces of shape parameters.

(3) Assembly/layout analysis of the functional accessories.

As we found in Fig. 5, the functional accessories are more independent of but necessary for driving safety because they must be appropriately collocated with the other components. The analysis of interconnected decision areas (AIDA), an analytical method for dealing with the determinations of related decision-making concerning design problems (Luckman, 1967), can be applied to facilitate layout design of the functional accessories.

As shown in Fig. 7, the AIDA method can clearly help us to understand all the compatible sets regarding the layout conditions of the functional accessories. There are 15 total pairs of

Table 4
Morphological chart of the shape parameters for the outer cover design

B	1	2	3	4	5	6
a. Headset						
						
	s_5	s_{11}	s_{12}	s_{21}		
b. Front fender						
						
	s_{21}	s_3	s_1	s_4、s_6、s_{11}	s_{17}	s_{22}
c. Mudguard						
						
	s_{17}	s_{19}	s_{11}	s_{22}		
d. Footrest board						
						
	s_{15}	s_6				
e. Body-board						
						
	s_1、s_{13}	s_{18}、s_{19}	s_3、s_{22}	s_2、s_{18}、s_{21}	s_{17}	s_9、s_{21}
f. Seat						
						
	s_7	s_{15}	s_{14}			

compatible solutions shown in Table 5, which were identified by the analysis of the decision areas. These solutions also can be considered a solution space in terms of the functional accessory subsystem.

4.4. Convergent stage of the design process

Because of a large number of problem solutions within the solution space, they must be converged and integrated into formal solutions, not only for

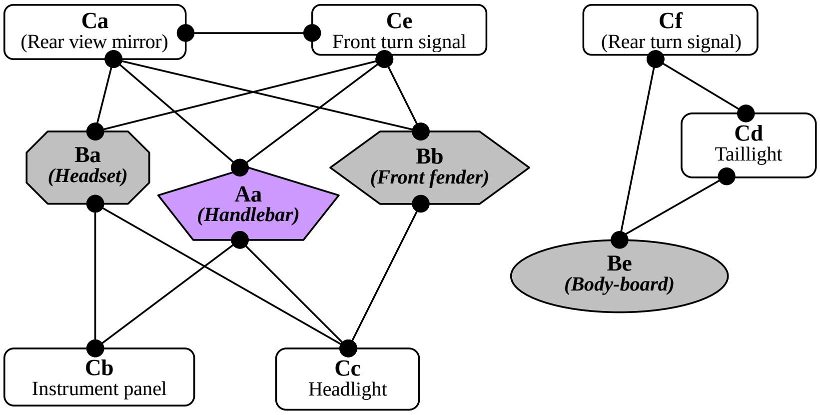


Fig. 7. AIDA for the functional accessory layout design.

Table 5
The compatible solutions identified by the analysis of the decision areas

Functional accessory	Pair(s)	Compatible sets
Rear view mirror	3	Ca—Aa, Ca—Ba, Ca—Bb
Instrument panel	2	Cb—Aa, Cb—Ba
Headlight	3	Cc—Aa, Cc—Ba, Cc—Bb
Taillight	1	Cd—Be
Front turn signal	4	Ce—Aa, Ce—Ba, Ce—Bb, Ce—Ca
Rear turn signal	2	Cf—Be, Cf—Cd

finding applicable sub-solutions but for evaluating an optimal design solution as well.

4.4.1. *Finding applicable sub-solutions*

Corresponding to the transforming process, the applicable sub-solutions can be found as follows.

(1) Determining the dimension parameters for the basic framework design. One vital purpose of product design is production. Thus, the involved dimension parameters must be determined. According to the defined dimension parameters shown in Fig. 6, the significant dimensions of the basic framework design were determined as follows: $L1 = 1200$ mm, $L2 = 1240$ mm, $H1 = 235$ mm, $H2 = 520$ mm, $H3 = 645$ mm, $H4 = 610$ mm, $H5 = 745$ mm, $H6 = 870$ mm, $H7 = 1020$ mm, $W1 = 120$ mm (rear wheel width: 130 mm), $W2 = 555$ mm, $W3 = 320$ mm, $u = 28°$, and $v = 38°$.

(2) Developing fundamental concept solutions for the outer cover design.
Based on morphological analysis shown in Table 4, we can theoretically produce 3,456 sets of conceptual possibilities; however, subsequent to concept assessment, there were just six sets of fundamental solutions chosen by rudimentary evaluation of 102 idea sketches. The six sets of fundamental concept solutions are shown in Fig. 8.

(3) Defining the boundary conditions for the functional accessory layout design.
For rational and practical options, boundary conditions of the compatible solutions should be defined. As shown in Table 6, the definition of boundary conditions can help us

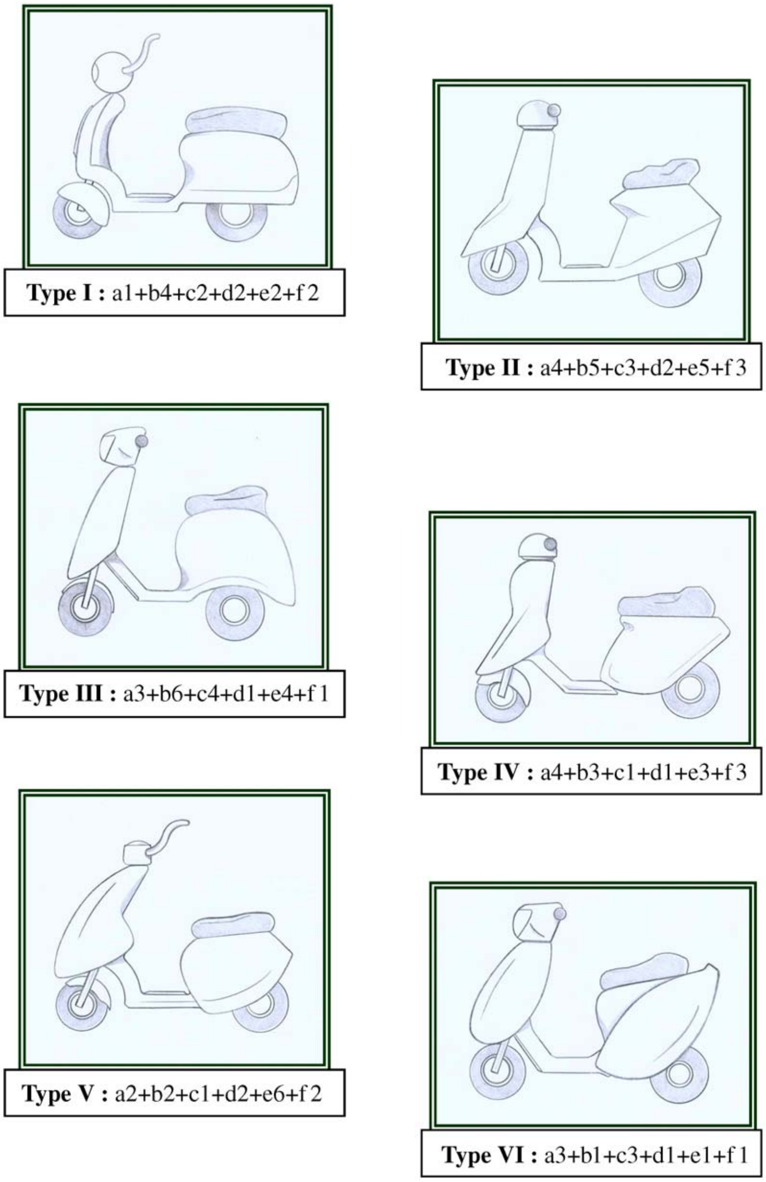


Fig. 8. Six sets of fundamental concept solutions in outer cover design.

to clarify the layout condition of each compatible solution, as well as to make an appropriate selection within the compatible sets.

4.4.2. Integration of sub-solutions for developing concept solutions

Based on the six sets of fundamental concept solutions shown in Fig. 8, the concept design for the electric scooter must be further developed by integrating the involved sub-solutions of the basic framework and the functional accessory subsystems. Through comprehensive evaluation and integration, we developed three sets of concept solutions for the electric scooter design as shown in Fig. 9.

Table 6
Definition of boundary conditions for the functional accessory layout design

C	Compatible solution	Compatible set	Description of the condition
Rear view mirror (Ca)	To set on the Handlebar	(Ca—Aa)	If the shape parameter of Headset is Ba1 or Ba2, the Rear view mirror can be directly set on the Handlebar.
	To set on the Headset	(Ca—Ba)	If the shape parameter of Headset is Ba3 or Ba4, the Rear view mirror can be easily set on the Headset.
	To set on the Front fender	(Ca—Bb)	It seems unfitting for our target product due to ergonomic considerations, but it can be considered to be used in a larger type of electric scooter design.
Instrument panel (Cb)	To set alone on the Handlebar	(Cb—Aa)	If the shape parameter of Headset is Ba2, the Instrument panel can be independently attached to the Handlebar.
	To integrate with the Headset	(Cb—Ba)	If the shape parameter of Headset is Ba1, Ba3 or Ba4, the Instrument panel can be integrated into the Headset.
Headlight (Cc)	To set alone on the Handlebar	(Cc—Aa)	If the shape parameter of Headset is Ba1 or Ba2, the Headlight can be set alone on the Handlebar.
	To integrate into the Headset	(Cc—Ba)	If the shape parameter of Headset is Ba3 or Ba4, the Headlight can be integrated into the Headset.
	To combine with the Front fender	(Cc—Bb)	If the shape parameter of Headset is Ba2, Ba4 or the Front fender shape is Bb2, Bb3 or Bb5, the Headlight can be combined with the Front fender.
Taillight (Cd)	To set alone on the Body-board	(Cd—Be)	This is a common use in current design. Besides, it also can be set on the Seat (Cd—Bf) or the Back holder (Cd—Af), but both of the locations are not considered feasible because of their impracticality for mass production.
Front turn signal (Ce)	To fix on both sides of Handlebar	(Ce—Aa)	This position provides for good signal visibility because both sides of the Handlebar represent the maximum width of the electric scooter frame.
	To attach to the Headset/combine with the Front fender	(Ce—Ba) / (Ce—Bb)	This is a common design for today's fuel-powered scooters.
	To integrate into the Rear view mirror	(Ce—Ca)	The pair of Ce—Ca provides more signal visibility than Ce—Aa, but the design may be expensive because of the need for standardization of parts.
Rear turn signal (Cf)	To integrate in the Body-board	(Cf—Be)	This design gives a smooth and aesthetic look.
	To be combined with the Taillight	(Cf—Cd)	This is an easy assembly but provides poor functional performance.

Concept solution	**Integration of sub-solutions of the subsystems** (Note that the modified shape parameters within the sub-solutions of the outer covering subsystem are under-lined)
 **※Solution 1**	**A. (Basic framework):** [Aa-Ab-Ac-Ad-Ae-Ag-Ah] **B. (Outer covering):** [Ba3-Bb4-Bc1-Bd1-Be2-Bf2] **C. (Functional accessories):** [(Ca-Aa)-(Cb-Ba)-(Cc-Ba)-(Cd-Be)-(Ce-Ba)-(Cf-Cd)]
 **※Solution 2**	**A. (Basic framework):** [Aa-Ab-Ac-Ad-Ae-Ag-Ah] **B. (Outer covering):** [Ba3-Bb4-Bc1-Bd1-Be3-Bf2] **C. (Functional accessories):** [(Ca-Aa)-(Cb-Ba)-(Cc-Ba)-(Cd-Be)-(Ce-Bb)-(Cf-Cd)]
 **※Solution 3**	**A. (Basic framework):** [Aa-Ab-Ac-Ad-Ae-Af-Ag-Ah] **B. (Outer covering):** [Ba3-Bb4-Bc1-Bd1-Be4-Bf1] **C. (Functional accessories):** [(Ca-Aa)-(Cb-Ba)-(Cc-Ba)-(Cd-Be)-(Ce-Aa)-(Cf-Be)]

Fig. 9. Three sets of concept solutions for the electric scooter design.

4.4.3. *Evaluation of concept solutions for an optimal solution*

For further conclusive design, an optimal solution must be determined among the three sets of concept solutions. In this study, we developed an operative decision-making model based on the weighted generalized mean method. The formula of the weighted generalized means is defined as below (Klir and Folger, 1988, pp. 58–61):

$$h_\alpha(a,w) = \left(\sum_{i=1}^{n} w_i \times a_i^\alpha\right)^{1/\alpha}, \tag{5}$$

where w_i is the parameter weight; $w_i \geqslant 0$, $\sum_{i=1}^{n} w_i = 1$, a_i the relative value of evaluation factors, the α the variable parameter, $-\infty < \alpha < \infty$.

The major difference between the weighted generalized means and the conventional weighted means is the involvement of α parameter. By varying the α parameter within the interval of $(-\infty, \infty)$, we can derive a homologous h_α value based on a multi-factor analysis, and then draw the $\alpha - h_\alpha$ curves. The $\alpha - h_\alpha$ curves can be used to rank the alternatives harmoniously so as to accurately identify an optimal solution among them.

Table 7
Statistical results of the quantitative judgments

Alternative	Evaluation factor	Good (0.5)	Acceptable (0.3)	Ordinary (0.2)	Relative value
Solution 1	Humanistic	51	62	40	0.52
	Innovative	80	92	77	0.83
	Stylish	62	75	53	0.64
	Aesthetic	58	63	55	0.59
Solution 2	Humanistic	69	76	54	0.68
	Innovative	87	95	80	0.88
	Stylish	66	70	65	0.67
	Aesthetic	50	48	53	0.50
Solution 3	Humanistic	66	75	58	0.67
	Innovative	84	93	75	0.85
	Stylish	56	62	57	0.58
	Aesthetic	70	81	58	0.71

Table 8
The weighted parameters of the evaluation factors

Score	Factor			
	Humanistic	Innovative	Stylish	Aesthetic
Sum	174	168	156	102
Average	4.35	4.20	3.90	2.55
Naturalization	0.29	0.28	0.26	0.17

The decision-making model for evaluating an optimal concept solution was developed and illustrated in the following steps:

Step 1: Establishing evaluation parameters

In accordance with product design objectives, we identified four evaluation factors: 'humanistic', 'innovative', 'stylish', and 'aesthetic', and three evaluation grades: 'good' (score: 0.5), 'acceptable' (score: 0.3), and 'ordinary' (score: 0.2). Based on quantitative judgments by design team members, the statistical results are shown in Table 7.

The relative values for each evaluation factor involved in the design solutions are summarized in a matrix below:

$$A = (a_{ji})_{3\times 4} = \begin{bmatrix} 0.52 & 0.83 & 0.64 & 0.59 \\ 0.68 & 0.88 & 0.67 & 0.50 \\ 0.67 & 0.85 & 0.58 & 0.71 \end{bmatrix} \begin{matrix} \text{Solution 1} \\ \text{Solution 2} \\ \text{Solution 3} \end{matrix}. \tag{6}$$

Step 2: Setting up the weighted function

In order to distinguish the relative importance of the evaluation factors, we defined the weighted function as follows:

$$w_i = (I_1/humanistic) + (I_2/innovative) + (I_3/stylish) + (I_4/aesthetic), \tag{7}$$

where I_i is the weight for each evaluation factor; $\sum_{i=1}^{4} I_i = 1$.

Further, we used an interaction matrix to analyze the relatively important degree among each pair of evaluation factors, and arranged them into a weighted parameter list shown in Table 8.

With the results, we constructed the weighted function and converted it into a matrix as below:

$$w_i = (0.29/humanistic) + (0.28/innovative) + (0.26/stylish) + (0.17/aesthetic), \tag{8}$$

$$w_i = [0.29 \quad 0.28 \quad 0.26 \quad 0.17]. \tag{9}$$

Step 3: The operation of weighted generalized means

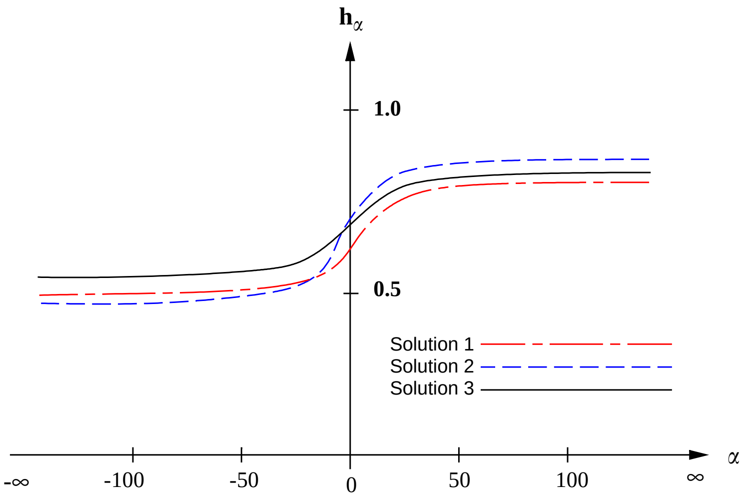


Fig. 10. The $\alpha - h_\alpha$ relation diagram of the weighted generalized mean solutions.

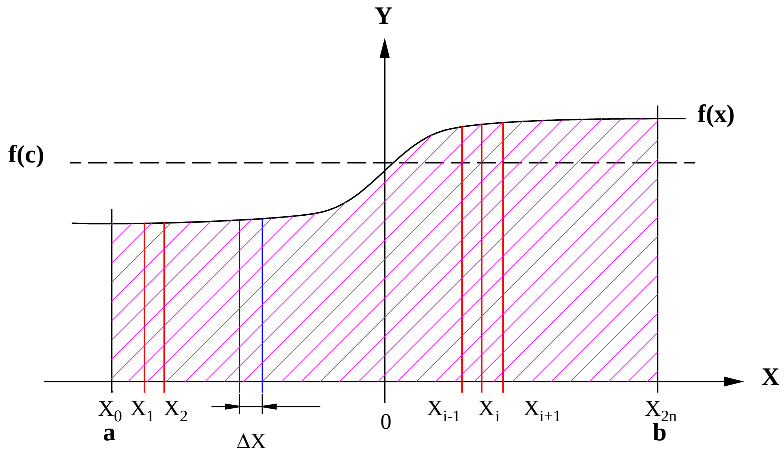


Fig. 11. Using Simpson's rule and the mean value theorem to obtain the averages of $\overline{h_\alpha}$.

Let $i = 4$, substituting the data of matrixes (6) and (9) into formula (5),i.e.

$$h_j(\alpha) = (w_1 a_{j1}^{\alpha} + w_2 a_{j2}^{\alpha} + w_3 a_{j3}^{\alpha} + w_4 a_{j4}^{\alpha})^{1/\alpha},$$
$$-\infty < \alpha < \infty; j = 1, 2, 3, \quad (10)$$

where j represents the jth solution.

After calculation, we obtained an $\alpha - h_\alpha$ relation diagram as shown in Fig. 10.

Step 4: Analysis of the results

As shown in Fig. 10, if $\alpha > 0$, the maximum of h_α is Solution 2; but if $\alpha < 0$, the maximum of h_α is Solution 3. For a more precise comparison, the average h_α of each solution must be solved.

Step 5: Solving the averages of $\overline{h_\alpha}$.

It can be observed in Fig. 10 that the curve $\alpha - h_\alpha$ levels out as the curve approaches either side of positive infinity and negative infinity. Hence, we applied Simpson's rule and the mean value theorem (see Fig. 11) to solve the averages of $\overline{h_\alpha}$.

Simpson's rule:

$$\int_a^b f(x)\,\mathrm{d}x \cong \Delta x\{f(x_0) + 4f(x_1) + 2f(x_2) + \cdots + 2f(x_{2n-2}) + 4f(x_{2n-1}) + f(x_{2n})\}/3. \quad (11)$$

Let $a=-100$, $b=100$; $f(x) = h_j(\alpha) = (w_1 a_{j1}^{\alpha} + w_2 a_{j2}^{\alpha} + w_3 a_{j3}^{\alpha} + w_4 a_{j4}^{\alpha})^{1/\alpha}$.

$$Area_j = \int_{-100}^{100} h_j(\alpha)\,\mathrm{d}\alpha \cong [h_j(-100) + 4h_j(-99) + 2h_j(-98) + \cdots + 2h_j(98) + 4h_j(99) + h_j(100)]/3. \quad (12)$$

Mean value theorem:

$$\because \int_a^b f(x)\,\mathrm{d}x = f(c) \times (b-a), \quad (13)$$

$$\therefore \int_{-100}^{100} h_j(\alpha)\,\mathrm{d}\alpha = \overline{h_{\alpha}^{j}}[100 - (-100)], \quad (14)$$

i.e.

$$\overline{h_{\alpha}^{j}} = Area_j/200, \quad (15)$$

where $\overline{h_{\alpha}^{j}}$ represents the $\overline{h_{\alpha}}$ of the jth solution, $j = 1, 2, 3$.

By applying formulas (12) and (15), we obtained results as shown in Table 9.

Step 6: Determining the optimal solution

According to the comparison of Table 9, we found that Solution 3 was superior to Solution 2 in terms of the conventional weighted means, but their averages were very close. For a more credible evaluation, the weighted generalized means was determined, and the result showed that Solution 3 was better than Solution 2. Accordingly, we chose Solution 3 as the optimal solution in this case study.

Table 9
Operational results of the decision-making model

	Area	$\overline{h_{\alpha}}$	E
Solution 1	134	0.67	0.6499
Solution 2	138	0.69	0.7028
Solution 3	142	0.71	0.7038

$E = \sum_{i=1}^{n} w_i \times a_i, w_i \geqslant 0, \sum_{i=1}^{n} w_i = 1$

5. Results and discussions

With the determination of the optimal solution, we made a 1/20 scale mock-up of the scooter from polyurethane foam for previewing the 3D appearance. Additionally, the conclusive design was completed by constructing and modifying the detailed contours according to the aesthetic principle of golden section proportion (Elam, 2001, pp. 5–42). The outcome of the appearance design is shown in Fig. 12, and has the following characteristics: (see Fig. 13)

(1) No front fender design gives people a new impression of an electric scooter.
(2) The body outline designed with the golden section proportion yields a scooter with a classical and elegant appearance.
(3) A rounded and smooth configuration gives the look of harmony and gracefulness.
(4) The digital luminescent instrument panel and metal accessories in chromate cladding reveal its modern technical aesthetics.
(5) The combination of a one-piece running-board and detachable battery module provides for operational stability.

Based on engineering drawings of the conclusive design, a prototype of the electric scooter was built as shown in Fig. 14. In addition, we patented this new styling design through the Intellectual Property Office of Ministry of Economic Affairs, Taiwan, R.O.C. in 2002. We have authorized the Flying electric motor company to use the patented design in future production.

6. Conclusions

Creativity as a tool plays an important role in new product development. It should be integrated into a product design process. In this research, we developed a creativity method called the sensuous association method (SAM), which can be employed to encourage designers' potential to produce innovative ideas quickly. Subsequently, we proposed a creativity-based design process integrating various systematic design methodologies

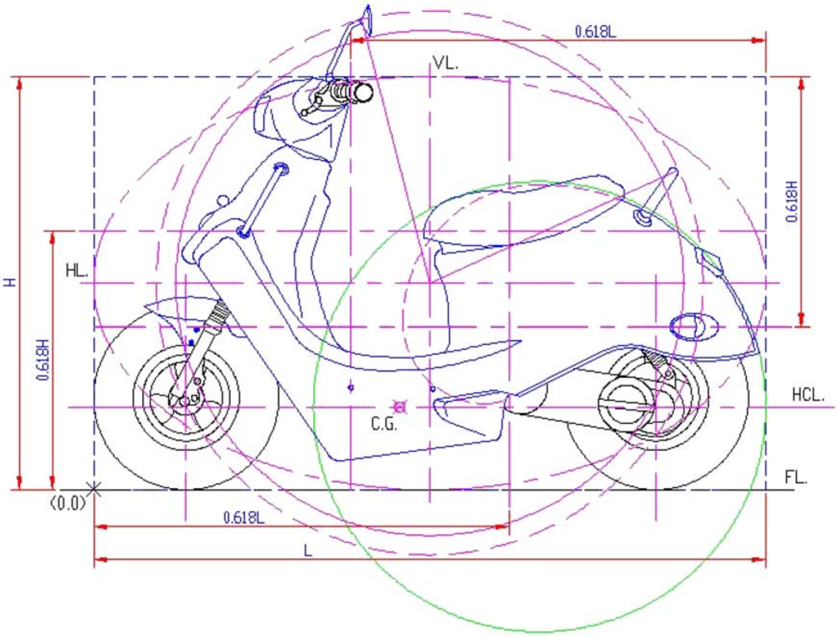


Fig. 12. Appearance design according to the aesthetic principle of golden section proportion.

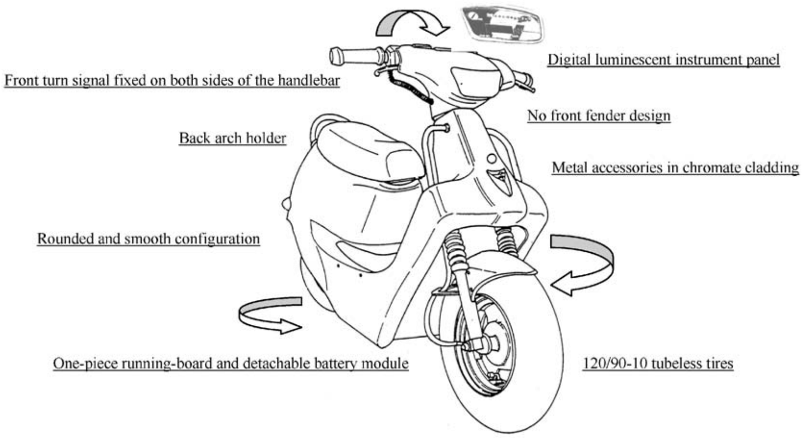


Fig. 13. Illustration of the conclusive design characteristics.

with the SAM. The proposed design process includes three essential stages: divergence, transformation, and convergence, whose essence is not the sole performance of the stages and the developed creativity tool but the coherent efforts among each involved technique of the process.

To illustrate the procedures of implementing and verifying the practicality of the proposed design process, a case study—appearance design for an electric scooter—was conducted step by step. By applying evolutionary thinking, systematic structure analysis, the sensuous association

Fig. 14. The prototype of the new electric scooter for this design case.

method, and other systematic approaches to the design process, not only the problem space was searched and identified, but also a large number of sub-solutions involved in the solution space were generated, particularly the six sets of fundamental concept solutions in outer cover design.

By integrating the applicable sub-solutions among each subsystem, three sets of concept solutions for the electric scooter design were developed, and then an optimal solution was determined by using the decision-making model based on the weighted generalized mean method. With the determination of the optimal solution, the conclusive design was completed by constructing and modifying the detailed contours according to the aesthetic principle of golden section proportion. A prototype of the electric scooter was also built.

In conclusion, the final work of the electric scooter design has met our initial product development objectives. We hope that the research can provide a new approach to the design process for industries, and allow companies to take advantage of the creativity-based design process to achieve the goals of innovative product design.

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References

Archer, L.B., 1971. Technological Innovation: a methodology. Inforlink, Frimley.

Bullinger, H.J., Lentes, H.P., Scholtz, O.H., 2000. Challenges and chances for innovative companies in a global information society. International Journal of Production Research 38 (7), 1469–1500.

Chaturvedi, K.J., Rajan, Y.S., 2000. New product development: challenges of globalization. International Journal of Technology Management 19 (7/8), 788–805.

Colella, W.G., 2000. Market prospects, design features, and performance of a fuel cell-powered scooter. Journal of Power Source 86, 255–260.

Cooper, R.G., 1996. Overhauling the new product process. Industrial Marketing Management 25, 465–482.

Cross, N., 1997. Descriptive models of creative design: application to an example. Design Studies 18 (4), 427–440.

Dorst, K., Cross, N., 2001. Creativity in the design process: co-evolution of problem—solution. Design Studies 22 (5), 425–437.

Elam, K., 2001. Geometry of Design: studies in proportion and composition. Princeton Architectural Press, New York.

French, M.J., 1971. Engineering Design: the conceptual stage. Heinemann, London.

Geschka, H., 1996. Creativity techniques in Germany. Creativity and Innovation Management (June), 87–92.

Goel, P.S., Singh, N., 1998. Creativity and innovation in durable product development. Computers & Industrial Engineering 35 (1–2), 5–8.

Goldschmidt, G., 1997. Capturing indeterminism: representation in the design problem space. Design Studies 18 (4), 441–445.

Griffin, A., 1997. PDMA research on new product development practices: updating trends, and benchmarking best practices. The Journal of Product Innovation Management 14, 429–458.

Hall, A.D., 1968. A Methodology for Systems Engineering, 6th Edition. Van Nostrand, Princeton, NJ, pp. 85–91.

Heap, J., 1989. The Management of Innovation and Design. Cassell, London.

Hubka, V., 1989. Principles of Engineering Design. Springer, New York.

Jones, J.C., 1992. Design Methods. Van Nostrand Reinhold, New York.

Klir, G.J., Folger, T.A., 1988. Fuzzy Sets, Uncertainty, and Information. Prentice-Hall International, London.

Krohe, J., 1996. Managing creativity. Across the Board (September), 16–22.

Lai, H.C., Liu, J.S., Lee, D.T., Wang, L.S., 2003. Design parameters study on the stability and perception of riding comfort of the electrical motorcycles under rider leaning. Mechatronics 13, 49–76.

Liu, Y.T., 2000. Creativity or novelty? Design Studies 21 (3), 261–276.

Luckman, J., 1967. An approach to the management of design. Operational Research Quarterly 18 (4), 345–358.

Lugt, R., 2000. Developing a graphic tool for creative problem solving in design groups. Design Studies 21 (5), 505–522.

Majaro, S., 1988. Managing Ideas for Profit. McGraw-Hill, Maidenhead.

McAdam, R., McClelland, J., 2002. Sources of new product ideas and creativity practices in the UK textile industry. Technovation 22, 113–121.

Pahl, G., Beitz, W., 1984. Engineering Design: a Systematic Approach. Chapter 3: The design process, Design Council, London.

Poolton, J., Ismail, H.S., Shahidipour, M., 2000. The new products process: effective knowledge capture and utilization. Concurrent Engineering: Research and Applications 8 (2), 133–143.

Stevens, G., Burley, J., 1997. 3000 Raw ideas = 1 commercial success. Research Technology Management 40 (3), 16–27.

Stevens, G., Burley, J., Divine, R., 1999. Creativity + Business Discipline = Higher Profits from New Product Development. Journal of Product Innovation Management 16, 455–468.

Tso, C., Chang, S.Y., 2003. A viable niche market—fuel cell scooters in Taiwan. International Journal of Hydrogen Energy 28, 757–762.

Villa, A., 1998. Product-process design and continuing innovation. Robotics and Computer-Integrated Manufacturing 14, 393–401.