# Knowledge system for early phase aesthetic concept generation in industrial design

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**Abstract:** The early phase of the aesthetic concept generation involves the tacit knowledge of the experts. There is general lack of formal models to capture and use this knowledge, as it is difficult to externalise, capture, express and reuse. This paper contributes to the development of formal models and an application framework for the knowledge involved in early phase aesthetic concept generation of industrial products. The models are based on four axioms. These axioms are used to develop two models; aesthetic design complex (ADC) and action grammar. These models are used to develop a design learning and generation framework. Soft computing techniques are used to capture, reuse and externalise the tacit aesthetic design knowledge. The tacit design is expressed as heuristics, which are validated by human-based evaluation. The developed prototype framework shows that such a computational support is possible to aesthetic design process, practice and education.

**Keywords:** design for aesthetics; knowledge-based system; cognitive process; action grammar; concept generation; early phase design; industrial design; expert systems; product design; artificial intelligence; artificial neural network; genetic algorithms; principal component analysis.

**Reference** to this paper should be made as follows: Soni, S., Tandon, P. and Khanna, P. (2018) 'Knowledge system for early phase aesthetic concept generation in industrial design', *Int. J. Intelligent Systems Design and Computing*, Vol. 2, No. 1, pp.45–75.

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## 1 Introduction

The computer aided design/computer aided styling (CAD/CAS) systems have made immense impact on product development process. As these technologies mature, their impact on product development will continue to increase. Despite that, such systems have been able to support only the later phases of the product design cycle (Pahl and Beitz, 2007). Some of the CAD systems are developed to support the functional design of industrial products. But, the early phase of the product design process; especially the concept generation for aesthetics in industrial design, is not well supported by present CAD/CAS systems. This phase is majorly dominated by the human designers, who use the tacit knowledge acquired through extended period of studio-based training for concept generation and exploration (Polanyi, 1966). In order to realise the benefits of the computational tools in the overall product design process, knowledge-based systems to support the early phase of the product design processes are very important. This paper presents an effort towards this objective.

The goal of the knowledge-based system is to capture the knowledge in such a way that the knowledge of the expert is available to less experienced users (Hsiao and Tsai, 2005).

Firschein et al. (1973) suggested that any expert system should support at least the design and evaluation process. This calls for two categories of knowledge to be captured. These are the design knowledge and critic knowledge.

The problem of capturing the design and critic knowledge is much more difficult in the domain of aesthetic design compared to functional design. As most of the design and evaluation processes take place in the human mind, they are difficult to model. These processes are governed by cognitive laws. As observed by Galanter (2013), a general aesthetic evaluator is almost impossible to develop with the current state of knowledge. What is proposed in this research is a domain specific aesthetic evaluator, limited to a given structure of the design form.

The proposed model is based on four axioms, these axioms formally defines various entities and their relationships in the aesthetic design process. These entities and processes define the aesthetic design complex (ADC). Two of the four axiom are axioms of object relations and axiom of human knowledge, as considered by Simon (1969, 1982), Zeng (2001), Salustri and Lockledge (1999) and Yoshikawa (1981) in various manners. The other two axioms are axiom of cognitive structuring and axiom of cognitive transformation. These are based on the work of Marr and Nishihara (1978), Siddiki and Kimia (1995) and Leyton (2001, 2006). Consideration of these four axioms also leads to the development of action grammar, which provides an alternative approach to the shape generation, description and evaluation. This grammar can model the product shape evolution in a generative manner by parameterising the cognitive processes involved in aesthetic design. The action grammar captures the design sketching process in a sequence of design action rules. This sequence defines the structure of the product form belonging to a design family.

A software prototype is developed using soft computing techniques to capture, reuse and externalise the aesthetic design knowledge. The automatic generation of the product form is achieved using a trained artificial neural network (ANN). This trained ANN is used with a genetic algorithm (GA)-based search to generate the design in response to a given set of aesthetic characteristics. The ANN is also used for evaluation of the designs. The generated designs may be evaluated by the human designers also and this knowledge can be captured. The process is repeated many times so that the knowledge system captured in ANN is robust and reflects the behaviour close to the human designers, both in generation and evaluation of the designs. In order to validate the design learning and generation of the design alternatives, human led survey is used to establish the validity of the proposed model and its implementation.

The rest of the paper is divided as follows. Section 2 reviews the efforts made in this domain by earlier researches. Section 3 presents the theoretical foundation of the proposed methodology with elaboration on ADC and action grammar. Various relationships for the development of the knowledge-based system are discussed here. Section 4 describes the implementation details of the prototype software. Section 5 discusses the case study of the car body profile for the development of the knowledge-based system. Knowledge extraction in the form of heuristics and their validation by human survey is also presented here. In Section 6, the results of the case study are discussed. Further, the manuscript is concluded with the observations on the feasibility of the knowledge-based system in the domain of aesthetic design.

## 2 Literature review

There have been several researches to formalise the aesthetic design process. Nagamachi (1995) developed the ‘Kansei engineering’ to systematise the process of associating the shape characteristics of the products to the aesthetic characteristics. Some of the other major contributions are made by Breemen et al. (1998), Hsiao and Wang (1998) and Chen and Owen (1998). Catalano et al. (2002) presented a comprehensive survey of the efforts to model the aesthetic design process.

## 2.1 Geometry and aesthetics

A number of researchers have attempted to define the relationship between aesthetics and geometric representation of the products. Breemen et al. (1990, 1999) suggested separation of products in categories sharing some common aesthetic characteristics and shape operations. Claessen (1996) explored the relationship of the aesthetics of industrial products with the colour and shape. Chek and Lian (1999) identified various measures of the aesthetics in products and tried to give the geometric interpretation of them. Fujita et al. (1999) derived some ratios for the lines and surfaces based on the curvature that correlated to the aesthetics of the product. Montalto et al. (2018) developed a formalism for linking the functional and aesthetic consideration. This formalism is used to for the abstraction of the frame geometry. This abstraction is used to design new product line using MATLAB and excel-based scripts. Giannini and Monti (2002) used the curvature variation along a curve to map the aesthetics operators like acceleration, convexity, crown, etc. used by the practicing designers. Case et al. (2002) gave an evolutionary approach to capture the aesthetic characteristics like simplicity, stability, softness dominance, etc. in terms of form characteristics defined by primitive shape, size and blending. Chen and Owen (1998) proposed a systematic methodology to describe the style profiles of the products.

## 2.2 Computational evaluation of aesthetics

Hsiao and Chen (2006) proposed a computer oriented method to develop products using aesthetic intentions. The European project FIORES II (2003) aimed at investigating the links between emotional shape perception and geometry. Podehl (2002) observed that the mapping between aesthetic characters and geometry could be achieved better by understanding and using geometric properties underlying the terms used by designers when evaluating/modifying the shape. Pernot et al. (2008) have developed a set of free form features modelling strategies. These strategies have an embedded correlation to the aesthetic preferences in the design form. Hsiao and Wang (1998) applied semantic transformation for product design. Mayer and Landwehr (2018) introduced two objective measures of design typicality, which are based on Euclidian distances between feature points and demonstrated that this typicality is captured in these geometric measure for the car models. They also validated that these measures though the user surveys.

Recently, there have been few attempts to automate the aesthetic/creative design process using various techniques. Koile (2006) gave a formal definition of the aesthetic characteristics. Banerjee et al. (2008) used GA-based collaborative model to capture group creativity, particularly the S type creativity. Arisoy et al. (2011) provided a mathematical tool to fit approximate surfaces to curve clouds for conceptual shape design and exploration, enabling early and quick visualisation. Tsutsumi and Sasaki (2008) proposed a method to drive the design of the building's roof by aesthetic consideration. The shape grammar has been extensively used in the formal representation of the designs, but there are some very serious restrictions on the use of shape grammar in freeform designs (McCormack and Cagan, 2006; McKay et al., 2012). Seckler et al. (2015) examined how objective design factors of a website are linked to different facets of subjective aesthetic perception on the different facets of subjective aesthetic perception (simplicity, diversity, colourfulness, craftsmanship). They found that structural factors like vertical and visual symmetry have a greater impact on the different facets of subjective aesthetic perception of the design than the colour. Chien et al. (2016) proposed a framework of data-driven product design for capturing product visual aesthetics to effectively identify the useful design concepts. The framework provided a set of rule which can be used for the new product design.

### 2.3 Soft computing in aesthetic design

Since the mapping between shape and aesthetic perception seem to be fuzzy, there have recently been several attempts to use soft computing techniques in this domain. Diyar and Kurt (2009) and Jianning and Fenqiang (2007) used neuro-fuzzy classification approach to identify the links between the form elements and user response of the products using the semantic differential scale.

Hsiao and Tsai (2005) used fuzzy neural network and generic algorithm to design product forms with intended aesthetic characteristics. Achiche and Ahmed (2008) proposed the semantic level of aesthetic design using fuzzy logic to link shape to emotion and express this knowledge in a manually constructed fuzzy rule-base. Cheah et al. (2011) used fuzzy cognitive map (FCM) and Bayesian belief network (BBN) to capture the causal design knowledge. Yang (2011) developed a Kansei engineering-based formal approach to identify critical product form features (PFFs) to help the design of aesthetically appealing products and to model consumers' affective responses (CARs). He used support vector machine (SVM) classification model is establish the relationship between CARs and the PFFs.

Tsai et al. (2006) proposed a neural network-based method considering colour and form and applied it to design door knobs. A similar study using a method based on neural network and grey relational analysis done by Lai et al. (2006). Fung et al. (2012) proposed a multi-objective GA-based rule-mining method for affective product design to discover a set of rules relating design attributes with customer evaluation based on survey data using the case of a mobile phone. Jose et al. (2016) presented a neural network-based approach to modelling CARs for product form design. This model was developed and tested across various categories of the products and its validity was evaluated.

Since the exact modelling of the aesthetic design cannot be established with the existing level of understanding, the design heuristics are found to be useful to capture the tacit design knowledge. Yilmaz and Seifert (2011) used the heuristics to explore the design concepts in early phase of the design. Daalhuizen et al. (2014) compared the systematic and heuristics-based approaches for design education. Chu et al. (2017) proposes a computational framework for personalised design of the eyeglasses frame based on parametric face modelling. The geometry of the product is form is correlated to a set of feature parameters to optimise the shape with specific aesthetic characteristics. Galanter (2013) argued that the computational aesthetic evaluation is quite difficult to implement in a computational system. Lo et al. (2015) proposed a set of aesthetic evaluations and an optimisation system for form aesthetics for all-in-one stereo system. Fuzzy methods were used for the calculation of the perceptual aesthetic measures of a product style. These aesthetic measures were combined with the GA and applied to the optimisation of the product's shape.

Most of the work cited above treats the subject of aesthetic design in an informal manner without establishing or relying on a formal foundation or consideration of the cognitive aspects of aesthetic design and evaluation. This renders the process difficult as far as the formal implementation for computational support to aesthetic design. Galle and Kroes (2014) observed that the design can be and should be treated as a scientific discipline, where the governing laws may be different but the design can be provided with robust foundation by systematic research.

The proposed methodology is an attempt to provide a formal model to the generation, evaluation and extraction of the tacit aesthetic design knowledge, in the domain of industrial design. The methodology tries to establish a preliminary theory of aesthetic design, based on the cognitive consideration involved in the design, as practiced by the human designer. The theory supports the shape description in terms of the cognitive processes using the action grammar.

## 3 Theoretical foundation

For the development of a knowledge-based system for aesthetic design, it is important to have a model which can capture and explain various processes and entities involved in the design process in a formal manner. Since the aesthetic design mostly involves the exploration of shapes, it is important to have a robust foundation for the shape generation and description.

Present research involves the development of an elementary theory to aesthetic design from the first principles to ensure its robustness and logical correctness of the conjectures. The foundation to these conjectures is provided by the four axioms. These axioms are used to develop the action grammar and ADC, which are discussed later.

### *3.1 Axioms*

The theoretical foundation to the formal model of the aesthetic design is based on four axioms, as:

Axiom 1 axiom of object relations (Simon, 1969)

Axiom 2 axiom of human knowledge (Simon, 1982; Zeng and Gu, 1999a, 1999b)

Axiom 3 axiom of cognitive structuring (Siddiki and Kimia, 1995; Leyton, 2001, 2006)

Axiom 4 axiom of cognitive transformation (Attneave, 1954; Marr and Nishihara, 1978; Siddiki and Kimia, 1995; Leyton, 2001, 2006).

The first two axioms lead to the development of an abstract model called general design complex. Use of the Axioms 3 and 4 support the development of action grammar and ADC. The details of the development of general design complex and action grammar are presented in Soni (2014).

### *3.2 Action grammar*

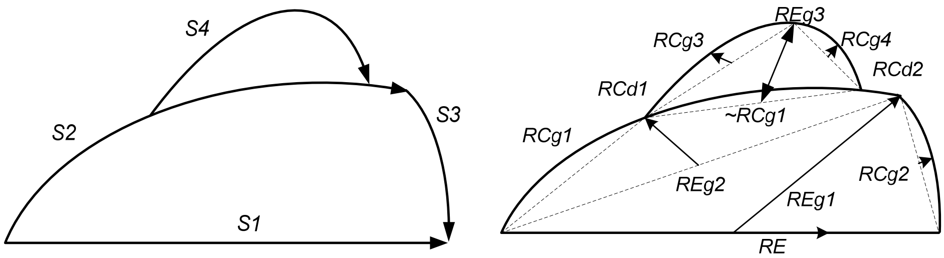
The studies on sketching have shown that the designer's strokes to define the shape capture the aesthetic design intent. Each stroke may carry multiple intents and references and relationships to existing elements. This process is very complex and difficult to externalise. The action grammar captures the design intent in a generative structure and defines the shape as well as the aesthetic characteristics in a parametric manner. The action grammar is defined as a set of action rules. The sequence of these actions describes the process of shape generation. The parameters defined during such generation, capture the essence of the shape and aesthetic characteristics.

In action grammar-based shape description, shape is represented as a generative process (Singh and Gu, 2012). Whereas, in conventional method of shape description, the shape is described using an additive process. In action grammar, the cognitive actions leading to different shape characteristics are implemented as grammar rules. These rules parameterise the cognitive process involved in the shape generation (Kavakli and Gero, 2002). Action grammar can be considered as a formal model of the design sketching process, as sketching during concept generation involves cognitive processes like emergence, abstraction and reinterpretation and the action grammar supports these processes. Thus, the action grammar can describe the product shape by parameterising the cognitive processes involved in design sketching and shape evolution (Soni et al., 2013).

Aesthetic characteristics of the product are determined primarily by the initial strokes used by the designers to define the aesthetic character of the product. These shapes are called aesthetically significant shapes (AeSS). The collection of such shape elements is named as the aesthetic form (*AF*) of the product. By using the action grammar, the aesthetic form of the product is defined by the action rule sequence.

An arbitrary shape and its description using the action grammar are shown in Figure 1. The sequential strokes from *S*1 to *S*4 define the geometric form as in Figure 1(a). Using the action rules (Soni et al., 2013), the rule description of the aesthetic form is as given in equation (1). Figure 1(b) shows the action rule structure of the shape.

**Figure 1** The sketch and its action rule representation, (a) sketch strokes (b) action rules-based representation




(a) (b)

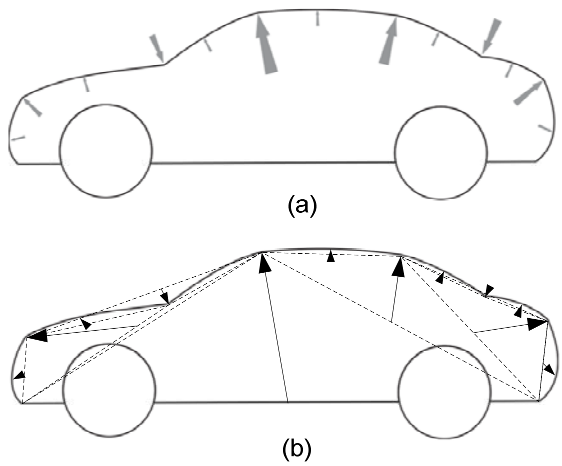
$$AF = RE\ REg1\ REg2\ RCg1\ RCg2\ RCd1\ RCd2 \sim RCg1\ REg3\ RCg3\ RCg4 \quad (1)$$

The aesthetic form (*AF*) represents the aesthetic intent of the product form. Figure 2(a) presents the cognitive processes perceived in the form of the product. These perceived processes (pulls and pushes) are seen as the determinant of the aesthetics of the product form. Action grammar modelling this process in terms of the action sequence generates the shape as in Figure 2(b).

Equation (2) gives the action rule description of the aesthetic form of the car body profile described in Figure 2.

$$RP\ RE\ REg1\ REg2\ REg3\ REg4\ REg5\ REg6$$
$$RCg1\ RCg2\ RCg3\ RCg4\ RCg5\ RCg6\ RCg7 \quad (2)$$

**Figure 2** Cognitive processes and action rule vectors for the car body profile




## 3.3 *Aesthetic design complex*

The general design complex comprises of the design, designer and critic; and various relationships among them (Soni et al., 2013). In the domain of aesthetic design, the 'design' is mapped to aesthetic form (*AF*). The 'designer' is mapped to shape characteristics (*SC*) and the 'critic' is mapped to the aesthetic characteristics (*AC*). Here, the aesthetic form (*AF*) is defined by the rule sequence defines the structure or generation plan of the product, as explained in Section 3.2. The shape characteristics vector (*SC*) is derived from the parameters of the design action rules used to describe the product form. The aesthetic characteristics vector (*AC*) is defined as the user evaluation of the product form on a uni-polar scale of semantic adjectives.

Thus, the general shape characteristics can be represented as a vector as

$$SC = [s_1, s_2, \ldots, s_m] \quad (3)$$

The aesthetics is defined as the property of the product form. It is formalised as a vector of emotional terms like elegant, sporty etc. A product form can exhibit multiple responses, thus the description of aesthetics can be given as vector (ordered set) of these emotional terms, measured on a suitable scale. The measurement of occurrence of any aesthetic characteristics is made by the human response to the product appreciation.

The aesthetic characteristics of a product form can be represented as vector as

$$AC = [s_1, s_2, \ldots, s_k] \quad (4)$$

The aesthetic form (*AF*), shape characteristics vector (*SC*) and aesthetic characteristics vector (*AC*) together defines an ADC.

Figure 3 shows these entities and various relationships among *AF*, *SC* and *AC*. Table 1 presents the relationship among the entities in ADC and their meaning. Different relationships describe different aspects of the aesthetic design process. Some of the important relationships which are relevant to the development of the knowledge-based system for aesthetic design, like $f^L$ and $f^S$ are explained in Table 1. The additional detailed about these relationships are presented in Soni et al. (2013).

**Figure 3** Aesthetic design complex

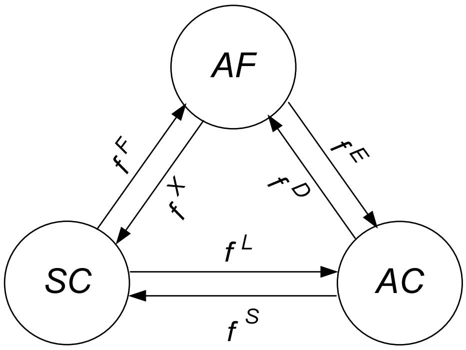



**Table 1** Various relationships in ADC

| *Relationship in ADC* | *Meaning* |
|---|---|
| $f^F$: $SC \rightarrow AF$ | Design form plan or action |
| $f^E$: $AF \rightarrow AC$ | Design evaluation |
| $f^S$: $AC \rightarrow SC$ | Design knowledge search |
| $f^X$: $AF \rightarrow SC$ | Design abstraction |
| $f^D$: $AC \rightarrow AF$ | Artefact design process (or case search) |
| $f^L$: $SC \rightarrow AC$ | Design knowledge learning |

### *3.3.1 Design knowledge learning*

Aesthetic design knowledge is defined as the mapping $f^L$ between the shape and aesthetic characteristics of the product form such as $f^L$: $SC \rightarrow AC$. The shape characteristics $SC$ is defined as vector comprising of the parameters of the shape actions used to generate the shape. The aesthetic characteristics $AC$ are defines as vector of the emotional response like 'elegant' or 'sporty'. These responses are parameterised using a bound scale of 0–10, within which the response is rated. The ordered set of such values for a product form defines the aesthetic characteristics.

The relationship $f^L$: $SC \rightarrow AC$ is the core of knowledge-based system for the aesthetic design generation. Suppose, there is a family of $n$ objects, which can be represented by a common structure, each object can define a relation $SC \rightarrow AC$. If there are $m$ elements in $SC$ and $k$ elements in $AC$, from equations (3) and (4), we have

$$SC = [s_1, s_2, \ldots, s_m] \text{ and } AC = [a_1, a_2, \ldots, a_k] \quad (5)$$

For a set of $n$ objects in the family, we can define a set of mappings as $SC_i \rightarrow AC_i$ or

$$[s_1, s_2, \ldots, s_m]_i \rightarrow [a_1, a_2, \ldots, a_k]_i \quad i = 1, n \quad (6)$$

If $\{S_i\}$ is the span (range) of $SC_i$, then, the space of shape characteristics is defined as

$$\Sigma_{SC} = \bigcup_{i}^{n} \{S_i\} \tag{7}$$

Similarly, if $\{A_i\}$ is the span (range) of $AC_i$, then, the space of aesthetic characteristics is define as

$$\Sigma_{AC} = \bigcup_{i}^{n} \{A_i\} \tag{8}$$

In the context of a design family, the relationship $f^L$: $SC \rightarrow AC$ defines the mapping between these two domains as

$$\Sigma_{SC} \rightarrow \Sigma_{AC} \tag{9}$$

The above mapping is the design knowledge. It relates the two domains belonging to a design family.

### *3.3.2 Design knowledge search*

The mapping $f^S$: $AC \rightarrow SC$ indicates the search of desired shape characteristics that is mapping to the needed aesthetic characteristics. As this mapping is non-deterministic, the estimation of the required shape characteristics involves a search process. As a function, the relationship can be expressed as

$$SC = f^S(AC) \tag{10}$$

### *3.3.3 Design knowledge extraction*

Aesthetic design knowledge captured in the mapping $f^L$: $SC \rightarrow AC$ is of integral nature and explicit statements about the relationship between shape characteristics and aesthetic characteristics cannot be made. This knowledge can be made explicit by their differential relationships. Using relationship $f^L$: $SC \rightarrow AC$ and equation (5), on differentiating $AC$ with $SC$, we find $m * k$ differential relationships, as

$$\frac{\partial a_i}{\partial s_j} \quad \text{here, } i = 1, k \text{ and } j = 1, m \tag{11}$$

Here, $a_i$ and $s_j$ are the elemental aesthetic and shape characteristics respectively. The above equation describes the effect/variation of aesthetic characteristics with the shape modification by design actions. For example, designers know that lowering the roof of the car makes it look more 'sporty' and 'elegant'. These derivatives capture such relationships.

These differential relationships form the basis for generation of the design heuristics. Design heuristics are the coarse expression of the tacit aesthetic knowledge represented by $f^L$: $SC \rightarrow AC$.

Since all the elements of the shape of the design do not affect the aesthetic characteristics equally, it is needed to identify the strong correlation among the aesthetic characteristics and shape characteristics, in order to generate the useful and valid heuristics. To identify such strongly correlated pairs of the aesthetic characteristics and shape characteristics, principal component analysis (PCA) is used.

In order to apply PCA for the identification of significant shape elements with respect to some aesthetic characteristics, the span of the aesthetic characteristics is considered. Suppose the effect of the shape characteristics on the aesthetic characteristics is to be evaluated. The span of $a_i$, given as $\{a_i\}$, is covered by $t$ discrete values, which corresponds to the valid shape variation possible, within an envelope, without violating the functional requirements for a product category. Thus,

$$\{a_i\} = (a_{i1}, a_{i3}, \ldots, a_{it}) \tag{12}$$

Using equation (10),

$$SC_t = f^S a_{it} \tag{13}$$

As $SC$ is a vector of m dimension, $SC_t$ is a matrix of $t * m$ dimension. Mapping $f^S$ is provided by the trained network.

PCA represents the dataset in an alternate coordinate space defined by the orthogonal components. These components are arranged in the order of importance, thus, the shape characteristics vector can be represented in the alternate coordinate space, as

$$PC^{(m)} = Q^{(m*m)} SC^{(m)} \tag{14}$$

$PC$ is the vector of principal components which are orthogonal to each other. $SC$ is the vector describing shape characteristics. Each of them is having $m$ elements. $Q$ is the transformation matrix. $PC$ defines the alternate coordinate system rotated by $Q$, in such a manner so that the components are arranged in the order of variance.

If on the investigation into the eigenvalues of $m$ components, only first $r$ components are found to be significant, then

$$PC^{(r)} = Q^{(r*m)} SC^{(m)} \tag{15}$$

Here, $PC^{(r)} = (c_1, c_2, \ldots, c_r)$ and $Q^{(r*m)} = \begin{bmatrix} q_{11} & \cdots & q_{1m} \\ \vdots & \ddots & \vdots \\ q_{r1} & \cdots & q_{rm} \end{bmatrix}$.

The elements in the principal component vector $PC$ are arranged in the order of significance (it is determined by the variance of the respective component). As there are few elements in the last, where are not very significant, these can be discarded to simplify the analysis, without much affecting the accuracy of the analysis. This results in a vector containing only the significant elements. $PC$ with $r$ elements defines this vector.

During the initial investigation, it is observed that first three components can define most of the correlation (called loading). Thus, only first three components of the new coordinate space are considered significant for variation in the aesthetic characteristics element. These are given as

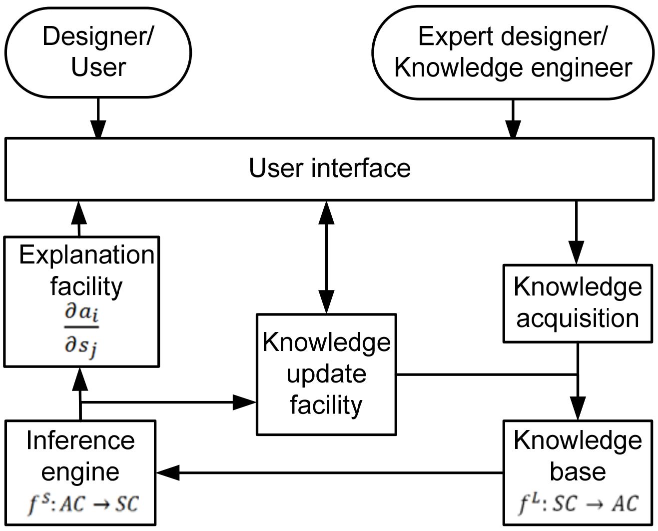
$$\begin{aligned} c_1 &= q_{11} \cdot s_1 + q_{12} \cdot s_2 + \cdots + q_{1m} \cdot s_m \\ c_2 &= q_{21} \cdot s_1 + q_{22} \cdot s_2 + \cdots + q_{2m} \cdot s_m \\ c_3 &= q_{31} \cdot s_1 + q_{32} \cdot s_2 + \cdots + q_{3m} \cdot s_m \end{aligned} \tag{16}$$

These equations provide the description of the elements in new vector $PC$, as linear functions of the elements in the $SC$ vector. These describe the behaviour of the design process. The coefficients in equation (16) determine the significant of the correlations to generate the heuristics.

### 3.4 The knowledge-based system

Figure 4 shows the main components of a typical knowledge-based system. The expert designer interacts with the systems through the user interface and presents the design knowledge to the system. The design knowledge is acquired and stored in the knowledge-base. This knowledge-base is implemented as the mapping between the shape characteristics and aesthetic characteristics as $f^L$: $SC \to AC$. The knowledge-base is used for the design decisions using the inference engine for the search of the required shape characteristics in response to the required aesthetic characteristics. The inference process is represented as $f^S$: $AC \to SC$. The design knowledge may be updated as more knowledge is available. The design decision made by the knowledge-based system is explained in an explicit manner by the explanation facility. This explanation is defined by the set of partial derivatives $\frac{\partial a_i}{\partial s_j}$ which have strong correlation.

**Figure 4** Knowledge-based system




#### 3.4.1 ANN and GA framework for knowledge-base capturing and use

The knowledge-base is designed as the mapping between shape characteristics and aesthetic characteristics as given by equation (9). This mapping is implemented using the ANN. Two different network topologies; MLP is used for the supervised learning to achieve the input-output mapping. The MLP network consists of three layers. The input layers and output layer form the interface to the user. MLP has greater ability for generalisation of the input vector (Wasserman, 1993).

In the cases where the training data does not sufficiently cover the complete space of the input vector, the training of the MLP results in over generalisation. In order to avert the problem of over-generalisation locally, radial basis functions (RBF) is used (Park and Sandberg, 1991). Only a small fraction of the units in an RBF network responds to any particular input vectors, therefore, the RBF networks are suitable for local approximation.

GA is used as the global search method. Here, the initial population is manipulated using the reproduction, crossover and mutation operators. Generally, the binary-coded GAs are most commonly used. But in the present research, the real valued representation is used. In real value representation, there is no need to convert chromosomes to phenotypes before each function evaluation and there is a greater freedom to use different genetic operators.

### *3.4.2 Input-output data*

The input data for the knowledge-base is the shape characteristics vector defined by the action grammar parameters for the product shape. The output data is the value of the aesthetic characteristics defined as the vectors.

### *3.4.3 The inference engine*

The inference engine for the knowledge system is designed for both forward and backward inference process. The forward inference uses the knowledge-base captured in ANN to evaluate the designs. The backward inference uses the GA-based (Mitchell, 1997) search to generate the designs with given aesthetic characteristics as the design search is a non-deterministic process. This process is represented by equation (10).

### *3.4.4 Externalisation of knowledge*

One of the important characteristics of any knowledge-based system is the ability to explain the captured knowledge. The explanation or externalisation of the aesthetic design knowledge is especially difficult to represent in the form of explicit rules. The major reason for this difficulty is the ill-defined nature of the aesthetic design knowledge. This knowledge resided tacitly in the designer's mind, which cannot be expressed in the form of universal rules. In the present research, the tacit design knowledge is externalised in the form of heuristics. The heuristics are the coarse knowledge about a product, process or system, which may not be true in all the cases, but using the heuristics in design process improves the chances of achieving a better design. These heuristics are derived from the correlations observed between various prominent parameters of the design. This correlation is achieved using PCA. Equation (11) facilitates the externalisation of the tacit knowledge in the form of heuristics.

## 4 Implementations

Above framework is implemented in a software environment using MATLAB as the base platform, having interaction with the 3D CAD software 3DStudioMax. The details of the software implementation are described next.

The case of a car body profile as shown in Figure 2 is used for the development of the design knowledge-base. Using the action grammar, the shape description of the car body profile is given by equation (2). This shape description defines the shape characteristics of the car body profile as a sequence of 26 elements, which describe the shape of the car body profile. Since each of these elements can be varied to achieve the different forms of the car body profile, these 26 elements can be called as the chromosomes of the design family as defined by equation (2). The software prototype is implemented with five aesthetic characteristics like 'elegant', 'slender', 'sharp', 'classic' and 'masculine'. More and different aesthetic characteristics may be chosen if the product category or the details of the aesthetic appreciation are refined, without affecting the models and implementation presented. For the present case as proof of concept, these five characteristics are assumed to be sufficient to represent the semantic appreciation of the car body profile. These five aesthetic characteristics can be represented as a set as defined in equation (4). Each of the aesthetic characteristics can be varied within the range from 0 to 10.

### *4.1 Modes of operations*

The software prototype is designed with a view to facilitate easy user interaction. Figure 5 shows the user interface of the software prototype implemented. The implemented software can work in four different modes. These are as under.

a the design generation using chromosome variation

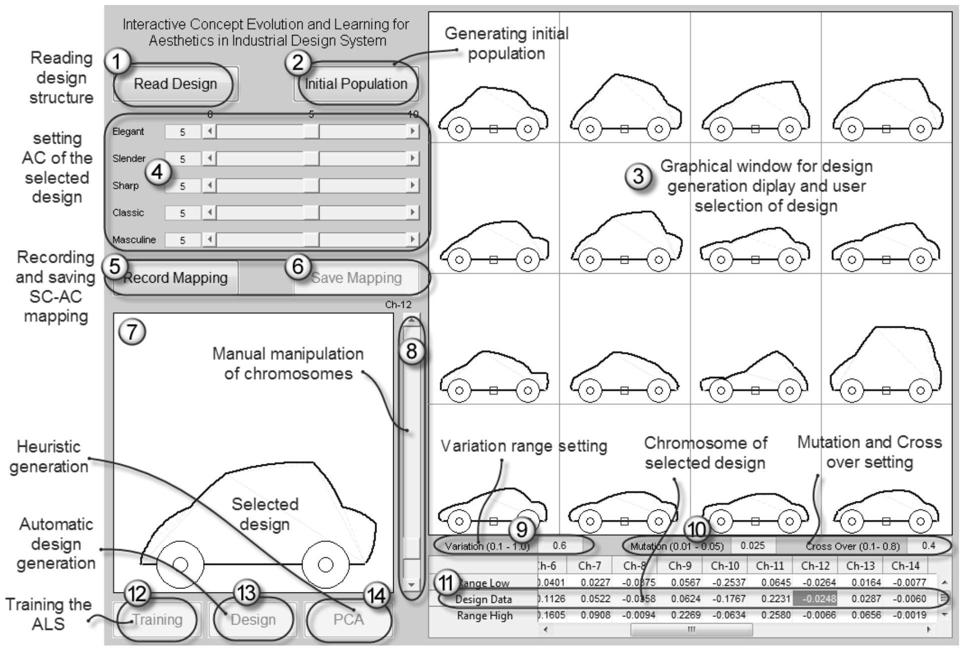
b the design generation using interactive GA (IGA using the human led fitness selection)

c automatic design generation using the ANN-based design knowledge (using mathematically defined fitness function)

d design knowledge extraction.

In Figure 5, button #1 is used to read the design form extracted from a 2D sketch. Button #2 is used to create the initial population using the random generation of designs. Window #3 shows the generated design. It also provides the user interaction by facilitating the selection of the designs to go to next generation for the IGA-based design generation. Sliders #4 are use to evaluate the selected design for the generation of the design knowledge in the form of the aesthetic characteristics-shape characteristics mapping. Buttons #5 and #6 are used for the recording and saving this mapping as the design knowledge respectively. Window #7 shows the selected design. Slider #8 is used to modify the design at chromosome level. The chromosomes of the selected design are presented in table #11. Text box #9 is used to set the chromosome variation. Text boxes in #10 are used for setting the mutation and crossover for the GA. The button #12 is used for training the system using the training data prepared by human design and evaluation. The button #13 is used for the generation of new designs using the captured knowledge. The new designs are generated in response to the aesthetic characteristics specified using the sliders #4. The button #14 is used for conducting the PCA, to extract the tacit knowledge (in the form of heuristics), captured in the ANN.

**Figure 5** User interface of the implemented software prototype framework




## 4.2 Design knowledge extraction process

The design data for knowledge-base is generated using the chromosome variation and/or the IGA. Each record of the design data comprises of the pair of the shape characteristics and aesthetic characteristics vectors. A set of such pairs is describes the design knowledge as given by equation (6). This design knowledge about the car body profile is captured in the ANN-based network learning. The acquired design knowledge is used to generate the designs by the automatic design generation using GA. Various studies are conducted to ascertain the parameters like ANN training accuracy, convergence in IGA, range variation, crossover and mutation, etc. In order to extract the design knowledge in the form of heuristics, the designs are generated for the complete range of each of the aesthetic characteristics using automatic GA using the fitness function. The fitness function for the GA is defined as the minimisation of the Euclidian distance between the required aesthetic characteristics and the aesthetic characteristics of the generated designs If $AC_j^R$ are the required aesthetic characteristics for design and $AC_j^G$ are aesthetic characteristics of the generated design, the fitness function is given by

$$\min \sum_{j=1}^{k} \left\| AC_j^R - AC_j^G \right\|^2 . \quad (17)$$

## 5 Case study

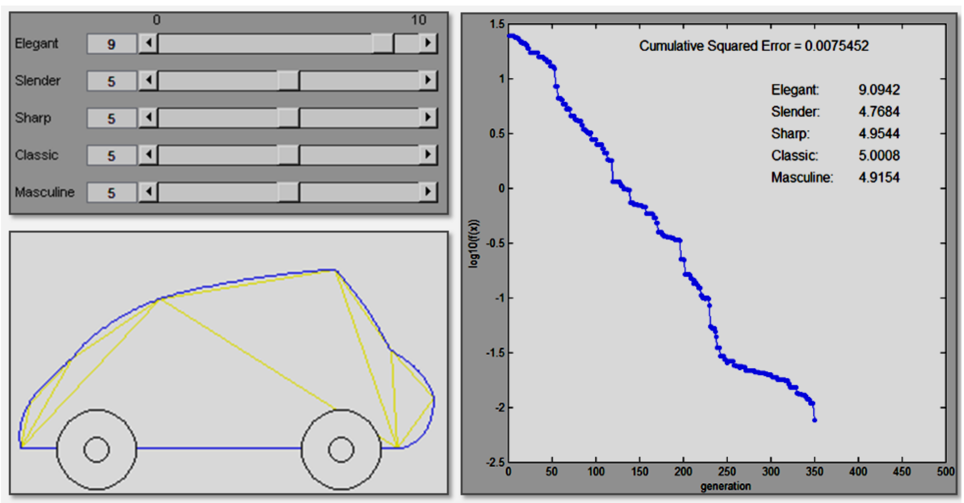
The case study uses the automatic design generation process at the core of knowledge extraction. The detailed method is as follows. The range of the aesthetic characteristics, for which the heuristics are to be generated, is divided into small intervals. For example, 'elegant' characteristic is divided into steps of 0.5. All other aesthetic characteristics are kept at mid value (5.0). For the aesthetic characteristics at each interval, the designs are generated automatically using the automatic GA. For this case, 21 designs are generated for each of the aesthetic characteristic. Thus, full scan of an aesthetic characteristic is covered by 21 vectors of chromosome. In order to identify the major drivers of the 'elegant' aesthetic characteristics in the product form, PCA is used to identify the principal components. PCA generates 26 components and their eigenvalues. Eigenvalues of the components show that only 1st, 2nd and 3rd components are important, as these explain almost 85 to 90% of the loading of the data distribution, which is considered acceptable for the qualitative assessment using PCA.

Here, the correlations are divided into two groups, strong (> 0.8) and normal (0.4 to 0.8). The strong positive correlation is represented as ++ and normal positive correlation is represented as +. Similarly, strong negative and normal negative correlations are represented as – – and –, respectively.

### *5.1 Design generation process*

The design generation from the learnt data is carried out as the search through the hyperspace of shape – aesthetic characteristics. Most of the searches have converged within 50–400 iterations or epochs. We also found some of the designs generated did not conform to the human evaluation. Such designs are discarded and considered to be the outliers or effect of over-fitting. This tendency of discard was seen to be reducing with richness of the training data.

**Figure 6** The convergence of design (see online version for colours)



The design generation process is computationally quite complex as the time required to converge a design search varied between 1 to 5 minutes on a computer system with dual core 2 GHz processor with 4 GB RAM and 1 GB graphics card. Figure 6 shows the snap shot of such a design search case.

## *5.2 Elegant: observations and heuristics*

Table 2 presents the eigenvalues for 'elegant' characteristics. Figure 7(a) presents plot of principal component and Figure 7(b) presents chromosome variation for 'elegant' characteristics. Following this data, the qualitative correlations drawn from the first three components are drawn. In the following tables, principal components are identified as PC. no., chromosome is identified as Ch. no. and heuristics are identified as H. no.

**Table 2** Eigenvalues for 'elegant' characteristic

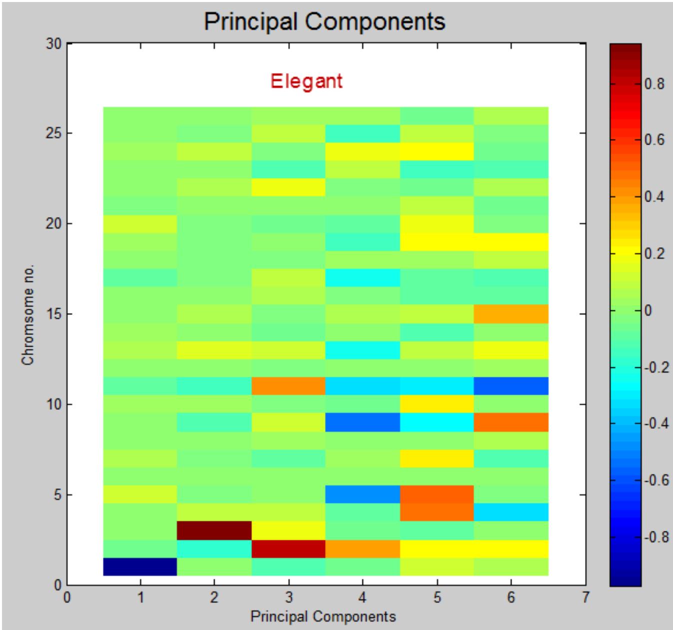
| *Eigenvalues ('elegant') × $10^{-2}$* | | | | | | *Loading on first 3 eigenvalues* |
|---|---|---|---|---|---|---|
| *E1* | *E2* | *E3* | *E4* | *E5* | *E6* | |
| 3.30 | 0.75 | 0.49 | 0.34 | 0.15 | 0.14 | 87.81 |

Ch1 to Ch26 define the elements of the shape characteristics vector. These are the characteristic definition of a shape, represented as a vector. This vector is created by collecting the parameters of the design actions rules in the sequence of action rules applied. They also determine the aesthetic form of the product. These can be seen as the genotype (genetic code) of the design whose values ultimately determine the phenotype (visual form) of the object. These are used in various processes in the design of knowledge-based system. During the design training, these elements are used for the knowledge mapping with the aesthetic characteristics vector. In the design generation process, these elements are determined in response to the given aesthetic characteristics. In the automatic design evaluation, these are used to predict the aesthetic characteristics of the given design.

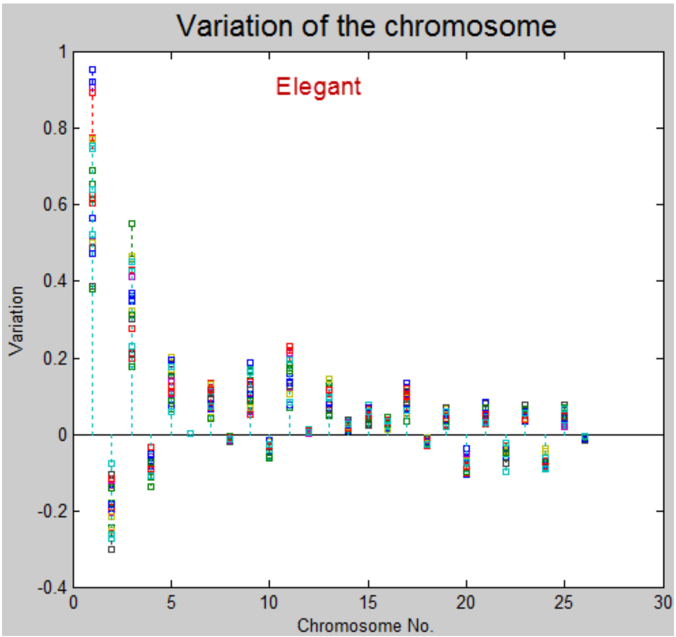
Figure 7(a) presents the PCA to identify the significant components and their correlation to various elements in the shape characteristics vector. Though first six components are plotted in the figure, it was found by the analysis of the eigenvalues that, only first three principal components can describe about the 95% behaviour of the system. Thus, first three components are used for the derivation of the heuristics. The colour strip on the right describes the correlation values. These are defined as positive being the 'red' and negative being the 'blue'.

In the plot, it is shown that the first principal component is highly negatively correlated to the first element in the shape characteristics vector. The coloured dots in Figure 7(b) mark the variation in the values of elements of shape characteristics. The variation signifies the search space covered during the design generation. Each colour dot refers to one case of design. It clearly shows that the first elements have a large variance, signifying that its importance to the design, as its variation affects the design most.

**Figure 7** PCA and chromosome variation for 'elegant' characteristic (see online version for colours)




(a)




(b)

Table 3 presents the correlation and heuristics for ‘elegant’ characteristics.

**Table 3** Correlation and heuristics for ‘elegant’ characteristic

| *PC. no.* | *Ch. no.* | *Correlation* $\frac{\partial Elegant}{\partial Ch}$ | *Variation of ch.* |
|---|---|---|---|
| 1 | 1 | – – | + |
| 2 | 3 | ++ | + |
| 3 | 2 | ++ | – |
| 3 | 11 | + | + |

### *Heuristics generated for effect on ‘elegant’ AC*

EL1 Decrease in ‘elegant’ with increase in Ch1.

*Increase in the height of the roof at the front reduces the ‘elegant’ characteristics.*

EL2 Increase in ‘elegant’ with increase in Ch3.

*Increasing the height of the roof at the back increases the ‘elegant’ characteristics.*

EL3 Increase in ‘elegant’ with increase in Ch2.

*Moving the start of the roof towards rear increases the ‘elegant’ characteristics.*

EL4 Increase in ‘elegant’ with increase in Ch11.

*Protruding the trunk increases the ‘elegant’ characteristics.*

Similar exercises are carried out for other four aesthetic characteristics. The correlation and heuristics for these aesthetic characteristics are presented in following tables.

## *5.3 Slender: observations and heuristics*

The correlation and heuristics for ‘slender’ characteristics are shown in Table 4.

**Table 4** Correlation and heuristics for ‘slender’ characteristic

| *PC. no.* | *Ch. no.* | *Correlation* $\frac{\partial Slender}{\partial Ch}$ | *Variation of ch.* |
|---|---|---|---|
| 1 | 1 | – – | + |
| 2 | 3 | ++ | + |
| 3 | 2 | ++ | – |
| 3 | 9 | + | + |

### *Heuristics generated for effect on ‘slender’ AC*

SL1 Decrease in ‘slender’ with increase in Ch1.

*Increase in the height of the roof at the front reduces the ‘slender’ characteristics.*

SL2 Increase in 'slender' with increase in Ch3.

*Increase in the height of the roof at the back increases the 'slender' characteristics.*

SL3 Increase in 'slender' with increase in Ch2.

*Moving the front end of the roof towards rear increases the 'slender' characteristics.*

SL4 Increase in 'slender' with increase in Ch9.

*Protruding the front end of the hood increases the 'slender' characteristics.*

## *5.4 Sharp: observations and heuristics*

The correlation and heuristics for 'sharp' characteristics are shown in Table 5.

**Table 5** Correlation and heuristics for 'sharp' characteristic

| *PC. no.* | *Ch. no.* | *Correlation* $\frac{\partial Sharp}{\partial Ch}$ | *Variation of ch.* |
|---|---|---|---|
| 1 | 1 | – – | + |
| 2 | 3 | ++ | + |
| 3 | 9 | + | + |
| 3 | 13 | + | + |
| 3 | 17 | – | + |

### *Heuristics generated for effect on 'sharp' AC*

SH1 Decrease in 'sharp' with increase in Ch1.

*Increase in the height of the roof at the front reduces the 'sharp' characteristics.*

SH2 Increase in 'sharp' with increase in Ch3.

*Increase in the height of the roof at the back increases the 'sharp' characteristics.*

SH3 Increase in 'sharp' with Increase in Ch9.

*Protruding the front end of the hood increases the 'sharp' characteristics.*

SH4 Increase in 'sharp' with Increase in Ch13.

*Increasing grill area curvature increases the 'sharp' characteristics.*

SH5 Decrease in 'sharp' with Increase in Ch17.

*Increasing the curvature of the front glass decreases the 'sharp' characteristics.*

## *5.5 Classic: observations and heuristics*

Table 6 shows the correlation and heuristics for 'classic' characteristics. Though some of the chromosomes in Component 3 are stronger than those in Component 2, but these are discarded from consideration in heuristics generation, as the eigenvalue of the Component 3 is much smaller than Component 2.

**Table 6** Correlation and heuristics for 'classic' characteristic

| *PC. no.* | *Ch. no.* | *Correlation* $\frac{\partial Classic}{\partial Ch}$ | *Variation of ch.* |
|---|---|---|---|
| 1 | 1 | – – | + |
| 2 | 2 | ++ | – |
| 2 | 3 | – – | + |
| 2 | 7 | + | + |
| 3 | 7 | + | + |
| 3 | 9 | + | + |
| 3 | 11 | ++ | + |
| 3 | 13 | ++ | + |

Here, it is observed that the heuristics CL4 and CL5 are same. These are coming from Components 2 and 3 respectively. It indicates that the Chromosome 7 is contributing almost equally to Components 2 and 3. The combined effect of the CL4, CL5 and CL7 is that, moving the trunk towards back and making it higher will increase the classic characteristics.

### *Heuristics generated for effect on 'classic' AC*

CL1 Decrease in 'classic' with increase in Ch1.

*Increase in the height of the roof at the front reduces the 'classic' characteristics.*

CL2 Increase in 'classic' with increase in Ch2.

*Moving the front end of the roof towards rear increases the 'classic' characteristics.*

CL3 Decrease in 'classic' with increase in Ch3.

*Increase in the height of the roof at the rear reduces the 'classic' characteristics.*

CL4 Increase in 'classic' with increase in Ch7.

*Moving the trunk start point towards rear increases the 'classic characteristics.*

CL5 Increase in 'classic' with increase in Ch7.

*Moving the trunk start point towards rear increases the 'classic characteristics*

CL6 Increase in 'classic' with Increase in Ch9.

*Protruding the front end of the hood increases the 'classic' characteristics.*

CL7 Increase in 'classic' with increase in Ch11.

*Moving the trunk towards rear and upwards increases the 'classic characteristics.*

CL8 Increase in 'classic' with increase in Ch13.

*Increasing grill area curvature increases the 'classic' characteristics.*

### 5.6 Masculine: observations and heuristics

The correlation and heuristics for 'masculine' characteristics are shown in Table 7. Here, it is observed that, heuristics MS1 and MS3 are same and MS2 and MS4 are in contradiction. It may be possible, as these belong to two different principal components, which are orthogonal to each other.

Also the strength of MS2 (as it belongs to component 1), is more than MS4 which belongs to Component 2, thus the chromosome Ch3 is contributing more to MS2 rather than to MS4, thus MS2, being stronger heuristics, will prevail. The shape characteristics represented by MS5 is observed in jeeps.

MS7 is considered despite the fact that Ch25 appears in Component 3 quite faintly. It is being considered as it has never appeared in any of the aesthetic characteristics. Also, it is neither contradicted nor supported by Components 1 and 2.

**Table 7** Correlation and heuristics for 'masculine' characteristic

| *PC. no.* | *Ch. no.* | *Correlation* $\frac{\partial Masculine}{\partial Ch}$ | *Variation of ch.* |
|---|---|---|---|
| 1 | 1 | + | + |
| 1 | 3 | – – | + |
| 2 | 1 | ++ | + |
| 2 | 3 | + | + |
| 3 | 2 | ++ | – |
| 3 | 11 | + | + |
| 3 | 25 | – | + |

#### *Heuristics generated for effect on 'masculine' AC*

MS1 Increase in 'masculine' with increase in Ch1.

*Increase in the height of the roof at the front increases the 'masculine' characteristics.*

MS2 Decrease in 'masculine' with increase in Ch3.

*Increase in the height of the roof at the rear reduces the 'masculine' characteristics.*

MS3 Increase in 'masculine' with increase in Ch1.

*Increase in the height of the roof at the front increases the 'masculine' characteristics.*

MS4 Increase in 'masculine' with increase in Ch3.

*Increase in the height of the roof at the rear increases the 'masculine' characteristics.*

MS5 Increase in 'masculine' with increase in Ch2.

*Moving the front end of the roof towards rear increases the 'masculine' characteristics.*

MS6 Increase in 'masculine' with increase in Ch11.

*Moving the trunk towards rear and up increases the 'masculine' characteristics.*

MS7 Decrease in 'masculine' with increase in Ch25.

*Increase in the bulge at the rear of the car increases the 'masculine' characteristics.*

The above study and generated correlation leads to various conclusions. These are presented as:

a For the aesthetic characteristics of the design, Ch1, Ch2, Ch3, Ch7, Ch9, Ch11, Ch13, Ch17 and Ch25 are significant.

b Among these, Ch1, Ch2 and Ch3 affect all the aesthetic characteristics quite strongly. It leads to the conclusion that position of the roof with respect to the car body plays the most significant role in the aesthetic characteristics of the car.

c Apart from the roof, Ch7, Ch9, Ch11 and Ch13, which affect the front hood and truck of the car, play a significant role in defining the aesthetic characteristics.

d The curvature of the front glass also affects the aesthetic characteristics of the car.

e The height of the roof at front affects the 'elegance', 'slender', 'sharp' and 'classic' characteristics negatively. It also means that these four characteristics move together. The height of the roof at the front affects 'masculine' characteristics positively; it means that increasing the 'masculine' characteristics will reduce the other four aesthetic characteristics.

f Moving the front of the roof backwards increase the 'elegance', 'slender', 'classic' and 'masculine' characteristics, but reduces the 'sharp' characteristics.

g Moving the roof up and backwards increases the 'elegance', 'slender' and 'sharp' but reduces the 'classic' characteristics. Its effect on the 'masculine' characteristics is ambiguous.

h Protruding the hood forwards increases 'slender', 'sharp' and 'classic' characteristics. Its effect on other characteristics is inconclusive.

i Protruding the truck outwards increases 'elegance', 'classic' and 'masculine' characteristics.

j Increasing the curvature of the grill area improves in 'classic' and 'masculine' characteristics.

### *5.7 Validation of the heuristics*

The generated heuristics are validated using a user survey. Each heuristics is used to generate two designs to highlight its effect on the 'average car'. The average car is defined as one having all the aesthetic characteristics values at 5.0. The generated designs are marked with the assertion inferred from the heuristics. These designs are presented to a group of users comprising the design and engineering professional as well as students. Based on their perception of aesthetic characteristics in the pair of designs, users are asked to record their opinion about the assertion made by the heuristics.

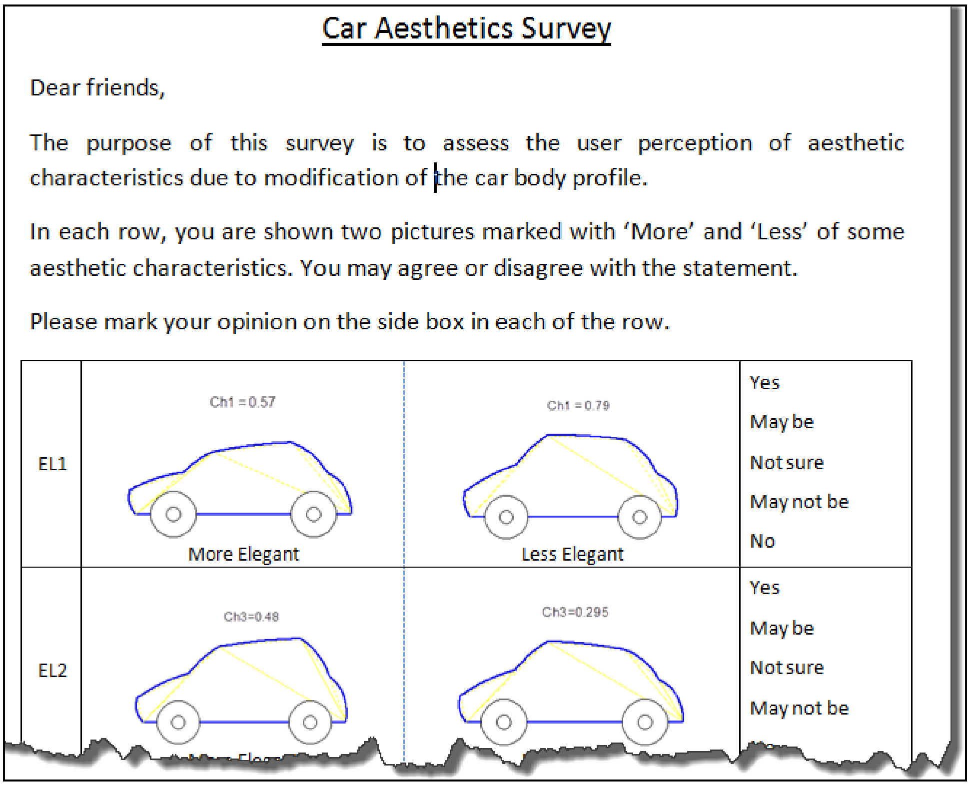
Sample of the survey form is shown in Figure 8. The user is asked to tick the option, which matches his/her opinion the most. The data is collected through online and offline survey. The collected data is analysed to assess the validity of the heuristics.

### *5.7.1 Survey data analysis*

The user opinion is assessed on a 5 point bipolar scale with range from –5 to +5. Score of the survey response is made as follows. Yes: 5.0; maybe: 2.5; not sure: 0.0; May not be: –2.5; and no: –5.0.

The survey was conducted involving mostly the graduate and post graduate design and engineering students. The total number of participants was 45, of which 27 were male and 18 were female. 28 questions in the form of assertions arising from the heuristics were posed to each participant. They were to respond by expressing their agreement (or otherwise) with the assertion.

**Figure 8** The survey form (see online version for colours)



The survey data for each of the heuristics are collected and analysed by calculating mean, standard deviation (SD) and score. Mean and SD have their usual definition. The SD signifies the spread in the opinion of the survey subjects. The high value of SD indicates that there is a significant variation in the subjects' opinion about the validity of the heuristics.

The score is defined as a measure of the validity of the heuristics. It is defined in a manner similar to Z score. If any value in the distribution is defined as $\chi$, the range average is defined as $\mu$ and the positive range of the bipolar scale is defines as $\mathcal{R}$, then the score $\alpha$ in terms of percentage is defined as

$$\alpha = \frac{\chi - \mu}{\mathcal{R}} * 100$$

A score less than 50% indicates the low confidence level in the on the validity of the heuristics. Thus, the heuristics with a score above 50% and with low SD are considered to be valid.

As the survey data is very large, a sample of the complete survey is presented in Table A1.

**Table 8** Summary of the heuristics validation

| *H. no.* | *Mean* | *SD* | *Score %* | *H. no.* | *Mean* | *SD* | *Score %* |
|---|---|---|---|---|---|---|---|
| EL1 | 3.83 | 1.47 | 76.67 | CL1 | 2.94 | 2.08 | 58.89 |
| EL2 | 4.00 | 1.24 | 80.00 | CL2 | –1.89 | 2.73 | –37.8 |
| EL3 | 2.61 | 2.72 | 52.22 | CL3 | 2.06 | 1.71 | 41.11 |
| EL4 | 3.22 | 1.57 | 64.44 | CL4/CL5 | 0.94 | 1.71 | 18.89 |
| SL1 | 4.44 | 1.59 | 88.89 | CL6 | 3.67 | 1.26 | 73.33 |
| SL2 | 4.11 | 1.43 | 82.22 | CL7 | 3.78 | 1.65 | 75.56 |
| SL3 | 1.94 | 2.12 | 38.89 | CL8 | 1.44 | 1.81 | 28.89 |
| SL4 | 3.17 | 2.16 | 63.33 | MS1/MS3 | 3.94 | 1.25 | 78.89 |
| SH1 | 3.94 | 1.36 | 78.89 | MS2 | 3.56 | 1.25 | 71.11 |
| SH2 | 1.78 | 2.17 | 35.56 | MS4 | –2.22 | 2.21 | –44.4 |
| SH3 | 0.67 | 1.88 | 13.33 | MS5 | –2.50 | 1.77 | –50.0 |
| SH4 | 3.00 | 1.37 | 60.00 | MS6 | 3.11 | 2.01 | 62.22 |
| SH5 | 3.50 | 1.63 | 70.00 | MS7 | 2.83 | 1.65 | 56.67 |

The survey data for each of the heuristics are collected and analysed by calculating mean, SD and score. Table 8 shows the analysis of the heuristics. The heuristics with a score of 50% and with low SD are seen to be valid.

The heuristics related to 'classic' characteristics especially are found to be particular weak. The heuristics MS4 is found to be contradicting to the user perception. MS4 had to contradict, as only one heuristics between MS2 and MS4 could be true, as both of them belong to the same chromosome. Thus, MS4 is discarded. The user survey result aptly confirms the assertion. CL2 and MS5 are contradicting the user perception. This shows that there is a contradiction in the user and designer perception about the effect of involved chromosomes Ch2. This parameter of the shape characteristics affects the shifting of the front end of the roof. The above conclusions are drawn with respect to the design form of a car body profile, so, their applicability of these heuristics is limited to the product form represented in Figure 2.

## 6 Discussions and conclusions

During the validation, most of the heuristics are found to be valid, i.e., the heuristics are found to match with the human understanding of the shape transformation. Some heuristics are found in contradiction with the user perception. Such heuristics are discarded. The set of validated heuristics can be considered as the externalised design knowledge belonging to a family of the designs represented by the common rule structure.

Experiments carried out using the prototype software have indicated that the presented theory and its implementation are consistent with the human practice of aesthetic design process and design knowledge. In the light of these results, it can be assumed that the action grammar is able to model and capture the cognitive processes involved in the aesthetic design sketching process; and ADC is able to model aesthetic design domain. The developed prototype software can contribute to support the exploration of conceptual design for aesthetics in various manners. Some of these are identified as:

a consultative system to guide novice designers

b automatic or interactive design of the particular family of products

c automatic evaluation of the designs

d explicit documentation of the design knowledge.

These features are helpful in various aspects of design such as development of design theory, improvement of practice and better design education. Although ADC and action grammar are in their early stage of the development, their effectiveness in formally defining the design processes and design sketching indicates that the concept generation process can be systematically analysed, understood and supported by the computational tools. The developed framework contributes

### *6.1 Future works*

The present work is an effort to formalise and model the complex industrial product design process through the analysis of sketching process.

There are many aspects which need to be investigated; some of them are discussed as under.

The present work only focuses on the 2D design. Further research is needed and will be focused on this aspect. The aesthetics is determined by not only the product form, but colour, light, texture and context also influence the aesthetic evaluation. These factors certainly need to be investigated for their influence of the aesthetics and formalised in a model.

The action grammar captures the sketching process, still, it needs human intervention to define the preferred path of shape generation. Automation of the sketching process to generate the product form is another major area which needs further investigation.

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## Appendix

**Table A1** A sample of the survey data

| *Heuristics* | | | | | *User* | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *U1* | *U2* | *U3* | *U4* | *U5* | ... | *U43* | *U44* | *U45* |
| EL1 | 5.00 | 2.50 | 5.00 | 5.00 | 5.00 | … | 2.50 | 2.50 | 2.50 |
| EL2 | 2.50 | 5.00 | 5.00 | 5.00 | 2.50 | … | 5.00 | 2.50 | 5.00 |
| EL3 | 0.00 | 5.00 | 5.00 | –2.50 | 5.00 | … | 5.00 | –2.50 | 0.00 |
| EL4 | 2.50 | 5.00 | 2.50 | 5.00 | 2.50 | … | 2.50 | 2.50 | –2.50 |
| SL1 | 5.00 | 5.00 | 5.00 | 5.00 | 2.50 | … | 2.50 | 0.00 | –2.50 |
| SL2 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | … | 2.50 | 2.50 | 2.50 |
| SL3 | 0.00 | 5.00 | 2.50 | 2.50 | 5.00 | … | 2.50 | –2.50 | 0.00 |
| SL4 | 0.00 | 5.00 | 5.00 | 0.00 | 5.00 | … | 5.00 | 2.50 | 0.00 |
| SH1 | 2.50 | 5.00 | 2.50 | 5.00 | 5.00 | … | 5.00 | 2.50 | 0.00 |
| SH2 | 0.00 | 2.50 | 2.50 | –2.50 | 5.00 | … | 2.50 | –2.50 | 0.00 |
| SH3 | 0.00 | 2.50 | 0.00 | 2.50 | 0.00 | … | 2.50 | 2.50 | 0.00 |
| SH4 | 0.00 | 2.50 | 2.50 | 2.50 | 2.50 | … | 2.50 | 2.50 | 2.50 |
| SH5 | 2.50 | 5.00 | 2.50 | 5.00 | 2.50 | … | 2.50 | 2.50 | –2.50 |
| CL1 | 0.00 | 2.50 | 5.00 | 0.00 | 5.00 | … | 5.00 | 2.50 | 0.00 |
| CL2 | –5.00 | 0.00 | –2.50 | –5.00 | –2.50 | … | 2.50 | –2.50 | –2.50 |
| CL3 | 0.00 | 2.50 | 2.50 | 2.50 | 2.50 | … | 2.50 | 2.50 | 0.00 |
| CL4 | 0.00 | 0.00 | 2.50 | 2.50 | 2.50 | … | 0.00 | –2.50 | –2.50 |
| CL5 | 0.00 | 0.00 | 2.50 | 2.50 | 2.50 | … | 0.00 | –2.50 | –2.50 |
| CL6 | 2.50 | 5.00 | 2.50 | 5.00 | 2.50 | … | 5.00 | 2.50 | 5.00 |
| CL7 | 2.50 | 5.00 | 5.00 | 0.00 | 5.00 | … | 5.00 | 2.50 | 0.00 |
| CL8 | 0.00 | 0.00 | 2.50 | 2.50 | 2.50 | … | 2.50 | 0.00 | 2.50 |

**Table A1** A sample of the survey data (continued)

| *Heuristics* | *User* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *U1* | *U2* | *U3* | *U4* | *U5* | ... | *U43* | *U44* | *U45* |
| MS1 | 2.50 | 5.00 | 2.50 | 5.00 | 2.50 | … | 5.00 | 2.50 | 5.00 |
| MS2 | 2.50 | 2.50 | 2.50 | 5.00 | 2.50 | … | 5.00 | 2.50 | 5.00 |
| MS3 | 2.50 | 5.00 | 2.50 | 5.00 | 2.50 | … | 5.00 | 2.50 | 5.00 |
| MS4 | –5.00 | 0.00 | –2.50 | –5.00 | –2.50 | … | 2.50 | –2.50 | –2.50 |
| MS5 | –5.00 | 0.00 | –2.50 | –5.00 | –2.50 | … | 0.00 | –2.50 | –2.50 |
| MS6 | 0.00 | 5.00 | 5.00 | 0.00 | 5.00 | … | 5.00 | 0.00 | 0.00 |
| MS7 | 0.00 | 2.50 | 5.00 | 2.50 | 5.00 | … | 5.00 | 2.50 | 2.50 |