Extended Axiomatic Design and Computational Support to Design for Aesthetics

Sitaram Soni[1], Pritee Khanna[2] and Puneet Tandon[3]

[1]PDPM IIITDM, Jabalpur INDIA, sonis@iiitdmj.ac.in
[2]PDPM IIITDM, Jabalpur INDIA, pkhanna@iiitdmj.ac.in
[3]PDPM IIITDM, Jabalpur INDIA, ptandon@iiitdmj.ac.in

ABSTRACT

The research describes the extension of the Axiomatic Design model to incorporate the aesthetic design as the customer requirement. It also proposes a computational model to support the formalization of aesthetic design in industrial products. The methodology takes into account the cognition process during the design generation and captures this behavior in a group theoretic structure. This approach leads to application of Axiomatic Design paradigm to the domain of the aesthetics. The proposed framework is implemented and validated by taking a design case of the consumer products.

Keywords: knowledge support, generative shape description, axiomatic design.
DOI: 10.3722/cadaps.2013.1-15

1 INTRODUCTION

Design is aimed to create artifacts with the intention to satisfy specific requirements in a novel way. In product design, these requirements form the specifications ranging from functionality and usability to ergonomics and aesthetics. Traditionally, designers focused on fulfilling the technical and functional requirements. This led to the development of advanced systems and tools for satisfying the functional requirements like Axiomatic Design (AD), Quality Function Deployment (QFD), House of Quality (HOQ), Theory of Inventive Problem Solving (TRIZ), etc.

Although the importance of a formal system to define and manipulate the aesthetic design of the industrial products is well understood, this was mostly considered merely as the constraints, rather than a requirement. The reasons for this apparent neglect can be attributed to at least two factors. One, in the producers' market, the functional satisfaction was considered to be sufficient for the acceptance of the product by the consumer and any investment on the aesthetics was considered to be a cost, which a consumer might not be willing to pay for. The other factor is concerned with the domain of the aesthetics design. It was considered a humanities subject with little understanding as a formal body of knowledge. This made the engineers uncomfortable to deal with due to the lack of exact rules and relationship observed in the other 'scientific' arena. This neglect of the domain of aesthetics is the prime reason that such a system is still not available. There is no formal theory or methodology for understanding the ‘Design for Aesthetics’ (DFAe) paradigm. Thus, the aesthetic design is still a human centric, informal and subjective process. Current Computer Aided Design (CAD)/ Computer Aided Styling (CAS) systems provide almost no support to aesthetics related knowledge except capturing some geometric constraints during the sketching process. The current feature/ parametric technology used in the design systems is heavily rooted in mathematical description of the shapes, with no support to the aesthetics related knowledge. The underlying data, representing the shape is devoid of any consideration of aesthetics. Podehl [18] observed that the integration of the styling and aesthetics into the overall product development process has still not been properly achieved. Breemen et al. [2] noted that computer support in the field of aesthetic design of industrial products is still in its infancy, partly because there is no methodology to incorporate aspects like appearance, pleasantness and human usage of a product.

In the present paper, it is proposed to extend Axiomatic Design framework to include the aesthetic consideration as requirements, rather than considering them as mere constraints. Thus a formal model of Design for Aesthetics (DFAe) is developed. Lastly, the model is validated by development of a computational support system to design the products with specific aesthetic characteristics.

The rest of the paper is divided as follows. Section 2 reviews the efforts made in this domain by earlier researches. Section 3 describes the extended Axiomatic Design model as the formal model of design including aesthetics. Section 4 analyses the aesthetic design process by the human designers and compares the shape representation practiced by the human designers vis-a-vis current CAD systems. Section 5 presents the implementation details of the proposed model for the aesthetic design as a computational tool. Section 6 presents a case study to considering the design of some industrial products to validate the model. The paper concludes with the discussion on the validity and applicability of the model along with directions for further exploration in Section 7.

2 LITERATURE REVIEW

Axiomatic Design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through mapping between Functional Requirements (FRs) and Design Parameters (DPs) [22]. The AD provides a systematic and logical method for deriving, documenting and optimizing designs and helps avoid traditional design-build-test-redesign cycles for design solution search and for determining the best design among those proposed [21]. The implementation issues are discussed by many researchers [13],[21]. A fundamental aspect of the mapping process is the idea of decompositions through zigzagging.

Several researches have been conducted to identify the possible associations between a product’s shape characteristic and its aesthetic or emotional characteristics. Catelano et al. [5] presented a comprehensive survey of the efforts to model the aesthetic design process. Nagamachi [17] presented the ‘Kansei Engineering’ to systematize the process of associating the shape characteristics of the products to the aesthetic characteristics. Some of the major contributions are made by Breemen et al.[2], Hsiao et al. [14] and Chen et al. [7] Breemen et al. [1],[3] suggested separation of products in categories sharing some common aesthetic characteristics and shape operations.

A number of researchers have attempted to define the relationship between aesthetics and geometric representation of the products. Chek and Lian [6] identified various measures of the aesthetics in products and tried to give their geometric interpretation. Fujita et al. [11] derived some ratios for the lines and surfaces based on the curvature that correlated to the aesthetics of the product. Cheutet et al. [8] and Giannini et al. [12] 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. [4] 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 [7] proposed a systematic methodology to describe the style profiles of the products. Claessen [9] explored the relationship of the aesthetics of industrial products with the color and shape.

A formal mapping of the aesthetic characteristics and the product form that could be implemented in a computational framework requires the identification of direct and robust relationship between its aesthetic characters and the geometric elements. Ideally, this mapping should specify the values of shape characteristics and parameters that conform to the designer's intention of the product form. Breemen et al. [2] provided some examples of possible relationship between aesthetic and shape parameters. FIORES-II project [10], after an extensive exercise with designers and stylists, described some verbal descriptions to the shape modification by specific operations intended to achieve the specific aesthetic characteristics. The reviewed work indicates that most of the research focused on finding the relationship between aesthetics and shape characteristics without any reference to the cognitive processes taking place during the design by human designers. Also the Axiomatic Design framework supports only the technical design with little considerations of the aesthetics. In order to apply the Axiomatic Design framework to the domain of industrial design, new domains relevant to the aesthetic design process need to be identified and integrated with the conventional Axiomatic Design framework.

3 EXTENDING THE AXIOMATIC DESIGN

The conventional model of Axiomatic Design provides the mapping between the Customer Attributes (CA), Functional Requirements (FR), Design Parameters (DP) and Process Variables (PV). This model is suitable to represent and generate the configuration design, but it does not support the embodiment design and the aesthetic characteristics. In the conventional AD, the consideration of aesthetics is generally made after the functional designs are achieved. This practice treated the aesthetic consideration only as the constraints or additional features, which might be desirable but not vital. Since the constraints are just the boundaries of the design space, which should not be violated by the proposed solution. This viewpoint does not guarantee the specific aesthetic characteristics. This treatment of the subject of the aesthetics has to be discarded and the consideration of aesthetics has to move from the domain of constraints to the domain of requirements, so that specific characteristics may be strived for. In order to incorporate the embodiment and the aesthetic characteristics in the existing Axiomatic Design model, the model needs to be extended. The revised Axiomatic Design model is shown in Fig.1.

Various domains in the conventional model retain their usual meaning. The CAs are divided in two categories. One is the functional CAs and the other is the aesthetic CAs. The Functional CAs are mapped to FRs to establish the product specification. The FRs are mapped to DPs to establish the product configuration elements or features as is done in the existing AD model.

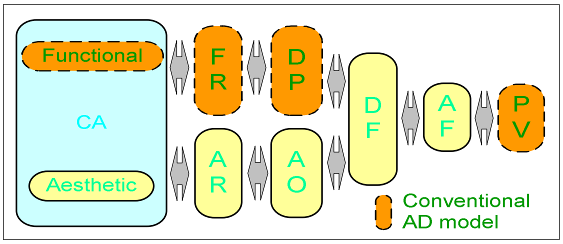

Fig.1: Extended Axiomatic Design Model.

In case of the industrial products, the aesthetic CAs are translated into aesthetic requirements (ARs). These ARs are the semantic expression used by the customer to describe the preference on the shape. These are also the specific properties expected or intended by the designer in the product form. These requirements demand the specific aesthetic operations (AOs) to be carried out to product design form (DF). The design form (DF) of the product configuration (DP) is the collection of the shape elements that are significant from the aesthetics point-of-view. These are not the exact shapes derived from the DP elements of the design, but are simplified shapes. The process of extracting the DF may involve some abstraction of the shapes or removal of details. The DF is also termed as the aesthetically significant shapes (AeSS) in the sketch. These are also the primary shapes with reference to the shape transformation. More details on AeSS are given in section 4.2. The significant shapes representing the DF are modified by the aesthetic operators (AOs) to achieve the aesthetic form (AF). The aesthetic form drives the secondary shape deformation to achieve the final product form. The final form of the product further needs to be evaluated against the constraints likes the ergonomics, manufacturability, etc.

The emphasis on the importance of aesthetics considerations, early in the design process motivates to devise a new design workflow. This workflow is described in Fig. 2. The customer requirements are to be divided into the functional and the aesthetic requirements. These requirements lead to the selection of the design form and the aesthetics operations as two separate, parallel processes. Further these two spaces are explored to achieve the desired aesthetic form of the product within the other constraints.

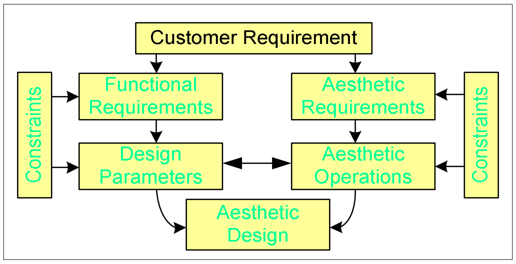

Fig. 2: New design workflow.

There are various computational tools like morphological matrix, design repository, catalogues, etc. available to achieve the CA-FR-DP mapping. The DP–DF mapping still needs some human assistance to identify the significant shapes. The most important mapping for the computational support to aesthetic design is the DF-AF mapping. This mapping is achieved using the artificial neural network.

4 THE AESTHETIC DESIGN PROCESS

Understanding the processes of design generation and exploration is not straightforward. Most of these processes are inaccessible because they take place in the designer's head. Comprehending how designers think and how they undertake their tasks is a problem that has intrigued many researchers. One plausible way of uncovering aspects of a designer's thinking process is through examination of the pictorial representations produced by him/her during the design exercise [23] .

The protocol analysis of the design process have indicated that these actions follow a general sequences with respect to the form definition of the product. The initial design actions are targeted towards the definition of the general form of the product whereas subsequent actions are aimed at deformation of the basic form at local level. Further actions are used for the dress-up operations like the chamfer and fillet. There is a sequential reduction in the extent of influence of the operation on the product form. Nevertheless, the importance of the operations lower in hierarchy may be pronounced in defining the aesthetic characteristics of the product.

4.1 Importance of Shape in Aesthetic Design

The aesthetics of the product are the cognitive reaction of the user when experiencing the product. This reaction is influenced by various characteristics of the product. The form of the product is the major driver of this reaction. The design of any product involves sketches that are characterized by various shapes and operations. While sketching during the product development, the designer is engaged in two-way communication with the sketch. The elements of the sketch are not only the externalization of the mental processes taking place in the designers mind, but also the interpretation of the sketch by the designers guides the thinking process of the designer. The shapes generated during the sketching define a domain representing the 'space of shape characteristics'. Other factors influencing this reaction are the color, surface texture, material, etc. But in the current research, the influence of these factors is ignored. The users can have the multiple reactions to the product. These reactions are expressed as semantic adjectives. The domain of these adjectives may be called as the 'space of aesthetics characteristics'. The most intrinsic problem in the development of a computational support system for the aesthetic design is to establish a mapping between these two spaces (shape ↔ aesthetics).

Further analysis of the mental processes taking place during the design exercise identifies certain phenomena like abstraction, approximation, (re-)interpretation and emergence. The two-way communication between the sketch and the mental intention of the designer to embed the specific aesthetics in the shape is characterized by a sequence of operations. These operations help to achieve a controlled and guided deformation/modification of the shapes to achieve specific aesthetic characteristics.

4.2 Aesthetically Significant Shapes (AeSS)

Analysis of the design process indicates that not all shapes in the product form contribute to the aesthetic appreciation. Some shapes draw more attention of the users. These shapes are called the aesthetically significant shapes or primary shapes in a sketch. Other shapes of the product form are known as the secondary shapes. The aesthetics is thought be embedded by the operations done to the significant shapes. The AeSS defines a region in space which may or may not contain the product features or form elements. Aesthetic operators are the actions used to modify the AeSS with an intention to embed the specific aesthetic characteristics in the product. The relationship of the AeSS with the product features is presented in Fig. 3.

AeSS act as the drivers of the aesthetic appreciation. The secondary shapes follow them. Secondary shapes are modified using three schemes, the rigid, semi rigid and flexible deformation. The rigid deformation just repositions the secondary shapes with respect to primary shapes using some positional relationships using translation and rotation, without modifying the secondary shapes. In case of the semi- rigid deformation, the secondary shapes are deformed using the stretch, shear or taper deformation [15] to follow the significant shapes deformation. In the case of the flexible deformation, the secondary shapes follow the deformation of the significant shapes according to the rules of shape morphing or field based deformation schemes such as free form deformation (FFD) proposed by Sederberg and Parry [19]. The two dimensional FFD is a map from $R^2 \rightarrow R^2$. It defines a new position for every point in a given (normally rectangular) region by m and n the degrees of the FFD function.

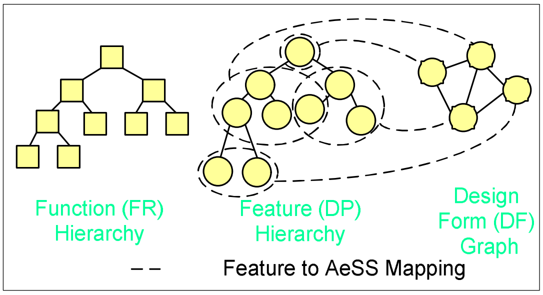

Fig. 3: Feature to AeSS mapping.

5 COMPUTATIONAL MODEL OF AESTHETICS DESIGN

The computational support to the aesthetic design is achievable only when the aesthetic operations used by the designers to modify the shape are captured in a robust mathematical structure. This structure should also support the expression of these operations in a hierarchy observed in the human design activity.

The shape description should map to the cognitive processes taking place during the design exercise. As described above, the process of design is characterized by the multiple levels of abstraction of the data set and movement between these levels for shape modification, driven by the aesthetics of the form. A formal model to capture the design operations carried out by the designer on the product form is provided by Leyton’s geometry [16]. Leyton demonstrated that human cognition system follows the Iwasawa decomposition (stretch, shear and rotation) in organizing the information. It is argued here that human designers use similar actions to modify the shape in order to achieve the specific aesthetic characteristics. It is also added that there are more perceptual global operations like taper, bend, blow, wave etc. observed in the design exercises having the design salience in shape modification.

The Leyton’s grammar is used for curves with C2 continuity without explicit curve segmentation, but the human perceptual system is tuned towards segmentation. Generally the negative minima are perceived to be the point of segmentation. Leyton’s grammar is more useful to capture the growth behavior of the natural objects. Our model is more suited to the industrial products where the segmented regions are perceived separately, with C0 continuity.

The basic construct used in generative specification of the shape is based on the hierarchical structure of operations. The structure helps to capture the history of operations in the form of a hierarchy. This model also ensures complete parameterization of the complexity of the shape, and no part of the shape description is left accounted for. Every aspect of the shape characteristics is understood and captured in the generative description of the shape.

The advantages of the hierarchical structure based description of the shape generation systematic mapping of various levels of abstraction during the design exploration with various stages of shape generation. Further, the shape modification process is completely accounted for, as the extending group captures the record of the previous stage and the generation operation to define the next stage of generation.

5.1 Generative Specification of the Shape

The generative specification of the shape is given by a group of three types of operations. The ordered set of the variables representing the generative groups of the shape deformation governs the sequence of action. The sequence of operations is predetermined and categorized in a hierarchy, as observed in the protocol analysis of the human sketching process during the design. The sequences is divided into following categories; Global, Local and marginal. These categories signify the influence of operations on the shape modification.

The global operations influence all the elements of the shape and any modification at this level is propagated to all elements. Local shape deformation affects only the selected individual element. The marginal operations influence the interfaces between two elements.

For a shape originating from the square (with restricted deformation rules), the sequence of operation is predefined and is described as under,

The generative sequence of a square is defined as the transfer of a linear element E by Z_4 symmetry group, thus a square is written as,

$E \odot Z_4$, here, $\odot$ denotes the group extension by wreath product.

This generation of the square may be expanded as,

$$[E1 \otimes E2 \otimes E3 \otimes E4\ ] \circledast Z_4 \tag{5.1}$$

Here, $\otimes$ denote the direct product, and $\circledast$ denotes the semi- direct product.

E1 to E4 are the edges of the primitive group transferred by the Z_4 symmetry group.

The global operations deforming the square shape are given by the group of stretch (A), shear (N), taper (T) and rotation (R). Thus, the generative sequence of the deformed square may be written as,

$$[E \odot Z_4] \odot A \odot N \odot T \odot R \tag{5.2}$$

The next level of operation comprises of the edge deformation by AN groups

$$[[E \odot Z_4] \odot A \odot N \odot T \odot R] \odot AN \tag{5.3}$$

Here, AN is the combination of the stretch and shear operations. As A and N can be represented as invertible square matrix, they can be combined to form a group.

The last level of the operations is the group of the marginal operations, denoted by F. thus the generative sequence becomes,

$$[[[E \odot Z_4] \odot A \odot N \odot T \odot R] \odot AN] \odot F \tag{5.4}$$

Using the proposed scheme to describe the generative specification of the product form, the complete generative equation of a shape with square as the prototype is written as under,

$$[[E1 \otimes E2 \otimes E3 \otimes E4\ ] \circledast Z_4]_{P1} \odot [A^{P1}]_{S1} \odot [N^{S1}]_{S2} \odot [T^{S2}]_{S3} \odot [R^{S3}]_{S4} \odot$$

$$[[AN^{E1}]_{S5} \otimes [AN^{E2}]_{S6} \otimes [AN^{E3}]_{S7} \otimes [AN^{E4}]_{S8}] \odot [[F^{C1}]_{S9} \otimes [F^{C2}]_{S10} \otimes [F^{C3}]_{S11} \otimes [F^{C4}]_{S12}] \quad (5.5)$$

The first operation by Z_4 generates the primitive P1, which is a square. The square is transformed by stretches (A) to generate shape S1. This shape is subsequently transformed by other groups of shear (N), taper (T) and rotation (R). These operations generate shapes S2, S3 and S4 sequentially.

Further, the shape is manipulated edgewise to generate shapes from S5 to S8. These operations happen at the same level of the hierarchy, so they are represented by the direct product. Finally, the corners are modified to generate S9 to S12. These operations also take place at the same level of hierarchy, but after the edge modification. Shapes P1 and S1 to S12 represent various levels of abstraction in shape generation process. Each edge deformation contains the generation of two daughter linear elements using AN group of linear deformation and each daughter element is further deformed using AN group for the curve deformation. For the sake of brevity, these deformation of the edges by AN groups are combined, which generate their own intermediate shapes. Soni et al. [20] provides more details on the shape generation process. Fig. 4. Shows the sequence of shapes generated using Eqn. (5.5). This is one instance of multitude of possible shapes that can be generated using a single generative specification given by Eqn. (5.5)

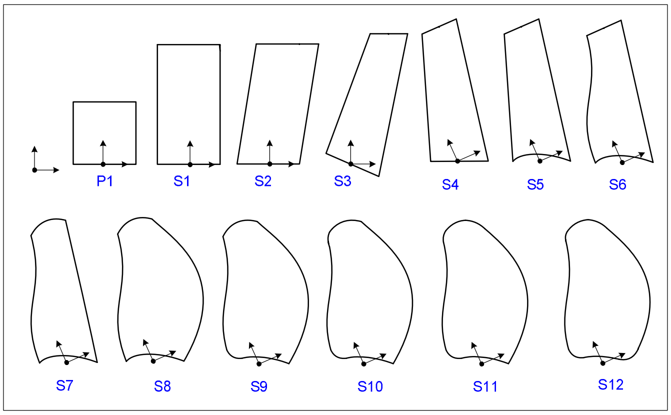

Fig. 4: Sequential shape generation.

The proposed model captures the design intelligence better than any other mechanism based on some ad-hoc geometric characteristic identified in the product form. Shape characteristics like number of corners, angle between the edges, golden ratio or any other observable features in the shape are use to relate the aesthetic characteristics in most of the work done in the area of aesthetics of industrial products. Our scheme provides a comprehensive description of shape transformation process, which captures all the shape features in an integrated definition. The generative specification is common to a large number of seemingly different looking shapes. In addition, each complexity or shape peculiarity in the shape is appropriately parameterized. Since the proposed model provides an exhaustive description of the shape characteristics having design salience, the shape characteristics are comprehensively captured in a framework of operations. These framework has a strong congruence with the cognitive processes taking place during the design exercise by the human designers. The proposed model also captures the phenomenon of abstraction by allowing access to the product form at different levels of details and opportunity to modify them at that level.

5.2 Aesthetics Learning and Aesthetics Embedding System

The computational support to the aesthetic design is achieved using a knowledge base (KB). The KB is developed in the form of a mapping between the generative description of the product form and the aesthetic evaluation of the product. In order to achieve this mapping, a large number of the products from various categories of the consumer products like perfume bottles, hand held devices like phone, watches, camera, game consoles etc. are analyzed. The design knowledge embedded in the product form is expressed as the sequence of action described as the hierarchical operations. These operations define the domain of the design operations. The aesthetic appreciation of the product form is evaluated through a user survey and is expressed as a uni- polar multidimensional semantic profile. The semantic adjectives used in the survey define the domain of the aesthetic expression of the products.

Since the aesthetic design of the product is a function of the design operations intended to achieve the specific appreciation, this relationship can be captured as the mapping between the domains of design operations and the aesthetic appreciation expressed as the semantic profile of the product. The ANN based mapping between the two domains and the GA based search tool are developed as an earlier exercise using supervised learning for network training [20]. These are called the aesthetics learning system (ALS) and aesthetics embedding system (AES) respectively. The major factor for the choice of ANN based mapping is the fact that it is not possible to define the link between the shape characteristics and aesthetics, as most of the process happens in human mind implicitly. Protocol analyses of the processes have shown that it is multi- to- multi with little guidance on the nature of the mapping. Hence, ANN is used to map the two domains. ANN helps to map two sets having complex relationship without the knowledge of the relationship between the set elements. It is also termed as black box mapping.

The learning process is applied on the deformation gradient of the generative sequence. The generative sequence is a set of ordered variables covering the global, Local and marginal deformation of the shape. In the present exercise, it is defined as a vector of 43 variables capturing all the shape peculiarities in a structure. The deformation gradient is defines as under,

If V is the vector defining the generative sequence of the shape, a vector B can defined such that B is isomorphic to V and represents the shape without aesthetics. Similarly, a vector S, isomorphic to V represents the shape with the aesthetics is defined. The deformation gradient is defined as

$$\triangle D = S - B \tag{5.6}$$

Seven aesthetic characteristics (Elegant, Cute, Traditional, Tender, Feminine, Sporty and Rational) are used to build the ANN model. Experience from the research indicates that these are the prominent aesthetic characteristics in the evaluation of the industrial products. The computational support to modify the design form and embed the required characteristics through a hierarchy of operations is achieved using a GA based search for the required operations using the ANN based map. The search is guided by an optimization routine using a fitness function defined in terms of the required aesthetic characteristics.

6 CASE STUDY

In order to validate the proposed model, the design of the two consumer products (A mixer grinder and a coffee maker) was undertaken. Two AeSS are identified for each product to define the DF. In the design of the mixer grinder, the significant shapes are the top body and the base. In the case of the coffee maker, the significant shapes are the front and the top view as shown in Fig. 5. In the present work, the significant shapes are extracted manually. As the development of shape extraction system capable to simulate the human cognition system is quite difficult and comprises an area of research in its own right. The relative importance of the significant shapes for each product is assumed to be 1:1. It means that both the shapes are equally important with respect to the aesthetic appreciation of the products. The basic form of these shapes is a square. The generative sequence of such shape is given in Eqn. (5.5).

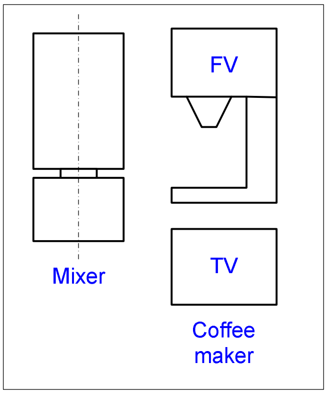

Fig. 5: The base form of the products.

Tab.1 shows the aesthetic characteristics to be achieved for various designs of the chosen products. Three variants for each type of product are designed to cover a sufficiently wide range of the aesthetic characteristics. Only four characteristics are chosen with the presumption that in real life, mostly three or four aesthetic characteristics are enough to define the products appreciation by the general user.

Product	No.	Cute	Strong	Slender	Elegant
Mixer	M1	9	8	3	5
	M2	3	8	4	8
	M3	6	6	2	3
Coffee Maker	C1	3	8	8	5
	C2	3	8	5	5
	C3	6	3	4	8

Tab. 1: Specified aesthetic characteristics.

6.1 Shape Generation Process

The shape generation process starts after the definition of the design for (DF) using the AeSS. Once the significant shapes are identified, the generative description of the shape is populated with random values. Using such random values, multiple instances of the shape are generated. These instances form the initial population of the GA. To reduce the search iteration, an extended random initialization procedure may also be used here to generate the initial population. This is achieved by searching the design data base used for the ALS to identify the cases which are closest to the required aesthetic characteristics. A major issue in the process of embedding the aesthetics is the identification of the AeSS. In the present work, the significant shapes are extracted manually. As the development of shape extraction system capable to simulate the human cognition system is quite difficult and comprises an area of research in its own right.

In order to generate the valid designs, certain constrains are to be applied on the generation process so that impractical shapes are avoided. The main constraint used in the present study is the constraining the lower element which forms the base of the product. This element is constrained to be only flat or concave. The convex shape of its element will violate the functional requirement of stability of the product.

The product shapes represented by this population are evaluated for the fitness either by the designer or by using the ALS. The fitness function used with the ALS is based on cumulative error minimization, as defined below.

If SAC_i are the specified aesthetic characteristics for a shape and CAC_i are the calculated aesthetic characteristics using the ALS, then fitness function is given by

$$Min \sum_{i=1}^{n} ||SAC_i - CAC_i|| \tag{6.1}$$

Here, n is the number of aesthetic characteristics.

The generation of the new population continues till the specified aesthetic characteristics are achieved in any one member of the generated population within the error limits. In this exercise, 5% error was set to terminate the generation process. In each generation, 10 shapes are randomly generated. These shapes are evaluated for the fitness. The selection, cross over and mutation are used to improve the fitness function. The convergence occurs mostly in between 500 to 1200 generations. Fig. 6. shows various intermediate stages of the shape generation process for the mixer. Shape (a) is the initial stage. Shapes (b) and (c) are obtained after the global operations. Shape (d) and (e) are generated by local deformation. Shape (f) is generated by the marginal operation.

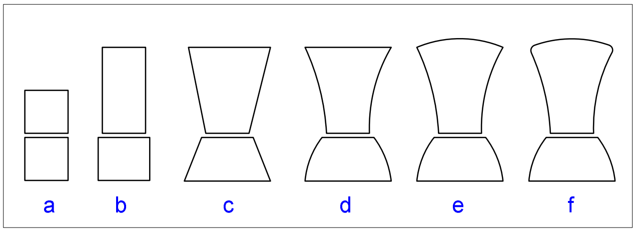

Fig. 6: The generation stages for the sample product.

The generated shape is used to modify the base design of the product. Here, only the general shape of the product is modified. The details like buttons etc. are added later to enhance the visualization of the product. Fig. 7. shows the generated designs.

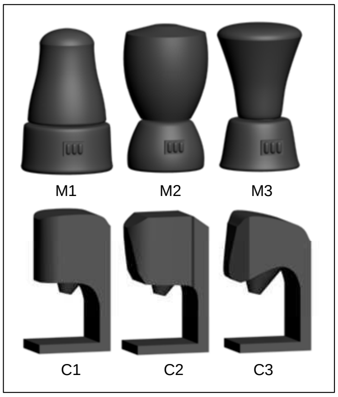

Fig. 7: The generated designs.

In order to validate the conformance of the generated designs to the prescribed aesthetic characteristics, the user survey was again conducted to evaluate the generated design and the results are compared with the specified aesthetic characteristics values. The mean values of the response were calculated and error between the specified value and mean value from the survey is estimated. There is a large deviation in the user response; it may be attributed to limited sample size. In future more robust user survey design will be used for the analysis. Fig. 8 shows the user response for the designed product M1. Tab. 2 shows the error in various generated designs.

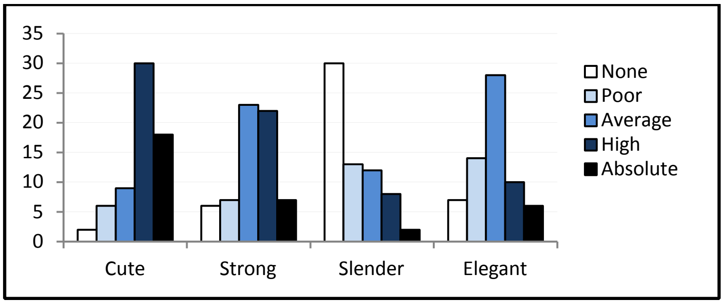

Fig. 8: The Response of user for product M1.

Product	No.	Cute	Strong	Slender	Elegant
Mixer	M1	10.14	11.40	22.32	24.13
	M2	15.04	12.95	12.58	13.60
	M3	9.32	4.39	14.12	11.10
Coffee Maker	C1	10.17	1.89	22.19	22.15
	C2	12.64	5.26	9.13	23.69
	C3	21.07	5.10	11.63	12.59

Tab. 2: Error in generated designs (%).

The design generation using the developed tools indicates that the proposed methodology based on the extended Axiomatic Design model of the product design shape generation seem to support the claim that it is possible to map the aesthetic design process in a mathematically robust model. From the error evaluation it is evident that most of the designed product forms converged to the specified values of the aesthetic characteristics, but there is a large error in the generated design characteristics. In order to make the proposed methodology more useful, identification of the causes of such deviations and suitable modifications are planned as further exercise.

There are several causes of the errors as identified below. The major cause of the error seems to be the perception of the survey subjects towards the aesthetics. The framework uses two dimensional shapes for the learning and generation of the designs, which may cause the error as sometimes the three dimensional form creates a very different impression than its two dimensional image. Another major cause of error may be the selection of the significant shape and effect of the secondary shapes in the aesthetic evaluation.

The learning process may also have the shortcomings as this is based on the appreciation of the single shape, which may not be suitable for the shapes having two or more significant shapes. In the current model the multiple significant shapes of a product are evaluated one at a time and the effect is combined using a weighted sum of them. This assumption may not be quite valid in the domain of design, where sum is more than its parts. The observation that the contribution of the parts is more than their sum in product design is evident from the fact that as we add elements to the shape more and more perceptual structures emerge. For example, if there a one curve in the shape, Eigen space of its modification are determined by its own characteristics only, but as another curve is added in the proximity, an additional symmetry axis passing between the two curves is perceived. This is in addition to the curves' own Eigen space.

7 CONCLUSIONS

The paper presents an extended Axiomatic Design model to incorporate the domain of aesthetic design of industrial products. It also formulates a computational model to support the aesthetic design. The basic foundation of design for aesthetics is based on the cognitive process knowledge modeled by the hierarchy of operations. The form of the product is used to extract the significant shapes from the aesthetics considerations. These significant shapes act as the driver of the form modification to embed the aesthetic characteristics in the product form. The methodology is validated using the data available from a set of limited users and products. Validation exercise confirms the usefulness of the framework as the support tool for the aesthetic design.

The Novelty of the model is to extend the Axiomatic Design framework to include the aesthetics as requirement. Development of the mapping between various conventional and extended domains is carried out. Also the computational tool to support the aesthetics in Axiomatic Design is developed, which complements the tools like TRIZ, QFD and HOQ etc. which are available for mapping the conventional AD domains.

In the present framework, only one significant shape is used for the learning model. For a more robust framework, multiple significant shapes should be considered simultaneously for evaluation and transfer of aesthetic characteristics. These are the indicators for the future direction where the research needs to be focused to make the model more useful. In conclusion, the propose methodology shows the potential as a knowledge support system for aesthetic design of industrial products.

REFERENCES

[1] Breemen, V. E. J. J.; Sudijono, S.: The Role of Shape in Communicating Designers' Aesthetic Intents. Proceedings of the 1999 ASME Design Engineering Technical Conference, September 12-15, Las Vegas, Nevada, 1-10.

[2] Breemen, V. E. J. J.; Knoop, W. G.; Horvath, I.; Vergeest, J. S. M.; Pham, B.: Developing a Methodology for Design for Aesthetics Based on Analogy of Communication. Proc. of the 1998 ASME Design Engineering Technical Conferences Atlanta, Georgia, USA, 1-4.

[3] Breemen, V. E. J. J.; Sudijono, S.; Horvath, I.: (1999). A Contribution to Finding the Relationship between Shape Characteristics and Aesthetic Appreciation of Selected Products. ICED99 Munich, 1999, 1765-1768.

[4] Case, K.; Graham, I. J; Wood, R. L.; Abdul Karim, M.S.: (2002). CAD Genetic Algorithms for Evolutionary Form and Function Design, 'Advances in Manufacturing Technology XVI', Proceedings of the 18th National Conference on Manufacturing Research, K. Cheng, D Webb (Eds), pp. 103-107.

[5] Catalano, C. E.; Falcidieno, B.; Giannini, F.; Monti, M.: (2002). A Survey of Computer-Aided Modeling Tools for Aesthetic Design, International Journal of Computing, Information Science and Engineering, 2(1), 2002, 11-20. http://dx.doi.org/10.1115/1.1481371.

[6] Chek, L. N.; Lian, S. T.: A Mathematical Theory of Interface Aesthetics, Multimedia University, Malayasia, 1999.

[7] Chen K.; Owen C. L.: A Study of Computer Supported Formal Design, Design Studies, 19(3), 1998. http://dx.doi.org/10.1016/S0142-694X(98)00002-7

[8] Cheutet, V.; Catalano, C. E.; Giannini, F.; Monti, M.; Falcidieno, B.; Leon, J. C.: Semantic based Operators to Support Car Sketching, Journal of Engineering Design, 18(5), 2007, 395 – 411. DOI: 10.1080/09544820701403714.

[9] Claessen, J. P.: Shaped by Colour, a Study on the Effect of Colour on the Perceived Shape of Objects, Ph.D. Thesis, Delft University of Technology, Delft University Press, Delft, 1996.

[10] FIORES II: Character Preservation and Modeling in Aesthetic and Engineering Design, 2003, GROWTH Project. G1RD-CT-2000-00037. www.fiores.com

[11] Fujita, K.; Nakayama, T.; Akagi, S.: Integrated Product Design Methodology for Aesthetics, functions and Geometry with Feature Based Modeling and Constraint Management, International Conferecne on Engineering Design, ICED 99, August 24-26, Munich.

[12] Giannini, F.; Monti, M.: CAD Tools based on Aesthetic Properties, Eurographics- Italian Chapter, July 11-12, 2002, Genova.

[13] Goncalves, C. A. M.; Mourao, J. F.: Axiomatic Design as Support for Decision-making in a Design for Manufacturing Context: A Case Study, International Journal of Production Economics, 109, 2007, 81-89. http://dx.doi.org/10.1016/j.ijpe.2006.11.002.

[14] Hsiao, S. W.; Wang, H. P.: Applying the Semantic Transformation Method to Product Design", Design Studies, 19(3), 1998. http://dx.doi.org/10.1016/S0142-694X(98)00009-X

[15] Leyton, M.: A Theory of Information Structure II: A Theory of Perceptual Organization, Journal of Mathematical Psychology, 30, 1986, 257-305. http://dx.doi.org/10.1016/0022-2496(86)90033-7.

[16] Leyton, M.: A Generative Theory of Shape, Springer-Verlag, Berlin Heidelberg. 2001, ISBN 3-540-42717-1.

[17] Nagamachi, M.: (1995). Kansei Engineering: A New Ergonomic Consumer Oriented Technology for Product Development, International Journal of Industrial Ergonomics, 15, 1995, 3–11. http://dx.doi.org/10.1016/0169-8141(95)90025-X.

[18] Podehl, G.: Terms and Measures for Styling Properties, Proceedings of the 7th International Design Conference, May 14th - 17th 2002, Dubrovnik, Croatia, 879 - 886.

[19] Sederberg, T.; Parry, S. R.: Free-form Deformation of Solid Geometric Models, In SIGGRAPH ’86, 151–160.

[20] Soni, S.; Tandon, P.; Khanna, P.: Capturing the Aesthetic Design Intention in product Design, Proceedings of TMCE 2012.

[21] Suh, N. P.; Do, S. H.: Axiomatic Design of Software Systems, Annals of the CIRP, 49(1), 2000, 95-100.

[22] Suh, N. P.: The Principles of Design, Oxford University Press, 1990.

[23] Tversky, B.: What Does Drawing Reveal About Thinking? Visual and Spatial Reasoning in Design, Sydney, Australia, 1999, 271-282.