INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

AESTHETIC FEATURE AS A TOOL TO PRESERVE THE DESIGN INTENT

Maura Mengoni[1] and Michele Germani[1]
[1]Polytechnic University of Marche

ABSTRACT
In the consumer goods field, the market offers to the customer a wide variety of possible alternatives to satisfy a specific need. Customers, generally, compare products evaluating the functionality and the congruency between price and intrinsic value, but the visual appearance plays a fundamental role in the final decision. During the creative phase, the industrial designer conceives the object in order to represent his/her own viewpoint on the design problem considering the context and the constraints given by the company image. The result of the work of the industrial designer is a set of sketches where curves, notes, shadows, and colours implicitly represent the creative ideas. These signs condense and concretise the design intent that, finally, will be transformed into product visual appearance. During the product development process, various actors are involved and communication problems deriving from the different individual training and experience can emerge. The main consequence is the loss of the original design intent. This is particularly evident in two different design situations: when the designer realizes a physical prototype and Reverse Engineering (RE) is applied to obtain its digital representation for the following product development phases, and when a product is subjected to Re-Styling (RS) in order to satisfy new emerging requirements.
Our research is focused on the definition of a well-structured methodology for free form surface reconstruction based on the recognition of the aesthetic features. Such features and their use in surface modelling can enable users to coherently and easily modify the model in the next design stages preserving the design intent. In this paper the CAD modelling operators are defined and their experimentation is applied on several industrial test cases related to reverse engineering and restyling.

Keywords: communication and collaboration, design intent, aesthetic feature, modelling strategy

1 INTRODUCTION
The design of aesthetic products is a set of complex and iterative decisional processes which involve different skill and which are influenced by multiple factors such as the evolution of taste, marketing requirements, ergonomic satisfaction, technical design constraints and manufacturing constraints. Due to the heterogeneity of actors with different insights, tacit knowledge and expertise, communication problems deriving from the different individual training and experience can emerge. Numerous design iterations and aesthetic errors are due to the difficulty to understand and preserve the design intent from the first conceptual phases to the following engineering developments.
This is particularly evident in two different design situations: when the designer realizes a physical prototype and Reverse Engineering (RE) is applied to obtain its digital representation for the following product development phases, and when a product is subjected to Re-Styling (RS) in order to satisfy new emerging additional requirements.
RE refers to the activity of creating 3D CAD models of existing physical objects [1]. The RE process is performed by using 3D scanners and dedicated CAD software packages to reconstruct the geometric model. The output of the scanning phase is a dense set of points, called cloud of points, that is the input for the geometric model reconstruction phase. If, during the surface reconstruction activities, the prime aesthetic properties of the physical prototype get lost, the full design intent related to the product may be frustrated; as a consequence, a high number of design iterations are required to achieve a compromise between the designer requirements and the technical ones.

Re-Styling refers to the activity of re-designing existing products in order to improve the product functions and aesthetics, to update the product from a technological viewpoint, and to meet the new quality standards, etc. [2]. RS starts by the recognition of the product properties that must be preserved and of those that must be changed. The product model must be reconstructed in order to meet the additional requirements. If the designer is not involved in the RS process, the design intent may be lost and the process could fail.
We define the design intent as the set of design values represented by the styling lines sketched in the early stages of the design and, hence, they become the set of shape features (aesthetic features) that must remain unchanged throughout the product development process. The aesthetic features determine the expressiveness of the product: they provide visual clues for perception and pattern recognition [3].
From an operational point of view, we define an aesthetic feature as a parametric description of a shape, containing the styling curves, the set of parameters and attributes that define them, and the aesthetic constraints that allow the modelling of the shape according to the concept-synthesizing process the designer adopts to generate creative ideas.
Such features and their use in surface modelling can enable users to coherently and easily modify the model in the product development stages.
The main scope of our research is to analyse the ideation process to recognize and formalize the aesthetic knowledge in order to support the reconstruction activities both in the RE and RS processes. The aim of the present work is the definition of a method both to identify the styling curves and the creative strategies used by the designer to conceive the product form and to model/reconstruct the product shape by using the recognized aesthetic features.
Our approach is based on the following considerations. The majority of design iterations is due to the difficulty of communicating the design values between the industrial designer and the CAD expert. Consequently, the RE and the RS processes have to be analysed from the communicative point of view in order to recognize the mechanisms and the channels for the transmission of the design values. Misunderstandings can be avoided by identifying a set of coding/decoding rules to link the design knowledge used to conceive the product design with product shape descriptors. More specifically, the application of these rules results into the formalisation of the design intent in terms of styling curves and modelling strategies, important to convey the 3D product form.
The proposed method can be synthesized into three main phases:

1. at first we extract the styling curves from the digitised model. A semiotic perspective is adopted in order to extract the design contents, whose articulation and choice constitute the whole sense of product shape, and to investigate how these contents are structured in the specialized modes of representation (the early sketches, the textual notes, the detailed sketches, the physical prototype, the digitised model and finally the CAD model for manufacturing);
2. subsequently, a cognitive perspective is used to analyse the generation/synthesis process in order to identify the ways of form generation that define the design intent;
3. finally, we translate the form generation ways into those modelling strategies useful to convey the 3D model by using the styling curves. The set of shape parameters and constraints is defined in order to manage the product modifications coherently with the design intent.

The proposed approach is illustrated using the re-styling of the well-known chair "Intervista" of Lella and Massimo Vignelli that was first subjected to RE and then to RS by a group of design engineering students. In the second phase, the approach has been tested on three real industrial problems in order to verify usability and timesaving.
The paper is structured as follows. Firstly, we analyse the RE and the RS processes in order to identify the common problems that run into the validation phase and how the proposed method can solve them. The purpose of the following section is to define what we mean by aesthetic feature and its role in the design process. After analysing the design contents, the channels for their transmission and the generation strategies to concretise them in the product shape, we describe the general method used to support the identified critical processes by identifying the styling curves, recognizing them on the digitised model, using them to reconstruct the surfaces by adopting the defined strategies and finally by imposing geometrical constraints to manage the following modifications. The preliminary experimental results are then presented and discussed.

2 REVERSE EGINEERING (RE) AND RE-STYLING (RS) PROCESSES

Industrial designers, despite the large diffusion of CAD systems in all productive fields, still prefer to follow the practice that the creative idea, conceived during the conceptual design phase, can be represented with the necessary freedom only by hand-made sketches [4]. Conceptual sketches and abstract diagrams seem to be able, more than any other medium, to characterise the designing process. Designers are able to see information in their sketches: they have a central role in the phenomena of emergence and interpretation [5]. New images are formed in the designer's mind by transforming, adding or developing previous sketches. Sketching activities include finding, adapting and combining new forms with previously learned shapes and structures, for example from design studio experiences, and case studies [6]. The act of drawing is important not only as a vehicle for communication; it actually helps designers to see and understand the forms they are working with [7].

The sketched idea, then, is usually converted into a physical prototype. Designers prefer to realize full-scale hand-made physical mock-ups that match the impressions and emotions indicated by the corresponding sketches on paper. They are made in order to actualise the ideas of the drawings, to evaluate the spatial effects of complex topological shapes and to assess the final product shape. The RE process becomes fundamental to obtain usable digital models.

The RE process in industrial design can be subdivided in the following phases: the physical prototype acquisition by using a 3D digitising system, the elaboration of the cloud of points in order to eliminate the noisy data and prepare it for the subsequent operations, the surfaces reconstruction to define the exact geometry of the digital model, the product engineering to meet the production and functional requirements, and, finally, the virtual product model validation performed by the stylist and the whole design team.

Surfaces reconstruction errors, mainly aesthetic errors, are due to the poor quality of initial styling information and to the large amount of data that has to be managed, which often can be noisy, sparse or incomplete. The high density of data and/or their incompleteness can hide aesthetic and functional features from the CAD expert who is forced to make autonomous modelling choices, pursuing the least time-consuming approach. Furthermore, the CAD model is subsequently modified in order to satisfy technical, functional and manufacturing requirements. This generally causes several process iterations in order to preserve the initial designer's intentions during the validation phase of product model. Therefore, only if the reconstructed model is coherent with the design intent, the validation phase can be successful. We argue that the process iterations can be avoided if the designer intentions are made explicit to the CAD expert during the surfaces reconstruction phase by extracting the aesthetic properties of the physical prototype from the cloud of points.

It is worth to notice that another critical process in the design development is the re-styling of existing products. When a product, which has been very successful on the market and represents the brand of the company, must be innovated due to the emerging market needs, it is generally re-designed. It can be improved in terms of additional functions, less expensive manufacturing processes or innovative materials, of eco-sustainability, of compliance to new standards or of style in order to be more attractive to the consumers. As current researches [8] have demonstrated, emotions play a decisive role in the customer decision-making process: preserving the design intent in the re-styling process is very important in order to maintain those aesthetic properties of the product shape that previously have appealed to the emotions of the consumers. RS can be performed by the designer or by the engineering staff of the company that manufactures the product. In the second case the company staff makes individual choices in the RS: the design intent may be lost due to the difficulty of identifying the design intent and modifying the product shape according to it.

The first RS step is the elaboration of a 3D CAD model. This is not a trivial task if the company does not have the original CAD model, or when the model lacks the necessary information to allow the aesthetic features recognition and their following modifications. This can be due to the fact that the model is stored in neutral formats, such as IGES, STEP, STL, etc. In the first case it is necessary to perform an RE process. In the second case the CAD model has to be elaborated in order to extract styling curves, modelling strategies and design parameters. The possibility of a loss of design intent in the RS, in respect with the original product design, leads to the problem of product model validation: the model needs to be submitted to the designer that can accept or reject the modified shape.

We argue that the analogy between RE and RS consists in the common properties of the cloud of points and of the CAD model that must be elaborated in RS. Both of them implicitly contain the aesthetic information that must be extracted in order to manage the design modification while the design intent is preserved. As a consequence, in this paper we will not distinguish between the first and the second type of virtual model: we will generally speak of 3D data sets.

3 AESTHETIC FEATURE AND ITS ROLE IN THE DESIGN PROCESS

In order to solve the RE and RS problems, two different approaches are proposed by literature [9]: *Design by Feature* and *Feature Recognition*. Although the *Design by Feature* approach can support the creation of aesthetic shapes by supplying the designer with those features that reflect the way by which he conceives the product form, the available CAD tools are not yet adequate to model free form shapes and intuitively control them in the first conceptual phase [10]. We believe that the *Feature Recognition* approach is more useful to manage RE and RS problems. In this case, it is possible to apply available CAD modelling rules to recognize styling curves, fit surfaces and set design parameters, as proposed by Ke [11].

The methods for aesthetic features recognition, starting from the analysis of 3D scanning data, are a widely explored topic in the CAS/CAID (Computer Aided Styling/Computer Aided Industrial Design) research community. Thompson et al. [12] proposed and implemented a method to recognize features from scanned data, but is application was limited to regular features. Recently, Langerak [13] studied an approach for recognizing free form features by using two different methods: template matching and feature line detection. In the first method he proposes an approach that uses shape matching to find regions on the digitised data that resemble the shape of a feature shape template. He establishes a set of independent template parameters to progressively search the shape similarity between a shape and an instance of template. The second approach is based on a slicing strategy to extract 2D profiles by taking as an input a feature library that is assumed but not defined. The method automatically performs RE activities but does not specify how the user chooses the intersection planes orientation to extract the features. As mentioned before, Ke [11] proposed a possible reverse engineering approach based on a 2D sketch space and traditional surface modelling rules such as extruding, revolving and sweeping the 3D profiles. In order to extract the layered sectional profiles the slicing technique is applied to the unorganised cloud of points, then he estimates discrete circular curvatures and derivatives at the points contained in the interested sectional profiles. The recognition of the slicing planes orientation and the classification of the aesthetic features is strictly dependent on human expertise. Consequently, we argue that if the expertise is not formalized, the choice and the identification of the aesthetic profiles depend only on the sensibility of the CAD experts. The RE/RS processes may be affected by interpretative errors and they could be re-iterated.

In our previous research [14] a 3D problem is simplified into a 2D sketch approach. The functional definition of the product allows the identification of the planes and of the 2D curves characterising the aesthetic regions of model shape. The strong user dependency of the method makes it difficult to objectify the design intent recognition on the points cloud.

On the other side we observed that the styling curves extraction is not the only useful element in the reconstruction process but also the identification of the proper modelling strategy to fit surfaces and the corresponding design parameters is very important. This paper represents a step forward in the achievement of the second task with regard to our previous researches [15]. It is worth noticing that in order to preserve the design intent, the modelling strategy used to fit surfaces should reflect the process of design idea generation: in fact, it affects the way of free from shape modification during the subsequent engineering phases.

4 THE FORMALIZATION OF THE DESIGN INTENT: THE APPROACH

By analysing the techniques and procedures of the creative design, Cross [16] identified four main descriptive models of idea generation: combination, mutation, analogy, emergence and first principles (figure 1). The choice and the combination of design strategies have several implications for CAD modelling. For example, in mutation, he underlined the necessity of the identification of which features of the existing design must be selected for modification or how the product behaviour can affect the deformation process. In analogy, the difficulty is in abstracting the appropriate features of an existing design or natural shape in order to create the product model.

Figure 1: the four descriptive models of creative design: design principles and applicative examples in industrial design

On the basis of these models, our approach adopts a cognitive and a semiotic perspective for recognizing the creative ideas on a 3D datasets and for defining a method to support the communication of the design intent through the various product development stages.

A cognitive perspective tracks the design process in order to link the design meaning with the geometric properties of the product shape for the identification of the styling curves and to recognize the creative strategies used to conceive the 3D product shape.

From the cognitive standpoint, the design process can be modelled through a framework made of perceptual and conceptual levels, containing logical structures and mental images, which are externalised by the designer through free-hand sketches and textual notes. Thinking, problem solving, reasoning, etc. are viewed as sequences of "cognitive states" that link a collection of "images" in two modalities: the perceptual and the conceptual one. Recalling previous designs and external world images suggests possible solutions, frameworks and design strategies. This is the first level of the ideation process. The perceptual level consists of several free-hand sketches as design elaborations of the external images and previous case studies. That phase structures the design space (domain).

In the conceptual level the designers define the design values drawing relationships between signs and concepts.

The semiotic viewpoint is helpful to interpret the structures of sketches, to understand how and to what extent product ideation can be conceived as an act of signification, how its results are affected by the interpretations of communicating actors, how concepts are linked to signs on paper and to recovery the generation/synthesis strategies.

Our operational approach starts from the definition of aesthetic feature and of its role in transmitting and understanding the message revealed in the product shape. Aesthetic features represent those characteristics and attributes of the shapes that allow the recognition of the style of certain products. In fact, style can be identified by the presence of recognisable features (forms) that appear in certain products designed by an individual or a group of individuals in a certain historical period and geographical area. As mentioned above we consider an aesthetic feature as a parametric description of a shape, containing the styling curves, the set of parameters and attributes that define them, and the aesthetic constraints that allow the modelling of the shape according to the concept-synthesizing process the designer adopts to generate creative ideas.

The design intent is generated by applying form, generating strategies, geometrical and functional relationships between forms, and by repeatedly using a set of prominent forms. This can be translated in the set of aesthetic features that remain unchanged throughout the product development process: the styling curves, the relationships between them (aesthetic constraints) and the strategies to combine them in fitting surfaces.

Free-hand sketches have a central role in the identification of the aesthetic information. We consider the sketches as a set of implicit and explicit features.

The explicit features are expressed as annotations, generally contained both in the early and detailed sketches. They may specify functional conditions (geometrical and dimensional) and generic product attributes (colour, material, number of interfaces, etc.).
The implicit features are the translation of creative and functional concepts in graphic signs in the hand made sketches (figure 2). These signs contain both the styling curves, meaningful for the shape definition, and the main specifications to understand and computationally replicate the process of form generation.
The design solution evolves as the designer switches from the conceptual level to the perceptual level. Concepts and sketches are strictly linked: the first ones stimulate the development of the others and vice versa. The evolutionary study of the sketches, (from the early sketches to the last measured and detailed drawings), of the related textual notes, and graphic symbols allows the creation of a relation between the product form and the design contents, between geometry and the product attributes. The achievable result is a set of interpretative schemata of the design intent in terms of styling curves and of relationships between them to fit surfaces.

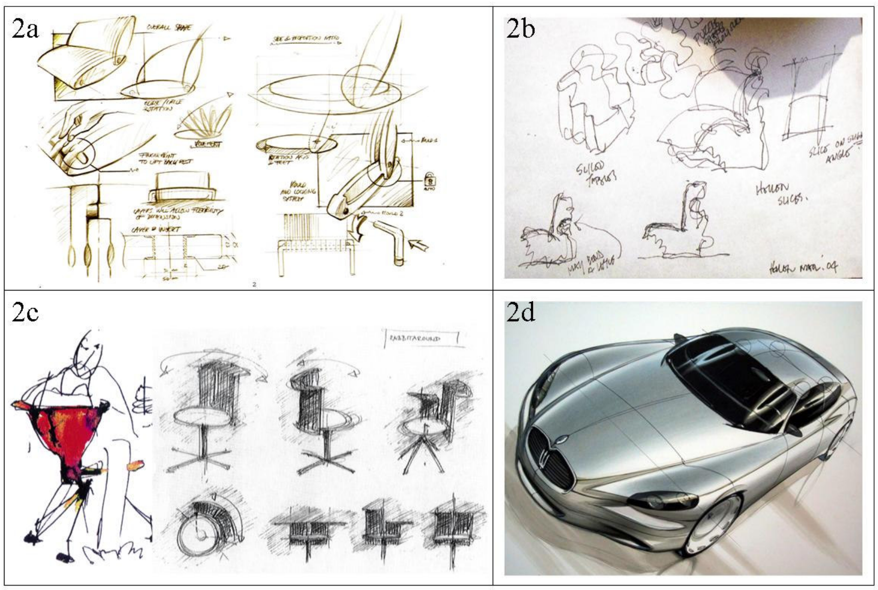


Figure 2: Examples of hand made sketches. In figure 2a (Double up chair by the Design Laboratory) the sketches reveal details of the structures and the main features of the backrest zones. Figure 2b (Easy chair by F.Gehry) points out that annotations are also contained in the early conceptual sketches. Figure 2c (Turnaround office armchair by U.Hasenbein) shows that annotations are also characterized by graphic symbols. Figure 2d (Maserati Quattroporte by Pininfarina) demonstrate how sketches express the design contents (sportive car) through the styling lines.

5 THE METHOD: STEPS AND TOOLS

The different steps that lead to styling curves extraction and modelling strategy definition are:

- extraction of the styling curves from 3D datasets;
- creation of a 3D skeleton of styling curves and grouping of them in accordance with the recognized way of design idea generation;
- translation of the generation/synthesis processes into surface modelling strategies and identification of the design parameters and constraints to manage design modifications.

5.1 Extraction of the styling curves from 3D datasets

We briefly summarize the main steps of styling curves extraction through the analysis of free-hand sketches.
Different types of drawings are associated with different stages of the design process. In the early stages of designing, the sketches are essential. The industrial designer identifies clues that can be used

to form and inform emerging design concepts. The designer uses a series of rapid sketches to generate images in his mind, to elaborate case studies and to adapt them to the specific design problem. They are abstract, vague and diagrammatic. Their ambiguity stimulates re-interpretation. They are characterized by monochrome line drawing without shading or colours. They have a uniform thickness.

The second set of sketches is a transformation of the first ones. The designer modifies the early sketches by adding, deleting or varying the initial curves drawn on paper. He generally varies the line thickness of the sketched curves. The designer highlights the lines that better match the design ideas, while the others are modified. These types of drawings may include brief annotations such as the main dimensions of the product parts.

The final sketches are detailed and measured drawings. They contain all the necessary dimensions and annotations that allow the creation of both physical prototypes and digital models of the product design.

By observing several hand-made sketches realized in different stages of the design process, we infer that:

- different free hand sketches reproduce the designer ideas as they evolve in his mind;
- the free hand sketches implicitly represent the designer's intentions;
- form curves appear in all different types of drawings: they are modified during the design evolution. The designer generally increases the thickness of the styling curves that better concretise his/her ideas;
- the freehand sketches contain textual annotations to communicate and clarify the design contents;
- the final sketches differ from the previous ones for the increased level of details;
- the visual assessment of the sketches evolution and their comparison show that there are some lines that remain unvaried. They are the styling lines as defined by Tovey [17]. These invariant lines are all articulated in the final sketches, while in the early drawings they do not contemporary appear. They may occur in different stages of the design process as soon as the design ideas lash-up in the designer's mind [18];
- the final sketches realized on orthographic/cross sectioning views, are the outcomes of the design reasoning activities. Therefore the sketches represent the result of the bedding and joining of the meaningful signs drawn in the previous sketches;

The result of the design observation is that the styling lines look like the invariant elements in the evolution of the free-hand sketches. The design intent formalization starts by searching these invariant lines, whose articulation generates the interpretative schema of the digitised data.

From these general considerations, we define the main steps to carry out the extraction of the styling curves from the 3D datasets:

1) To measure the similarity between the early sketches and the final ones. The Chalechale method [19], based on angular partitioning of two images, is adopted to extract the invariant curves between the first diagrammatic sketches and the detailed ones that are all scaled in accordance with the 3D dataset dimensions. The articulation of the invariant curves in the same reference plane generates the interpretative schemata. We obtain a number of interpretative schemata equal to the number of final sketches. Textual notes and graphic symbols play a crucial role in right scaling and positioning both free-hand sketches in order to extract invariant curves and interpretative schemata in the 3D CAD modelling environment. As they contain annotations about the overall dimensions of the product, they allow the dimensioning of all sketches in accordancewith the 3D datasets measure, as they give information about the reference view to which they are related, they allow the comparison of early and detailed sketches and the recognition of the reference planes in the 3D CAD environment. (figure 3)
2) The replication of the interpretative schemata in the 3D CAD modelling environment. The sketches allow the recognition of the reference planes to which the interpretative schemata are related. The interpretative schemata are positioned in the corresponding plane in the 3D dataset and replicated as B_Spline curves. Each B_Spline curve is characterized by parameters such as the position, the curvature and tangency of the control points.

3) The extraction of the styling curves. Each 2D B_Spline curve is projected on the cloud of points along perpendicular directions to the reference planes. The projection of the interpretative schemata detects a set of points that are imposed as the control vertices of the 3D styling curves. The result is a set of styling curves on the 3D dataset.

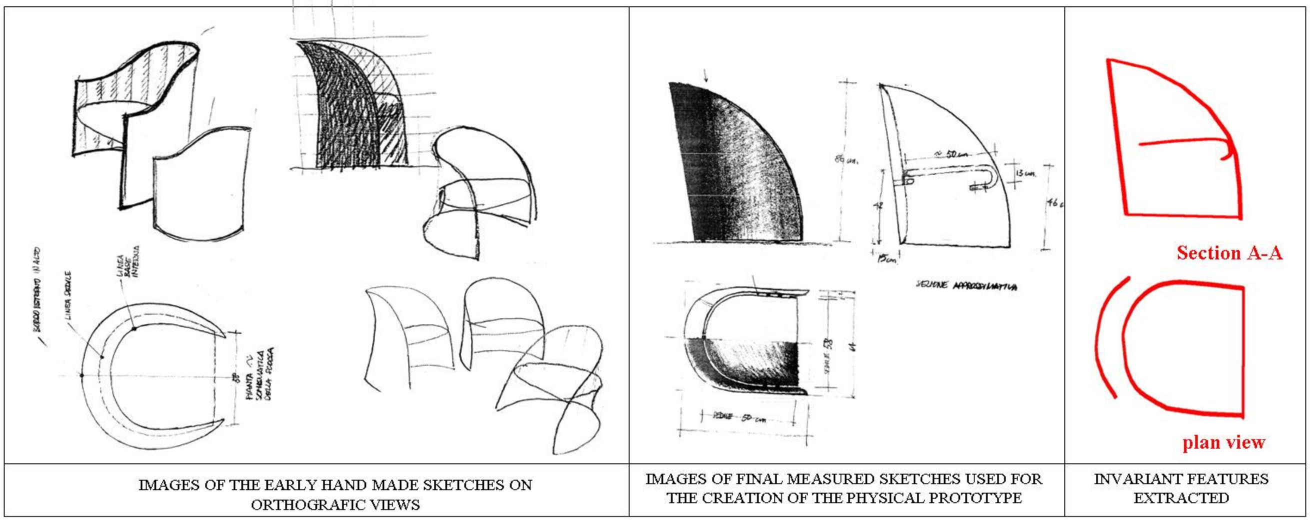


Figure 3: Searching for invariant curves (interpretative schemata) in the "Intervista" product. The early sketches are compared with the detailed ones in order to recognize the styling curves on the 3D dataset. The interpretative schemata are extracted in the same reference planes of the final sketches.

5.2 Creation of the 3D skeleton

The characteristic curves and character curves on the 3D model are meaningful geometric elements for aesthetic features definition. The first ones are tangible curves, such as boundary edges, internal edges and fillets edges. The second are only visually perceived. They are the styling curves meaningful for conceiving the 3D product model. Furthermore, there is another type of curves that is important for surface modelling but without a specific aesthetic meaning: they are the cross-sectioning curves. They can be extracted by sectioning the 3D dataset with perpendicular planes to the character curves. They are low-level geometric elements that are related to the styling curves and allow a direct control of the product shape. They are particularly useful when the projected schemata do not perfectly coincide with the visually perceived styling curves on the 3D dataset. The lack of the correspondence can be due to small errors that may occur in the extraction of the interpretative schemata from the final sketches.

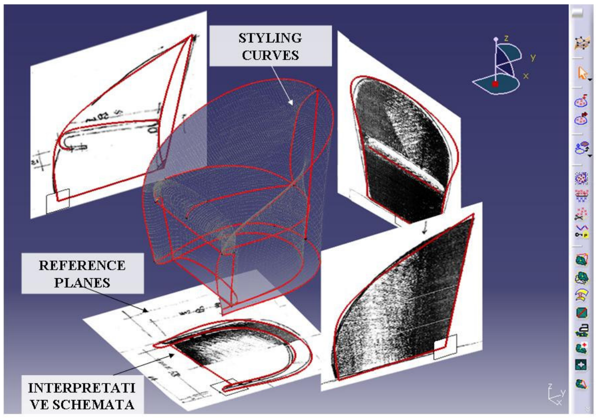
The 3D skeleton results from the extraction and elaboration of styling curves, characteristic and cross-sectioning curves. All curves are smoothed in order to avoid noisy data and reach the required degree of surfaces' quality.

For complex free form shapes, all extracted curves should be grouped into smaller sets of curves in order to allow the easy management of the surface modelling. Each group represents different aesthetic and functional parts of the product model.

The free-hand sketches are still useful to assembly these curves: for example, designers draw arrows to indicate relationships or movements of the product parts: in this way the main functions and instructions for the use of the product are defined. It is possible to identify the main functional parts of the product. Designers usually label design concepts and parts names in their drawings. Furthermore, by adding colours in the sketches can be useful to identify parts with different aesthetic properties.

The extracted curves must also be grouped in accordance with the identified modelling strategies: it is necessary to identify which curves belong to each strategy and their role in it.

As the modelling strategies correspond to different ways of idea generation, each group of curves reflects the aesthetic and functional properties of the product design. Therefore, the grouping of 3D skeleton curves in accordance with the modelling strategies is coherent with the designer intent. (figure 4)



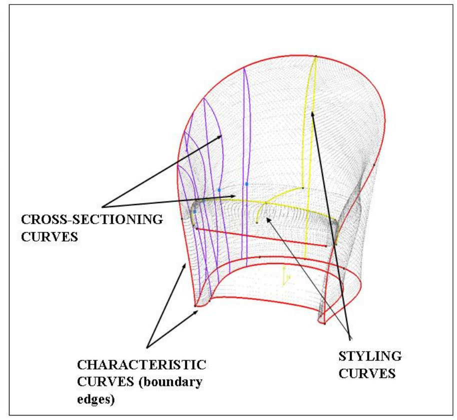


Figure 4: Extraction of the styling curves, characteristic and cross-sectioning curves from the 3D dataset

5.3 The translation of the form generation process into the set of modelling strategies

Our assumption is that the result of the parametric surface modelling and the coherence of the CAD model's modifications to the design intent, strictly depend on the type of the strategy used to realise a surface and on the hierarchical chain of operations used to the whole surface model.

In the context of free form shapes, two of the prescriptive models of creative design proposed by Cross, are representative of organic shapes: mutation and analogy.

Mutation can be realized by applying different transformation actions:

- fusion or melting: when two or more forms are combined and their edges are strictly interconnected. It is not possible to distinguish when the first form ends and the second begins. The product form is the result of the interaction between the original shapes;
- global deformation: when a form is modified by applying forces along different directions and with different weights;
- morphing-like deformation: when a shape is generated based on the weighted average of two other existing shapes.

In all mutation strategies, the problem regards the definition of which surface entities are subjected to deformation and of the constraints that will drive the deformation. The choice of the firsts influences the seconds. Catalano [20] classified the free form features by defining three different types of deformations and related constraints: point-driven deformation, curve-driven deformation, surface-driven deformation. In order to apply the deformation operation, it is important to translate the mutation strategy into CAD modelling operators and for each operator to identify the parameters and constraints of the entities used to fit surfaces.

In creative and conceptual design, designers often refer to books, magazines, and other collection of images to find forms they can adopt and adapt in designs. They use references – images of natural and artificial world from rocks and flowers to boats and buildings, internal images that come from their experience of reality– as visual analogies and metaphors. All images are arranged in different ways according to the design values they aim to communicate trough the product shape. The use of precedents and analogical reasoning are strategies on which designers rely heavily. Sketches analysis can be useful to retrieve these images and recognize the terms of similarity.

Analogy is a key point in the idea generation process in many works of contemporary designers (Karim Rashid, Future Systems, Frank O'Gehry, Michael Graves, Massimiliano Fuksas, Philippe Starck, etc.)

Nowadays analogy may be used in terms of similarity both between the product shapes and natural forms, and between organic processes and form generation processes.

As analogy can be defined as the process of relation between two entities, a possible classification of analogical reasoning strategies starts from the identification of the terms of similarity:

- analogy between forms;

- analogy between open or close sections.

In the first case, the analogy can be created by morphing two forms: the first can be retrieved from a 3D library where the designer collects interesting forms, case studies and previous works, the second can be a primitive shape or a low elaborated shape. The problem is related to the definition of the relationships between geometrical properties of the initial and the target forms: key reference points or curves. This generation process is similar to the morphing-like deformation process in mutation.
In the second case, when two forms are similar in the morphology of some section curves, it is important to identify the process through surfaces have been generated from these sections:

- process of sliding of one section along another, or process of translation, rotation, extrusion along a direction;
- process of joining and connecting multiple sections.

The existing feature-based CAD tools difficulty support the design of free-form features obtained by using one of the mentioned generation processes, because they allow only the transformation of existing surfaces by arbitrary changing the position of the control points. It is difficult to identify the proper CAD modelling strategy to be adopted to fit surfaces, the hierarchical chain of operations to be used to the whole product model, which entities and parameters can be modified, which constraints can be used to express the aesthetic properties of the shape. Tables 1 and 2 try to map the ways of idea generation with available CAD modelling strategies.

The ways of idea generation	Entities subjected to deformation or to analogical reasoning	CAD modeling strategies operators
MUTATION BY FUSION AND MELTING	Closed or opened curves (curve driven deformation)	- GRID or PATCH
MUTATION BYGLOBAL DEFORMATION	Anchor points or the grid that contains the surface or control points (point driven deformation or surface driven deformation)	- PATCH
MORPHING-LIKE DEFORMATION OR ANALOGY BETWEEN FORMS	Key reference points or closed/opened curves (definition of the correspondence between the initial and the target surfaces)	- GRID or PATCH
PROCESS ANALOGY (TRANSLATION, ROTATION, SLIDING OF ONE SECTION ALONG ANOTHER, EXTRUSION OF CLOSED/OPENED SECTIONS)	Opened curves	- LINEAR SWEEP - REVOLUTION SWEEP - SWEEP ON ONE RAIL - SWEEP ON TWO RAILS
PROCESS ANALOGY (MELTING, CONNECTING AND JOINING MULTIPLE SECTIONS	Closed or opened curves	- LOFT OF OPENED CURVES - LOFT OF CLOSED SECTIONS

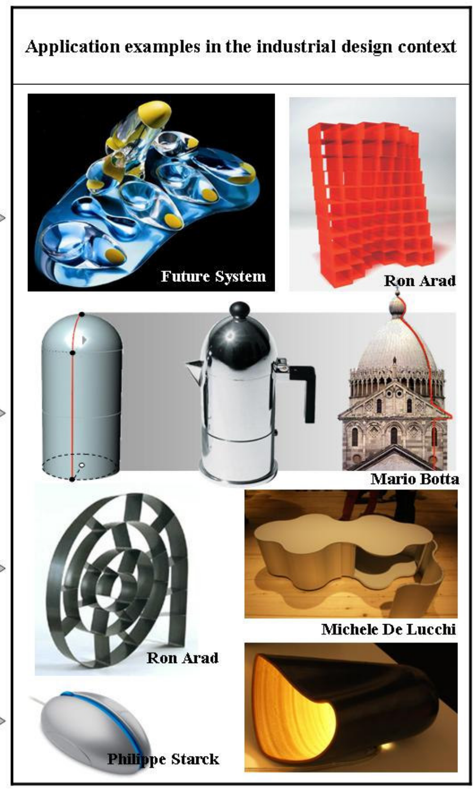


Table 1: Classification of the creative process of free form generation. Mapping with 3D CAD modelling strategies.

Free-hand sketches evolution analyses are very useful to understand designer's intentions and the ways of free form shapes generation. For example, designers draw arrows and lines to indicate the main directions of the orthographic and sectional views, the main movements or relationships between the product parts. They also draw lines characterized by conventional styles to signify symmetry axes, parallel planes, perpendicular lines, etc., but also trajectories of sliding, of translation, etc. They use to underline key reference points or curves. Designers, who prefer aesthetic proportions and balance, sketch lines to form grids that may constitute geometrical constraints for the following engineering developments. The use of big arrows generally indicates the weight of the forces that are applied to the shape. They usually write words, stick images, make collages, in order to recall precedents and meaningful reference images. Finally, designers write numbers to prescribe the overall dimensions, the product parts interfaces: this type of data is necessary not only for scaling the sketches in order to extract the interpretative schema from them, but also to identify parameters and constraints, such as position parameters, dimensions, angles of revolution, etc.

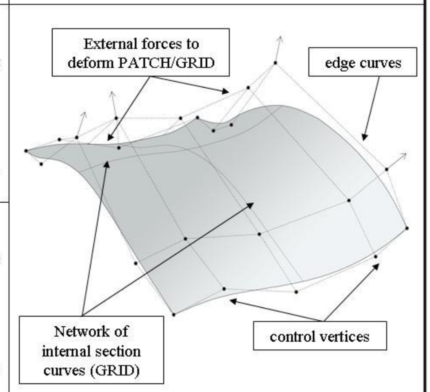
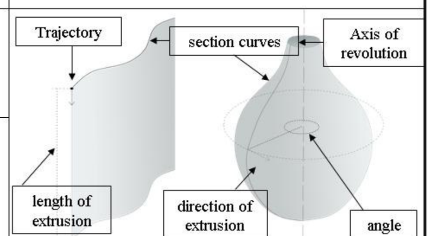
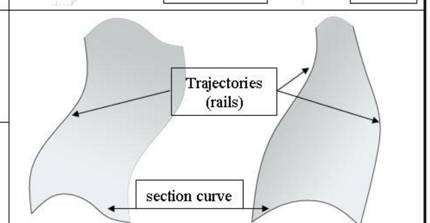
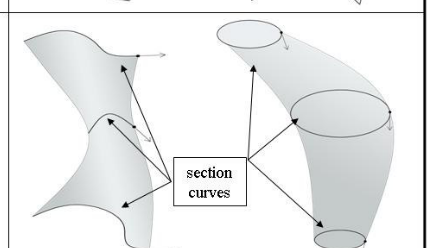
CAD modeling strategies operators and types of target surfaces	Geometric entities engaged in the modeling strategy	Parameters and constraints for the control of shape modifications	Examples
PATCH	Definition of the 4 edges of the patch as B_spline curves	-Position and number of the control vertices -dimension of the external grid of points -direction and weight of the external forces -continuity condition between adjacent patches (boundary conditions) -position, tangency and curvature of the control vertices of the edge curves	
GRID	Definition of a network of section curves	-Position and number of the control vertices -dimension of the external grid of points -direction and weight of the external forces -continuity condition between adjacent patches (boundary conditions) -position, tangency and curvature of the control vertices of the edge curves	
LINEAR SWEEP (generates a sweep-like surface)	-definition of the profile (section curve) as a B_spline curve -definition of the extrusion direction	-Position and tangency conditions of control vertices of the B_Spline curves -Boundary conditions - Length and direction of extrusion	
REVOLUTION SWEEP (generates a revolution-like surface)	-definition of the planar profile as a B_Spline curve - Axis of revolution (curve or a line) (position and orientation)	-Position and tangency conditions of control vertices of the B_Spline curves -Boundary conditions - Angle of revolution	
SWEEP ON ONE RAIL (generates a sweep-like surface)	-definition of the profile (section curve) and of the rail (trajectory curve) as B_spline curves	-Position and tangency conditions of control vertices of the B_Spline curves -boundary conditions	
SWEEP ON TWO RAIL (generates a sweep-like surface)	-definition of the profile and of the two or multiple rails as B_spline curves	-Position and tangency conditions of control vertices of the B_Spline curves -boundary conditions	
LOFT OF OPENED CURVES	- definition of the section curves as B_spline curves	-Position and tangency conditions of control vertices of the B_Spline curves -boundary conditions	
LOFT OF CLOSED SECTIONS			

Table 2: CAD modeling strategies using commercial CAD/CAID systems. Definition of the parameters and constraints to control shape modifications for each strategy.

Once the styling curves have been extracted and grouped according to the aesthetic properties of the shape, the choice of the modelling strategy starts from the analysis of the sketches evolution in order to search for the geometric entities that should be engaged in fitting surfaces. For example, if a revolution axis and a styling curve nearby are identified in the sketches, the revolution sweep strategy has to be adopted, or if the product shape results from the deformation of a grid of curves, the grid strategy may be the best to fit surfaces. As we have defined possible parameters and constraints to manage modifications for each strategy, the whole parametric model is achieved by identifying the proper chain of CAD operators. (figure 5)

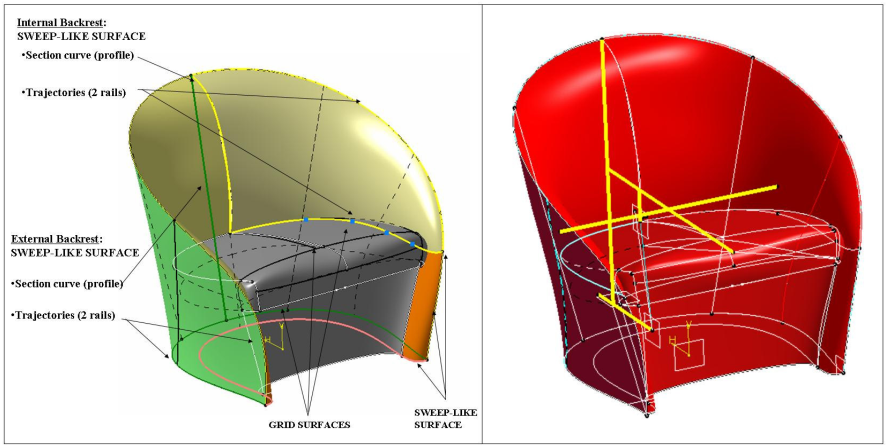


Figure 5: Grouping the extracted curves in accordance both with the modelling strategies and with the aesthetical and functional properties of the product parts..The parameterization of "Intervista" surface model. As the balance among the product parts represents one of the designer's intentions, shape deformation is constrained to a grid (yellow lines in the figure at right) that was drawn on the early sketches. The restyling process is due to the need for an improvement of the ergonomic characteristics: enlargement of the dimensions of the seat, lowering of the backrest.

6 EXPERIMENTAL RESULTS AND CONCLUSIONS

The design of two new products (mouse and telephone, figure 6) and the restyling of an armchair (BiBi by Massimiliano Fuksas, figure 7) have been developed in collaboration with two Italian companies in order to validate the methodology in terms of usability and time savings. In the first case the reverse engineering process has been applied to convert the physical prototypes into digital models; in the second case the CAD model of the existing product has been used as reference to re-design a new office armchair. The method has been applied using CATIA v.5; some specific functionalities have been implemented simply in order to semi-automate the proposed approach.

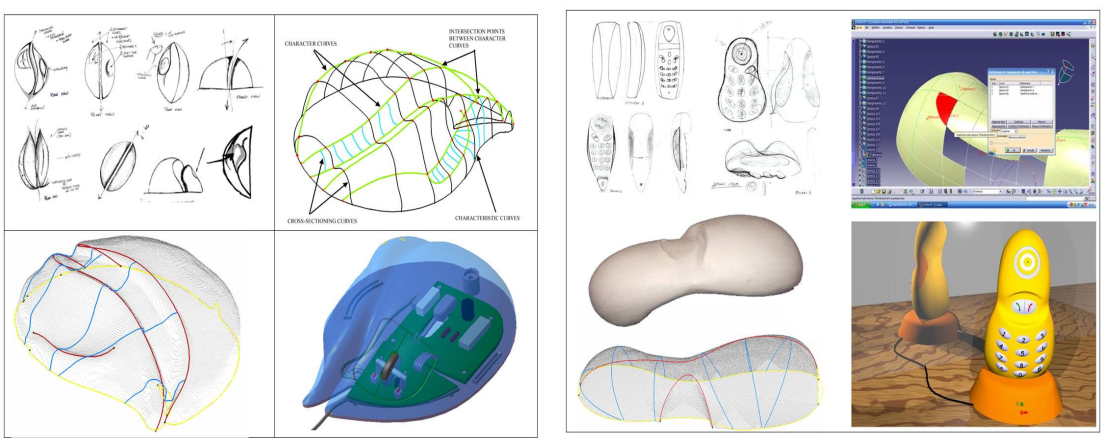


Figure 6: From left to right, a mouse and a telephone prototypes.

A list of metrics has been established to evaluate the efficiency of the proposed method. The metrics are mainly related to the time needed for the surfaces reconstruction and product validation phases. We also assess the number of hours needed for prototyping new physical mock-ups when validation fails and it is necessary to re-engineer the product model. We evaluate the hours for CAD model modifications after the product engineering phase (evaluation of the correspondence between the designer intentions and the final product shape). In order to assess the validation metrics, design processes performed with traditional RE techniques are measured.

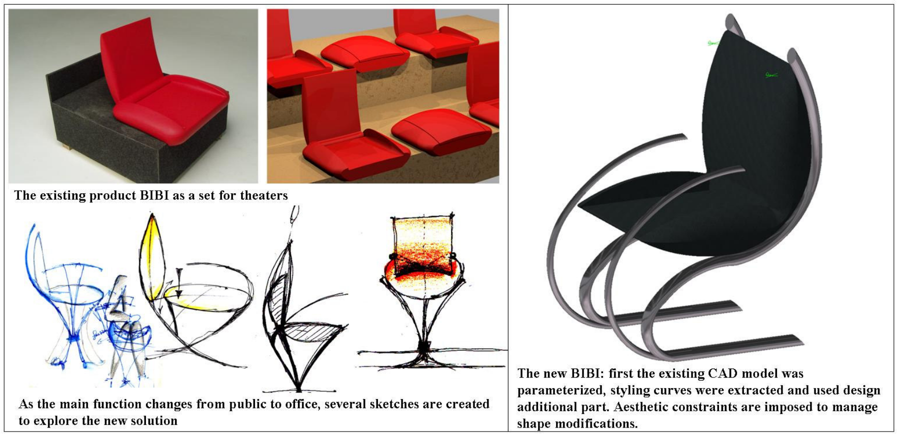


Figure 7: The BiBi restyling.

		Surfaces reconstruction or CAD modelling time	Time for physical prototyping for the final approval (number of physical mock-ups)	Time for surface reconstruction of the new mock-ups	Validation time (hours)	Number of modelling hours for CAD model modifications	TOTAL HOURS FOR PRODUCT DESIGN
Armchair “Intervista”	Traditional RE/RS process	6	10 (2)	12 (6 hours for each prototype)	1,25	3	32,25
	RE/RS performed by the proposed method	9	5 (1)	0	0,5	1	15,5
Mouse prototype	Traditional RE process	6	4 (2)	12 (6 hours for each prototype)	1	5	28
	RE performed by the proposed method	12	0	0	0,6	2	14,6
Telephone prototype	Traditional RE process	6	2 (1)	4 (2 hours for each prototype)	0,3	1	13,3
	RE performed by the proposed method	8	0	0	0,15	0,5	8,65
BIBI chair	Traditional RS process	24	12 (2)	12 (6 hours for each prototype)	2	5	57
	RS performed by the proposed method	20	6 (1)	6	1	2	35

Table 3: Validation results

By analysing the first validation results (table 3) we can infer the following considerations: the modelling time increases because of the addition of more steps such as the recovery of the sketches, the extraction of the interpretative schemata and of styling curves and the analysis of the creative process. The application of our method eliminates the need to construct additional physical prototypes when the validation is not successful and finally design iterations are reduced.

The proposed method is based on the formalization of the design intent into the styling curves and the CAD modelling strategies. The hand-made sketches evolution analysis constitutes the starting point for aesthetic features definition. Four different application examples in the industrial design field have been described. They have been used to demonstrate the approach applicability in the cases of products characterised by complex free form shapes. The method application has shown positive results in terms of increased timesaving, improvement of the model surfaces' quality, and of the accuracy and flexibility of the obtained CAD model, coherently with the design intent.

REFERENCES

[1] Varady T., Martin R. and Cox J. Reverse Engineering of Geometric Models. An introduction.

Computer Aided Design, 1997, 29, 255-269.
[2] Ravasi, D., Lojacono, G., Managing Design and Designers for Strategic Renewal, Long Range Planning, 2005, 38, 51-77.
[3] Chan C.S. Can style be measured?. *Design Studies*, 2000, 21, 277-291.
[4] Van Dick C.G.C. and Mayer A.A.C. Sketch input for conceptual design. *Computer in Industry*, 1997, 34, 125-137.
[5] Menezes A. and Lawson B. How designers perceive sketches. *Design Studies*, 2006, 27, 571-585.
[6] Do E.Y.L. and Gross M.D. Drawing analogies finding visual references by sketching. In *Association of computer Aided Design In Architecture, ACADIA'95, Vol. 1,* Seattle, October 1995, pp. 35-52 (B.Kolerevic & L.Kalisperis Eds.).
[7] Fontana M, Giannini F. and Meirana M. Free form features for aesthetic design. *International Journal of Shape Modelling*, 2000, 6 (2), 273-302.
[8] Norman D.A., *Emotional Design: Why We Love (or Hate) Everyday Things*, Basic Books, 2004.
[9] Mandorli, F., Cugini, U., Otto, H.E. and Kimura, F. Modeling with self Validation Features. *Fourth ACM Symposium on Solid Modeling and Applications, Solid Modeling '97, Vol.1,* Atlanta, May 1997,pp. 88-96 (Morgan Kaufmann Publishers Inc.).
[10] Sèquin C.H. CAD tools for aesthetic engineering. *Computer Aided Design*, 2005, 37, pp. 737-750.
[11] Ke Y., Fan S., Zhu W., Li A., Liu F. and Xiquan S. Feature-based reverse modelling strategies. *Computer Aided Design*, 2006, 38, pp.485-506.
[12] Thompson W.B., Owen J.C., de St.Germain H.J., Stark S.R. and Henderson T.C. Feature-based reverse engineering of mechanical parts*, IEEE Transactions on robotics and automation,* 1999, 15(1), pp.57-66.
[13] Langerak T.R. and Vergeest J.S.M. A new framework for the definition and recognition of free form features. *International symposium on Tools and Methods of Competitive Engineering, Vol.1*, Ljublyana, April 2006, pp.359-370, (Imre Horvat and Joze Duhovnik eds.).
[14] Germani M., Corbo P. and Mandorli F. Aesthetic and functional analysis for product model validation in Riverse Engineering applications. *Computer Aided Design*, 36, 2004, pp.65-74.
[15] Mengoni M., Mandorli F. and Germani M. Surface reconstruction method for reverse engineering based on aesthetic knowledge. In *International symposium on Tools and Methods of Competitive Engineering, TMCE 2006, Vol. 1,* Ljubljana, April 2006, pp.251-262, (I.Horvat and J. Duhovnik Eds.).
[16] Cross N. Descriptive models of creative design: application to an example. *Design Studies*, 1997, 18, 427-455.
[17] Tovey M., Porter S. and Newman R. Sketching, concept development and automotive design. *Design Studies*, 2003, 24, pp.135-153.
[18] Molotch H.L. *Where Stuff Comes From: How Toasters, Toilets, Cars, Computers and Many Other Things Come To Be As They Are (Brochè)*, Routledge , part of Taylor and Francis Books, Inc, 2003.
[19] Chalechale A., Naghdy G. and Mertins A. Sketches-based Image Matching Using Angular Partitioning. *IEEE Transactions on Systems, Man and cybernetics – part a: systems and humans,* 2005, 35(1), pp.57-66.
[20] Catalano C.E., Falcidieno B. and Giannini F. Introduce Sweep features in Modelling with Subdivision surfaces. *Journal of WSCG*, 2004, 12 (1), pp. 81-88.

Maura Mengoni
Polytechnic University of Marche
Department of Mechanics
via Brecce Bianche
I-60131, Ancona, Italy
Phone +39 071 220 4969
Fax +39 071 220 4801
e-mail m.mengoni@univpm.it