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Generative engineering design methodology used for the development of surface-based components

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ABSTRACT
The presented paper introduces a methodology of Generative Engineering Design of surface-based components in the automotive development and its general use. In addition, the required tools for the application of the presented method within complex CAD systems are described and discussed. Application of presented methodology is shown within the development of an exemplary class A surface of a sport vehicle front part. In the context it is shown, that Generative Engineering Design methodology provides an automatic adaptation of detailed design in case of styling modification, leading to automatically recreated linked features, e.g. component boundaries, if designer's styling (CAS) is changed.

KEYWORDS
Generative Engineering Design; surface-based component; class A surface

1. Introduction

The main idea within CAD development was always to provide easier work for design engineers or other users. It is one reason for research activities, which are linked to CAD software, to accentuate simplification of design workload. Easier and more efficient use of CAD systems supports engineers in designing complex models effectively. Which product is one of the most complicated and sophisticated nowadays? It is an automobile. This is caused not only by the development level of powertrain and chassis. Other aspects are also on a high level, even though they do not look very complex on a very first sight. CAD applications help to provide realization of various shapes of car body and its components. Generative Engineering Design, as following step of Parametric Modeling, has been brought to research community's attention [11]. Still, it has not been strictly defined what is Generative Engineering Design and where are boundaries of its application. Apart from Parametric Modeling, Generative Engineering Design offers tools and algorithms for the creation of surface-based components, such as complex shaped components of car body. For example, it enables a heuristic point of view to be broadly involved into the whole development process. The automotive styling process styling is not just a part of initial phases. Demonstrated by some applications, there is wide use of Knowledge Based Design referring to the presented method [9].

2. Description of generative engineering design methodology

During dozens of years in CAD research, there appeared space for improvement of product development in several fields. Firstly, it occurred in architecture and artistic fields. However, later there appeared other areas appropriate to work with advantages of such a method.

In [6], generative design is explained through various automated design and development functionalities. The method described by authors is focused especially on generating multiple variants and alternatives of one proposed product without human intervention. Actually, the publication represents one of the seldom works, which broadly describe the methodology of generative design within product development in CAD software.

The procedure described in the following, refers to Generative Engineering Design methodology of surface-based components. It can be characterized as the ability to generate shape features and their sets through input and output data with evaluation of their relevance in a closed loop. Such a loop is shown in Fig. 1. This procedure allows realization of dynamical solutions and is able to absorb and share information back to the initial process, so that further optimization can be accomplished. Deterministic and heuristic features of engineering design are applied during the preparation of this process. According to previous efforts, several definitions have originated in the field of automatized designing. For the purpose of

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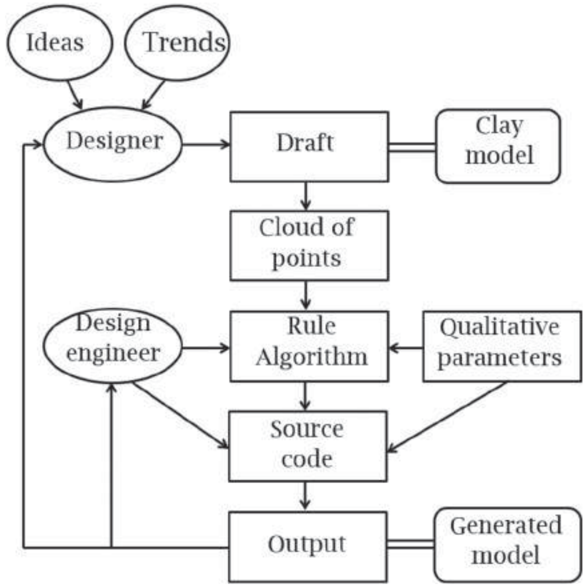

Figure 1. The loop of Generative Engineering Design procedure within the designer-engineer cooperation.

Generative Engineering Design described in this paper, it is possible to abstract the following definition:

Generative Engineering Design is a process in which the draft or model is made based on quantitative and qualitative parameters or aesthetic inputs, using algorithms created by individual human intervention for the purpose of generating a variable set of subsequent models following accurate relations and according to hierarchical connections.

Even though they may appear similar, the fundamentals of Generative Engineering Design are in principle different from Parametric Modeling. Generative engineering relies partly on generic parametric models. Parametric models are numerically controlled deterministic representations of design solutions, which result in a new product with similar geometrical values (quantity indicators such as dimensions, weight etc.), but dissimilar quality characteristics (e.g. aesthetic indicators, subjective user requirements and needs). This means that generative design in context of new design and innovation processes offers more than purely geometric modelling. It offers a whole complex of information about a new product, which has not only a deterministic nature, but also a heuristic one.

Some terms are used in this manuscript multiple times:

Engineering Design = Development process with respect to manufacturing processes, including materials, stiffness, assembling, etc. Engineering design is accomplished by CAD-based modelling.

Designer = Creative member of the team responsible for styling creation. Designers are creating virtual models using free form applications within CAS (Computer Aided Styling) software.

Design Engineer = Member of the team responsible for engineering-related development. Design engineers are working in CAD environment and have to consider all functional and production-related technical aspects. They receive information about styling from designer, respectively the design department.

3. Cooperation of designer and design engineer

Prototyping processes involve transformations and changes between the different stages of product maturity until the detailed design is finalized. In every step of styling improvement, a transformation of geometrical data from CAS to CAD is necessary. Modern CAD systems enable direct interactive styling in specific workbenches [7]. Other possibility involves the physical creation (materialization) of styling models and subsequently performed 3D scanning, resulting in CAS surface data. In these styling laboratories, optical 3D scanning device are used, which provide high sophisticated scanning technology based on two cameras with different positions [3]. In any case, there are several stages in between transformation of designer's class A surface styling data to CAD data (Fig. 1). The hierarchy of individual steps are as follows:

CAS (Styling) – Draft data are created in computer graphics environment by polygonal modeling techniques (often in conjunction with subdivision algorithms). Shape of such draft geometries is modified by changing the position of control points, which influence the definition of approximated curves and surfaces resulting in an overall preliminary design. This polygonal modeling technique is usually linked to freeform surface modeling tools within CAS software. An application of CAS is shown in Fig. 5. In this way, styling development usually represents an initial step of automotive development processes.

Clay Model – CAS models are created by use of traditional or rapid prototyping technologies. A physically product model is built up and modified in real space. After confirmation, the hardware model is scanned by use of 3D scanning devices.

Cloud of Points – 3D scanning devices collect point clouds and points' positions using triangulation procedures. The output of such process is a (text) file containing all point coordinates. There are several possible formats available, e.g. ASCII, Steinbichler, IGES. [1]

Meshed Surface – Specialized software tools provide algorithms that generate triangular meshes from Clouds of Points (COP) and so the final surface can be interpolated. [4]

Interpolated Surface – Surface interpolation out of meshed surfaces represents the final step in styling surface creation. There are different kinds of interpolation procedure available. The selection of a proper type depends on required output properties; automatic interpolation is time-saving but lower quality. Apart from that, power fit interpolation is time-consuming but reaches higher quality of surfaces [3].

CAD (Detailed Design) – Engineering-related development out of given surface data under consideration of technological, functional and manufacturing-related aspects. As a basis for engineering-related development, the CAD models are built from interpolated surface data. There are different kinds of surface interpolation suitable for various applications [3, 13].

Modern development processes including concurrent and simultaneous engineering allow prolongation of styling stages within the whole prototyping processes. The main reason for this is the possibility to change the styling even after a detailed model is created. The output model is generated automatically with the goal to broaden the range of styling possibilities that can be automatically processed into valid CAD models. It means a class A surface, class B surface, interfaces and results are modelled only once and any subsequent changes are made with minimal human intervention or completely automatically. Tools enabling these functionalities are described in following section.

4. Application of generative engineering design methodology in the automotive industry

The presented advanced methodology requires enhanced functionalities, which are provided by complex CAD systems, e.g. [2, 8]. In this context, effective surface-based component development requires the following functionalities:

Logical algorithms/rules – Provide conditional definitions (e.g. IF-THEN-ELSE), which are defined in CAD system directly or by use of its programming language. These functionalities are not limited to purely geometry creation, but also included structural operations, e.g. in the CAD model history tree structures.

Mathematical rules/parametrical rules – Include exact definitions of graphical principles represented by functions, equations, or even problem-specific programs. Commonly used are parameters linked to geometrical dimensions, or entities driven by rules or formulas.

Geometrical and topological rules – Apart from mathematical rules, procedures can involve some specific conditions, which need to be obeyed. Topologically, there is a difference between open and closed curves, so these characteristics have to be taken into account, e.g. if a boundary of one component needs to be a closed curve to enable cutting of surface geometries.

Groups of geometrical entities – Tree history folders of one separate file in complex CAD system. Commonly used to build one functional feature.

Links – Represent connections between separate files by some particular references such as parameter, associative geometry elements, etc.

Described tools enable design engineer to build up so-called intelligent models/generative models [11]. This approach is widely used for solid objects, but surface modeling is more complex to be generalized [5]. The following proposed procedure is based on work in automotive industry supplier companies. Even though these methods had been used for a few years now, there was no particular definition of links between separate files with respect to theoretical framework. Team of the Laboratory of Generative Engineering Design has explored possibilities to define the Generative Engineering Design methodology with broader theoretical definition. It has also improved the practical use of the method in cooperating companies.

The unique advantage within the introduced component shape design lies in the possibility to define geometrical models by the shape and position of surfaces. For example, surfaces of contact are difficult to be invariably referenced in solid modeling using boundary representation. Surface-based modeling allows to reference objects with changing topology. The presented methodology is based on a proper hierarchy of operations throughout surface-based component modeling. Such a component needs to be built up step by step, as shown in Fig. 2. The main advantage of the methods lies in a hierarchy of separate files created in the applied CAD system. This means that the whole design work involves files with groups of surfaces. Those files are divided into clusters as follows:

A - Class A surfaces – Represent visible surfaces of components or input surfaces. Considered are quality of connections between patches, as well as aesthetics, aerodynamics, and passive safety related aspects.

B - Class B surfaces – Represent internal and/or functional surfaces. This cluster exemplary includes derived surfaces created by offset operations from class A surfaces to define the thickness of material. In this file it is important to link class B surfaces geometrically (normal vector of each patch or connection) to enable an adaptation to class A surfaces automatically in case of styling change.

I - Interfaces – Represent connections between parts. In each interface file, there are functional surfaces such as shape boundaries, contact surfaces, etc. They are responsible for additional changes to be made between parts, propagating the change to all interfaced parts. Interface creation is one of the most important features of

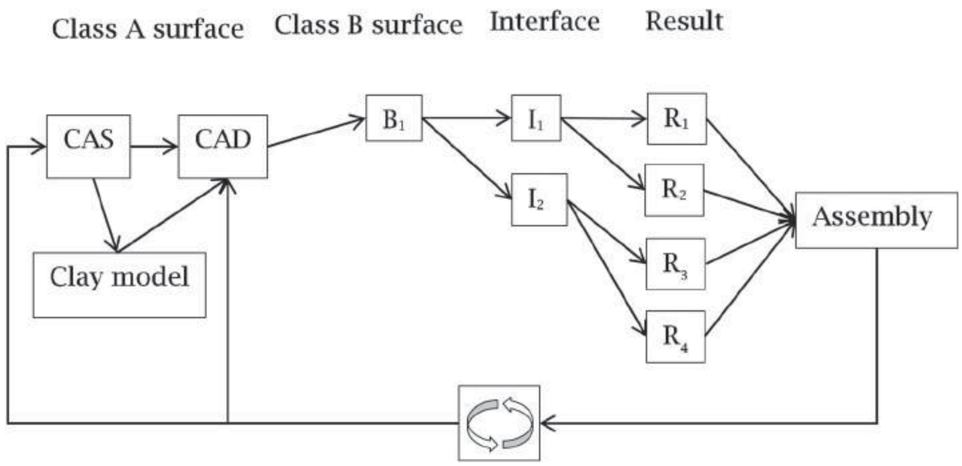

Figure 2. The loop of Generative Engineering Design procedure suitable for the development of surface-based car components.

automatic modification during the subsequent stages of product development processes. In case of a class A surface restyling, modifications of any affected parts are performed automatically by so-called generatively transformed design.

R - Results – Represent the final closed volumes of components. The hierarchy of input files and finishing operations define the final component shapes. This procedure involves a creation of functional features, e.g. clips and ribs.

The proposed scheme shown in Fig. 2 is exemplary suitable for designing processes of vehicle body components. The particular example of separate file management is shown in Fig. 3. As an exemplary application, it has been fully realized in the assembly of a vehicle front bumper. Each separate file represents a part within the applied CAD system, in which files are linked to each other following the development procedure. In this way, application of the introduced Generative Engineering Design approach has been carried out during the virtual development of a sports car, which has been one main goal of activities in the Laboratory of Generative Engineering Design at the Slovak University of Technology in Bratislava. Firstly, there was a CAS drafted by designer for the whole body of vehicle (Fig. 5). For this purpose, freeform surface modeling was used. For

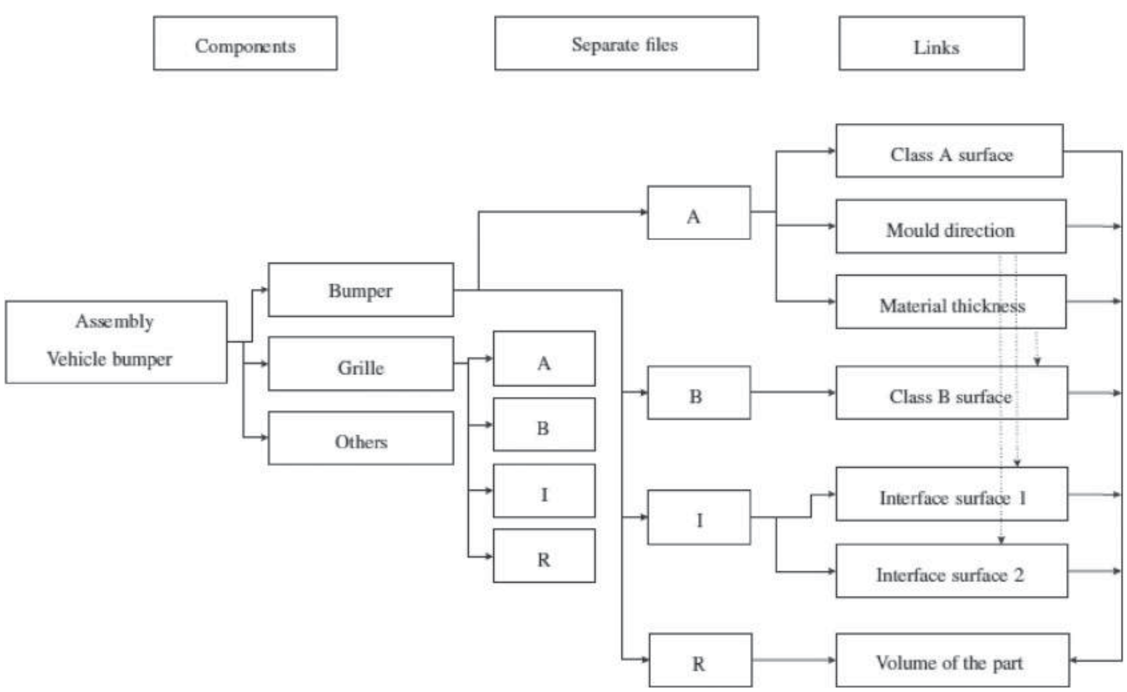

Figure 3. Exemplary Generative Engineering Design application within the expanded assembly of vehicle bumper.

efficient work, CAS was directly used as reference for modeling of class A surfaces, which provides a different and more precise mathematical description of surfaces suitable for CAD.

5. The development of class a surfaces of a sports car front part

Surface analyses are important to optimize the quality of class A surfaces. Fig. 4 includes an analysis process, considering three main points. First point refers to aesthetical and optical criterions. There are possible qualitative indicators mentioned, whereby all of them require certain attempts for implementation into automated algorithms.

Designers try to explore separate fields of generative styling modifications, because styling creation of visible surfaces is based on ideas and trends. In case of generative design as generative styling, there is a possible involvement of evolution in nature or by use of mathematical descriptions of aesthetics aspects.

For engineers, it is crucial to provide hierarchical steps of development. Therefore, the qualitative evaluation should follow a methodological scheme to improve partial class. It is difficult to define, which criterions have higher priority. Therefore, principles of concurrent engineering should be applied to improve the way, how optimizations complement each other. The optimum represents an ideal cooperation, which is often not possible to be established in practice.

Second point refers to safety criterions. Active safety is linked to e.g. aerodynamics and passive safety is linked to e.g. minimal radii for pedestrian protection.

In the third point, there are criterions based on economic and environmental aspects. Those are also linked to aerodynamics, which needs to be improved to minimize fuel consumption.

The development of class A surfaces described in this paper is based on styling data (CAS) from artistic designer. These styling data serve as input information and are shown in Fig. 5. Such a styling model consists of many patches of approximated freeform surfaces, which can be modified by positions of control points. Mathematical description of styling models made by CAS tools is not appropriate for a class A surface development within CAD environment. The main reason lies in the

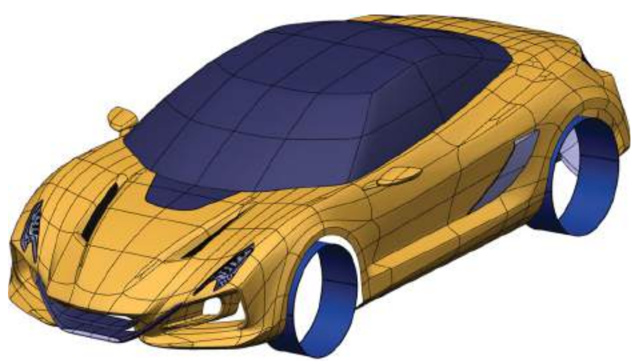

Figure 5. Styling of a virtual sport vehicle designed in the Laboratory of Generative Engineering Design at STU in Bratislava.

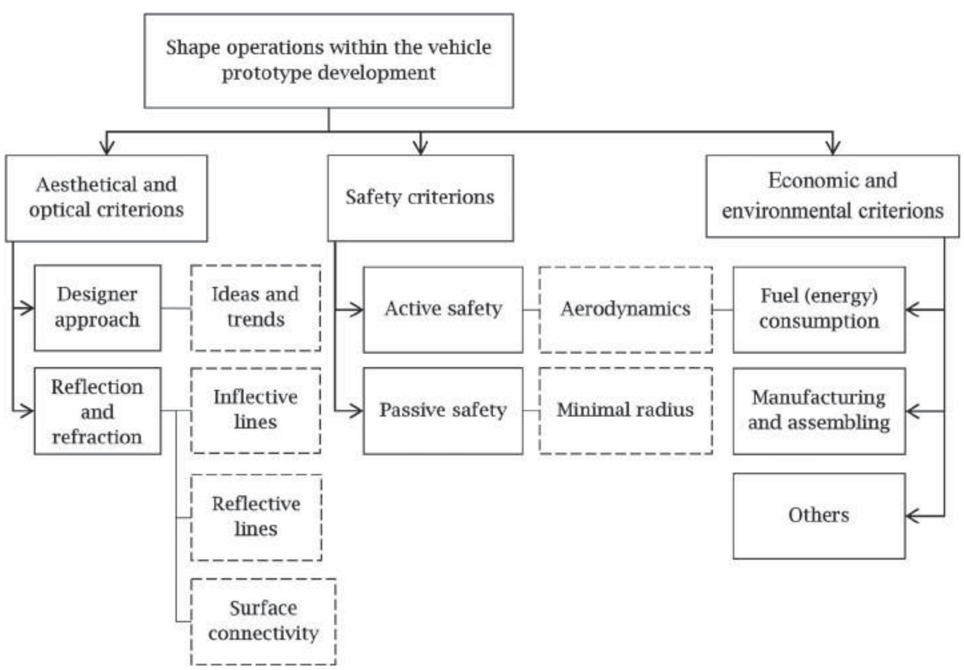

Figure 4. Examples of different shape analyses based on three main groups of criteria [12].

necessity of class B surface creation, which is done by creation of parallel surfaces according to the direction of normal vectors. CAD representation of class A surfaces is then created by tools of the applied CAD program or specialized software. In cooperation with designers, engineers modify surfaces based on analyses under consideration of quantitative parameters (e.g. minimal radius, class of continuity) or under consideration of qualitative parameters (e.g. shape of inflective lines, continuity boundaries). Apart from traditional class A surface modeling, there were also used mathematical and geometrical rules, e.g. to provide proper description of patch boundaries. Such rules are able to support and deliver automatic adaptation of a class A surface CAD data to a styling modification.

Required overall shape of output class A surfaces is provided by specific boundaries. Boundaries exist between two patches of a surface; four cases of continuity are considered here. In case of C^0 continuity, there is a sharp edge, therefore the connection is not smooth. This case is also called point continuity. In case of C^1 continuity, there is a smooth but visible connection. This case is also called tangent continuity. In case of C^2 continuity, there is a smooth connection with lower level of curvature deviation. It is also called first curvature continuity. In case of C^3 continuity, there is a smooth connection, including high quality curvature progression. It is also called second curvature continuity. For any higher continuity of C^n, where $n > 3$, the connection considered as smooth. Generative Engineering Design methodology enables automatic control of quantitative and qualitative parameters with minimal or no human intervention. The procedure of CAD surfaces creation (divided to patches) includes the following steps:

- Specialized software or software module for class A surface creation loads styling data as a package of frozen surfaces (Fig. 5).
- Patches of surface areas are extracted to be formed as freeform surfaces (Fig. 6).
- Patches are connected with lower class of continuity, such as C^0 or C^1, to form an intermediate model with sharp connections (Fig. 7).
- Interfacing curves (or boundaries) are defined on patches with respect to the shape of the future output model. During any following modification, boundaries are generated automatically.
- Connecting surfaces of patches are created with boundaries derived from interfacing curves. Important is a higher class of continuity, such as C^2, C^3, or higher, to achieve smooth output surfaces (Fig. 8).

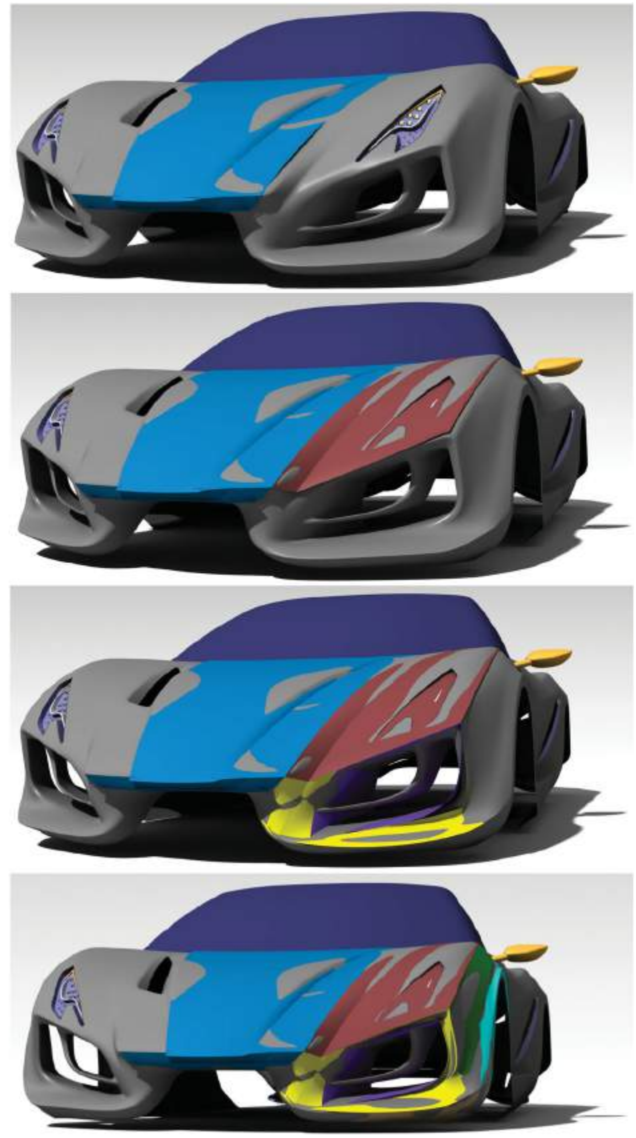

Figure 6. Images over time of extracted patches from a styling within the procedure of class A surface creation.

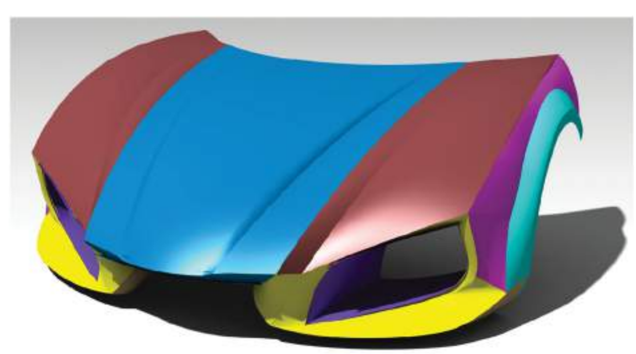

Figure 7. Sports car front part with continuity of C^0 and C^1 between surface patches.

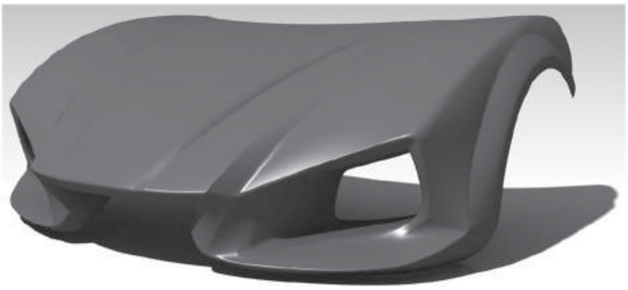

Figure 8. Complete sports car front part with smooth continuity.

The exemplary presented class A surfaces were developed by use of the Generative Engineering Design method [10]. Therefore, all the connected patches are adapted automatically if there is a change of any patch required, following proper quantitative and qualitative parameters.

6. Advantages and disadvantages of generative engineering design

The following summary provides a selection of pros and cons, based on experiences with the introduced Generative Engineering Design approach, which was applied in a development process of automotive surface-based components.

Advantages:

- Styling (CAS) modification is supported during detailed design phase by automated geometry adaptation features, which shows clear advantages in comparison to procedures with frozen styling data.
- The open configuration of the design process allows an involvement of different design engineers, which supports involvement of design engineers from different countries working on the same global project. In case the team is changed, any design engineer can continue working with the design models.
- Virtual modelling of functional features such as clips, ribs, holes and their modification is easier with the Generative Engineering Design method since the complete data structure and the workflow are well-organized.

Disadvantages:

- Increased demands on knowledge of design engineers in terms of enhanced CAD methods.
- Each member of the team needs to follow the predefined methodological rules.
- The methods is only applicable with enhanced CAD software, which provide functionalities for parametric-associative surface modelling.

7. Conclusion

The new age of CAD application enables a reduction of development time and an increase of data quality in the development of surface-based components. In automotive applications, the most time consuming part of engineer's work occurs, when styling of components is changed, or in case of the appearance of human mistakes. The presented new Generative Engineering Design methodology describes a comprehensive workflow including links and tools to support collaboration of styling creation and engineering-related design. It is capable to provide both improving data quality and reducing development time.

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