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

# RE-ENGINEERING EXTERIOR DESIGN: GENERATION OF CARS BY MEANS OF A FORMAL GRAPH-BASED ENGINEERING DESIGN LANGUAGE

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## ABSTRACT
The exterior design of cars is considered to be a highly creative task typically executed by experienced human designers. Based on a case study of the Audi car family, both a careful analysis of the human-assisted exterior design process has been assessed, as well as the syntax, semantics and pragmatics of a formal, graph-based engineering design language for the exterior design of cars with class A surface quality has been created. The design language allows for the almost complete reconstruction of the exterior design of the Audi car family (only smaller details such as side and rear mirrors, door seals, etc. have been omitted) and is demonstrated in this study to be able to re-engineer the exterior of an Audi A3 Sportsback. The syntax of this styling language consists of so- called characteristic lines and elements ("design genes", according to consistently used company terminology) and is used to create a graphical representation of an Audi specific design graph. The design graph is automatically translated into a 3D-CAD model using CATIA V5 as the geometry engine and is finally subject to a visual surface quality check using the isophotic analysis menu in CATIA V5.

*Keywords: Exterior design, automated surface reconstruction, characteristic lines, characteristic elements, design graph, design rules, design language, design compiler*

## 1 INTRODUCTION
With the change of the automobile from a luxury to a commonly used lifestyle product, the importance of its exterior design as a means to express individual customers preferences and social standing has considerably increased. It is therefore not surprising that the time spent in styling a new automobile in order to optimally address a certain target group is nowadays considered as one of the most important parts in the design decision making process. While the technical and technological parts of the product creation process are investigated in a variety of other research activities to accelerate and/or optimize parts of the design process by specialized software tools, the actual exterior design process still lacks such support greatly and is until today characterized by repetitive manual tasks executed by human designers. However, designers do have a number of "design rules" in mind (i.e. the corporate identity style guide and package concept requirements) when styling a car. It is therefore one of the central scientific questions raised and investigated in this work as to what an extent such styling rules, which may obviously be hard to grasp in a technical sense, can be expressed and incorporated in a formal graph-based design language. Since designers have to keep in mind restrictions concerning packaging and law regulations affecting the exterior of the automobile however, it seems obvious that at least these aspects may be formally expressed as rules in such a design language.
Design languages, also known as design grammars, have already been successfully applied to a variety of related design and styling tasks. In [1] a shape grammar has been developed together with expert designers to draw the characteristic lines of the front, side and rear views of future cars, allowing by a careful intermixing of the conceived rules the creation of so-called "cross-over products". Further design examples of applications of all kinds of string-based, shape-based and graph-based design languages can be found in a very up-to-date literature overview [2]. The effectiveness and efficiency of rule-based mechanisms has been demonstrated in [3], where a rule-based mechanism is iteratively used for the generation of characteristic lines used for the contour definition of a future product to be. The introduction of small disturbances into this rule-based creation process allows hereby the fast exploration of the design space and a significant relief of the designer from tedious routine tasks.

The work presented here is organized as follows: Section 2 provides an in depth look at the exterior design process in order to identify repetitive tasks performed by designers to lay the foundation for the use of rule in a graph-based design language. In section 3 formal commonalities of automobiles are derived, beginning with the separation of the automobile market in structurally similar archetypes followed by the identification of characteristic elements in the form of curves, common parts and part assemblies on the exterior car body also referred to as "design genes". These are translated in section 4 into rules in a formal graph-based design language in order to re-engineer the actual exterior of an existing automobile of the Audi car family. What has been achieved is followed by a critical discussion in section 5, covering advantages and disadvantages as well as possible refinements of the method. Finally, section 6 closes with a summary and outlook to further work.

## 2 REVIEW OF THE STYLING PROCESS

Much of today's methodology of the exterior design process has evolved from methods first applied by Harley Earl, who in 1927 founded the worldwide first independent styling department in auto-mobile history at General Motors. According to a recent investigation in [1], the exterior design of cars may be decomposed in a number of discrete steps. The resulting basic flow diagram of activities can then be further refined in accordance with [2] and [3], which contain additional information about the exterior design process itself, but neglected certain aspects described in detail by others.
In contrary to common thought the styling process does not start with the first line brought to paper by the designer. It starts with the determination of the goals which have to be achieved. Therefore the anticipations of the people relating to the later product are of importance. Humans however do have different product expectations, according to their social background. At the same time, an auto-mobile is also a product which has to be produced in larger quantities. It is thus obligatory to conceive a product development scenario concentrating on a sufficiently "right-sized" target group with similar expectations concerning the final product. In [4] and [5] a profound overview about possible separations of the different social settings is given. This scenario is later crucial for the commercial success of the future car. The scenario of activities is visualized in form of a flow diagram in Figure 1.

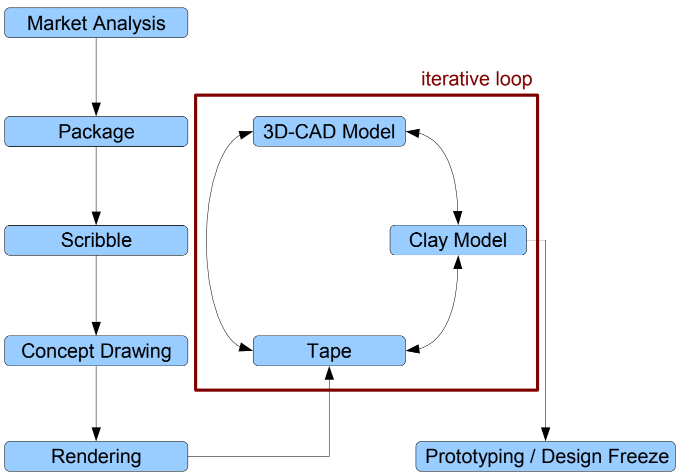


*Figure 1. Flow Diagram of the Exterior Design Process [18]*

The scenario for conception of a new auto-mobile in Figure 1 is separated in 5 linear design steps. It is followed by a series of 3 mutually dependent steps, in which each step is affecting another, leading to an iterative loop, followed by the creation of the prototype itself and the freeze of the actual styling. Starting with the market analysis, which is also containing the aforementioned analysis of the target group and eventual competitors, the design management and marketing together evaluate the initial possibilities and chances of success of a new product. Therefore a very general requirement specification is being issued, containing the most important design parameters in relation to eventual current and future competitors (e.g. price, volume of the trunk, power, and so on). Refer to [6] for an in depth overview of possible parameters and their application in different social groups.
The requirement specification is followed by the so called c*onstructive* p*ackage*. A specialized design department of engineers is translating these initial requirements and design parameters contained in

the requirement specification into concrete concepts. Therefore the main components of the auto-mobile, like the motor interior, passenger compartment and trunk are collocated according to the aspired archetype and defined in the main views, thus creating a basic volume which the designer in later steps may not fall below, as is described in [7] in detail. This helps the designer find a overall concept for the exterior.

The commonly known phase of the exterior design is now about to begin with the creation of the so called s*cribble*, followed by the more detailed c*oncept* d*rawing* and the very precise r*endering*, as seen in Figure 2. The scribble is characteristic for the phase of brainstorming, see also [2] and [3], as the designer starts out by drawing thump sized sketches, in order to quickly visualize different ideas, most of the time only recognizable to himself. Though there is no common rule where exactly the creation of the scribbles starts, it is commonly agreed on that the successive concept drawing is strongly dependent of the constructive package and is therefore a follow up. The actual concept drawing is in all aspects a fully fledged and completely presentable drawing, though it may be exaggerated, in order to further emphasize the styling ideas. These concept drawings are now evaluated and a pre-selection is being made, with the best ideas being selected for further elaboration. This is achieved in the form of the rendering, a very lifelike, often true scale drawing of the later auto-mobile. These renderings are then presented to the top-management for evaluation.

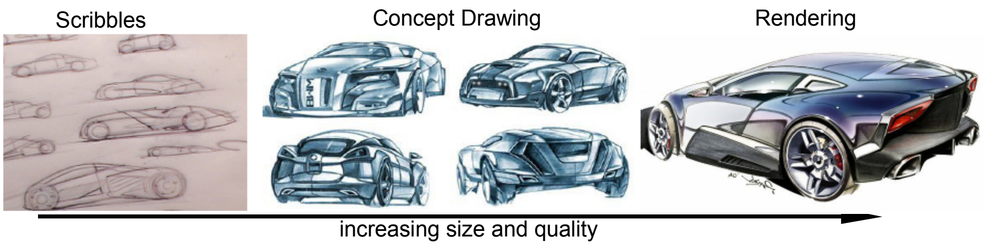


*Figure 2. From Scribble to Rendering*

This process is of special interest, as during the creation of the exterior design the designer tends to use a predefined set of lines and proportions, depending on the company she/he is styling for and the archetype she/he intends to create. These lines will be identified and further characterized in chapter 3. The completion of the rendering is followed by the translation of the exterior in its true scale front, rear, side and top views. This is accomplished using the so-called *tape*, the name of the drawing derived from the material used to create it: black tape. Drawn over the package, the tape includes all relevant visible lines and borders, clearly defining their exact coordinates in three dimensional space, as for instance splices, part borders and skin discontinuities. This gives the designer a good overview of the interaction of diverse characteristic lines and therefore of the overall feel of the car, as the tape is creating a strong contrast on the tracing paper. At the same time its usage allows for easy correction of already drawn lines, which will be necessary in order to improve the surface quality of the exterior, which is of great importance for the overall quality of the later styling as stated in [8].

Depending on the company's styling philosophy, the tape is followed by a 3-dimensional computer-based drawing, herein referred to as the *3D-CAD drawing*, or a real 3-dimensional model of the later auto-mobile, the c*lay model*. These models expand the line-model drawn tape by the creation of surfaces in order to further elaborate the exterior design. Whereas the clay model provides a means to visualize the 3-dimensional interplay of lines and surfaces, the 3D-CAD model allows for the definition of mathematical curvature and surface analysis and represents a basis for the subsequent engineering compartments working on the more technical aspects of the auto-mobile.

With the completion of this loop in Figure 1, the exterior design enters its final stage, the so-called *prototyping*. Its start marks the end of the actual styling process and the *design freeze*, after which no further changes to the styling may occur.

## 3 FORMAL COMMONALITY OF AUTO-MOBILES

Although auto-mobiles appear in a great variety of different shapes and sizes, they also possess a number of commonalities. These reach from sharing a similar package or bodywork, herein referred to *archetype*, over the usage of characteristically formed parts relating to a certain brand identity. These will be further specified and defined in the following sections using the specialities of the Audi car family as an example.

### 3.1 Car Archetypes

The separation of cars in different archetypes is often used for classification. This classification is based on characteristics of the constructive package in a dimensionless form, following thoroughly the basic topology, usage and the number of persons carried.

Since the work here concentrates on passenger cars other types of motor vehicles, such as motorcycles, trucks and buses have been excluded from this categorisation. The archetypes referred to in Table 1 have been derived from [10], which categorizes motor vehicles in general. Due to the age of the standard however, updates have been made as necessary, introducing new specialized categories of personal vehicles such as the SUV (sports utility vehicle), Coupé, City Car and Van. Counter-checked with [11], 5 main categories including the subcategories known to date have been identified with their descriptions in Table 1. If not stated differently, the standard bodywork is characterised by a four wheel car with four side doors, one trunk-door, notch back and notched front end. Also, the number of tiers (seating rows) has been included as a matter of completion.

*Table 1. Archetypes and their Bodywork (adapted from [10, 11])*

| Segment of passenger car | Different archetypes in the segment | Description of bodywork |
|---|---|---|
| Limousine | including city car, mini, sub compact-class, compact-class, middle-class, upper middle-class, upper-class and luxury-class | |
| | city car | hatchback and hatched front end, two side doors, one tier |
| | sub compact car | hatchback, two side doors, max. of two tiers |
| | compact car | hatchback, two rows of seat |
| | standard limousine | - |
| | station wagon | hatchback |
| | pull-man limousine | enlarged interior, max. of six side doors |
| Van | including compact-bus, minivan, micro van, compact van | |
| | van | hatchback and hatched front end, maximum of three tiers |
| | compact-bus | hatched front end, box-shaped bodywork, vertical rear end, max. of three tiers |
| Convertible | including convertible limousine and roadster | |
| | roadster | open bodywork, two side doors, two tiers |
| | convertible limousine | same as limousine model, open bodywork |
| Sport Car | including compact sport car, super sport car, coupé, sport-limousine | |
| | coupé | two side doors |
| | sport-limousine | four side doors |
| Off-Road Vehicle | including SUV, softroader, all-terrain vehicle | |
| | sport utility vehicle | hatchback, four side doors, increased ground clearance |
| | all-terrain vehicle | Four side doors, box-shaped bodywork, vertical rear end, increased ground clearance |

### 3.2 BRAND IDENTITY / DESIGN GENES

In contrary to the categorisation of auto-mobiles by archetypes, brand identity is no global similarity feature but a local one. Depending on the manufacturer a variety of specific characteristic lines and elements used in the exterior design, these characteristic lines and elements are, within the auto-mobile industry, often also referred to as design genes [3].

As names for these genes vary drastically depending on the company's standards, the English names will be given with their German counterparts in parentheses. Additionally their appearance on the auto-mobile is indicated using a representative drawing of a none-existent Audi for visualisation purposes. The following car models and archetypes of the Audi car family have been taken into account: A3 Sportsback 1.6 FSI Ambition (compact, 2005), A6 3.0 TDI Quattro (limousine, 2004), A8 4.0 TDI Quattro (limousine, 2004), A3 1.6 Attraction (compact, 2003), A4 Cabriolet (convertible, 2002), A2 1.4 (subcompact, 2000), and the A4 Avant 2.0 (station wagon, 2002).

### *3.2.1 Characteristic Elements*

Parallel to the previous categorisation of the auto-mobiles in manufacturer independent archetypes, it is possible to concentrate on cataloguing the parts and assemblies, which all together represent the exterior. The exterior is visually separated by splices of different sizes, with the exterior borders of these splices representing the part borders respectively.

Some of these parts have of course similar builds all over in the auto-mobile market. Although their surfaces might have differences in size position and length, research has shown that they are still very similar. For example, they always share a constant amount of border lines, like for the hood and front-window having 4 border lines, and their single surfaces can be obtained by straight sweeps along these borders. Such simple surface parts are represented by slanted font in Figure 3.

Opposing to these simple parts or assemblies, also more complex ones exist, often having a specific peculiarity. These parts do not consist of only one surface, but of more than one, and may contain additional unsteadiness in their construction. They are represented in normal font in the Figure below. Often following a certain pattern, a careful comparison reveals that though these parts widely differ from manufacturer to manufacturer, they still thoroughly resemble each other within one single brand.

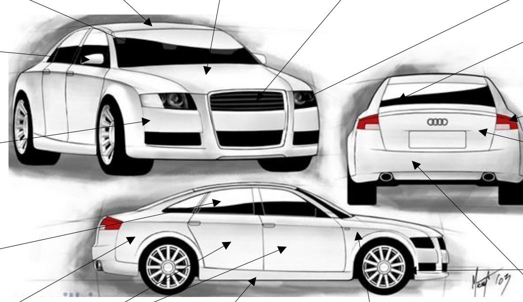


*Figure 3. Characteristic Elements and other Parts (slanted font)*

The characteristic elements indicated in Figure 3 also visualize their common appearance in the Audi car family. They are referred to in normal font and are defined as follows:

- the *grill*, also referred to as single-frame grill by Audi, due to its surrounding chrome track, is located at the front of the auto-mobile, being the external shape of the cooler. *(0/4)*
- the front engine *hood* concealing the engine, is defined by multiple discontinuities close to the grill in the driving direction. *(6/3)*
- head- and rear *lights* are integrated in the form of a combination unit. As indicated in the drawing, specialized lighting for different weather conditions has not been taken into consideration. *(4/1 front, 3/1 rear)*
- front- and rear *fenders* and their wheel lips are prominent features on the auto-mobiles flanks, needed for complete concealment of the wheels. The wheel lips have hard borders or curvature discontinuities ($C^1$-discontinuity) at the outer edges. *(11/3)*
- finally the front- and side and rear *bumpers* and *bumper guards* conceal stiffeners of the front, rear and side impact structures accordingly. Characteristically for the Audi car family is the visual partition of the front-bumpers in three parts. *(8/3)*

Additionally, a surprising observation was made during the comparison process: although the characteristic elements vary strongly between manufacturers, the number of $C^1$-discontinuous border lines and resulting single surfaces within the company-specific elements do not (at least within the Audi car family), remain constant for each part of the different archetypes. The number of these discontinuities are indicated in brackets at the end of each entry in the form of *(A/B)*, with *A* representing border discontinuities and *B* representing the surface-number. This could be a coincidence, although a very accidental one. However, this additional insight will be very useful in the implementation in the graph-based styling language in form of a vocabulary and design rules.

### *3.2.2 Characteristic Lines*

Similar to characteristic elements, the cars of a single manufacturer also possess a variety of so called characteristic lines. According to their definition in [12] these lines are “curvature-continuous curves, indicating a change in surface-continuity along their way”. Some of these lines are also referred to in the exterior design literature, as in [3], [13] and [14], clearly naming them and most specifically describing their relative position on the auto-mobile.

Although sometimes there is a certain disagreement as to where certain lines should be found (as for instance the shoulder-line). In general, most of these lines are named after their respective places on the human body, with the upper car body representing the human head, the lower car body its torso and feet. Due to this it sometimes happens that the very same line name is found in different sources for different positions or the car, meaning thus another line existing on the exterior body.

All the lines used here are shown in Figure 4, again on the same Audi-type car as in Figure 3. These lines are consistently used on all Audi-models, with closely related positions, although the length and the curvature may of course vary depending on the archetype. Most of these lines are also commonly used by other auto-mobile manufacturers, they might then however have completely different courses, touching and interactions other parts.

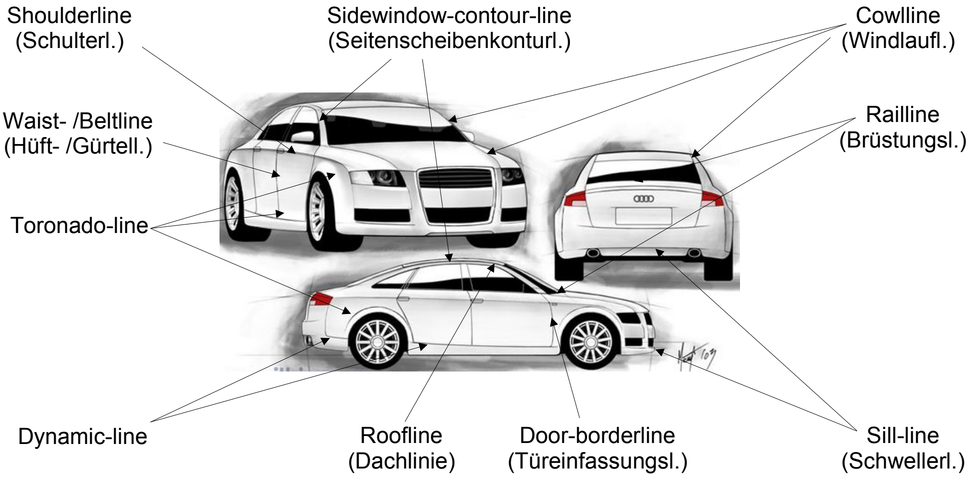


*Figure 4. Characteristic Lines*

In the following a quick overview on the characteristic lines will be given, including a short pointed description and the influenced parts. This will be done in certain order to clearly define their positions in accordance to Figure 4, and to prevent confusion. Additionally, their (original) German name is found in parentheses following the English translation to help the consistency with the literature.

- the *roof line* (Dachkonturlinie), visible in the side-view only, is starting at the intersection of front-window and hood and ends at the intersection of trunk and back-window. It is also the contour of the upper vehicle, defining the windscreen and rear-window and the roof.
- the *cowl line* (Windlauflinie), starting on the hood, near the grill and extending along the A- and C- pillars, it incorporates the engine hood, windscreen and rear-windows, roof and trunk. It is the only characteristic line found at the same time on the upper and lower car body.
- the *rail line* (Brüstungslinie) separates the upper car body from the lower and borders all windows, as well as the doors, pillars, fenders, trunk and hood. Its classic height is two third of the total auto mobile height above ground.
- the *side window-contour-line* (Seitenscheibenkonturlinie), generally represents the uppermost borders of the flank's windows
- the *shoulder line* (Schulterlinie / Schulterunterkantenlinie), starting at the upper outer corner of the headlights and terminating at the rear lights. Fenders and side doors also are defined by it.
- the *belt line* (Gürtellinie, also referred to as *waistline*) is connecting the outermost points on the auto-mobile flanks in height of the bumper coiling. Influenced parts: same as shoulder line.
- the *toronado line*, slightly above the wheel lips and the side-bumper, it marks the location where the surface-flexion changes from concave to convex. See shoulder line for influences.
- the *sill line* (Schwellerlinie) runs along the upper borders of the front side and rear sill boards.

Together with the dynamic-line it is the only characteristic line broken by the wheel-boxes. Additionally to the parts already mentioned it also influences the fenders.

- the *door borderline* (Türeinfassungslinie) should be self-explaining, bordering the side-doors, as seen in Figure 4. The side window-contour-line runs very close to it at the upper car body.
- last, the *dynamic line* is running all around the car, except the frontal part between the headlights bordering fenders, lights and bumpers. It is also running through the trunk-door.

## 4 Implementation of a Graph-based Styling Language

With the development of the design genes as shown in Section 3 it is now possible to derive a vocabulary and rules, which form a formal graph-based styling language. Using this language, it will be possible to create a complete auto-mobile exterior. This process will be shown presenting the example of the re-engineering of the exterior of an Audi A3 Sportsback (see later Figure 11).
The "Design Compiler 43" [24] is a software tool able to compile graph-based design languages. It originates from a former cooperation of the ISD at the University of Stuttgart [23] and the IILS mbH company [24]. It offers a domain-independent, multi-disciplinary solution for the problem of model-driven design, using a rule-based design language with a graph representation. Up to date, several design languages for engineering problems, such as the conceptual design of space station, satellites, airships, automotive structures [19] and air planes [22] have been developed. In the following a short introduction on the Design Compiler 43 and its defining elements will be given. Then a set of graph-based design rules for automatic surface reconstruction will be introduced. Finally, the complete exterior reconstruction of an Audi A3 Sportsback will be shown.

### 4.1 The "Design Compiler 43" and its integration in the design process

Similar to a spoken human language, a graph based design language such as one processed by the design compiler 43 consists of three components. The first components is the *vocabulary* being the analogue to the words, followed by the second, the *design rules* which could be described as the languages syntax or grammar. The third element are *production systems* which equal sentences and which are the collection of the design rules necessary to create a design.
The vocabulary represents the usable objects (or entities) in the course of the design process. The vocabulary stores the internal data (parameters, equations and program scripts) allowing their representation in different domains by triggering external programs. The interfaces to external programs like Catia V5, Mathematica or Excel are called *plug ins*, and are executed during the rule execution. The vocabulary also exchanges selected information for communication if connected to each other via a link. In Figure 5 the vocabulary (i.e. graph nodes A to D) are connected via links.

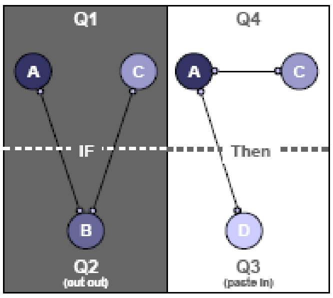


*Figure 5. The Four-Quadrant-Scheme [18, 19, 20, 21 and 22]*

The design rules, (often also called design patterns) are the main part of the language expression syntax. They regulate during their execution the flow of the design information via their management of the interactions (i.e. the coupling) between the individual vocabulary nodes. The design rule in Figure 5 transforms the current state of the design (i.e. the so-called design graph) during is execution (e.g. cut-out the B-node and paste-in the D-node and rearranges the context via link manipulation). The rule definition follows the so-called 4-quadrant scheme illustrated in Figure 5, working according to a *if* → *then* execution scheme. In analogy to classical, string-based computer programming languages, sequences of design rules form a so-called production system. In this respect a production system is not only the container of a complete design blueprint (however in incremental, unexpanded form), but also of the complete history of design which can thus be replayed over and over again.

## 4.2 Structuring exterior design and the general design graph

The purpose of the section is to motivate the synthesis of a formal representation of the exterior of a car and its design (i.e. the information from the different archetypal bodyworks with the information about the parts and characteristic lines) with the approach of a graph-based design language for automatic processing (i.e. rule execution). In order to achieve this, the necessary vocabulary and rules have to be derived. They should be sufficiently general as they should not change much for every variation of topology and parameter modification that is made later to the exterior design.

Therefore, the abstract exterior vocabulary "auto-mobile" has to be further detailed by dividing the complete exterior surface into the single surfaces of the parts. As separation scheme, the car is divided in the upper and lower car body along the rail line. Both are then subdivided in the front, flank and rear. The single parts themselves are then associated with the car's front, flank and rear according to Figure 6. Obviously, topological variations of the car have little or no effect using this partition and it is easily possible to introduce additional doors or windows. The convertible archetype would have almost the same representation like the limousine, just the form the roof would be different.

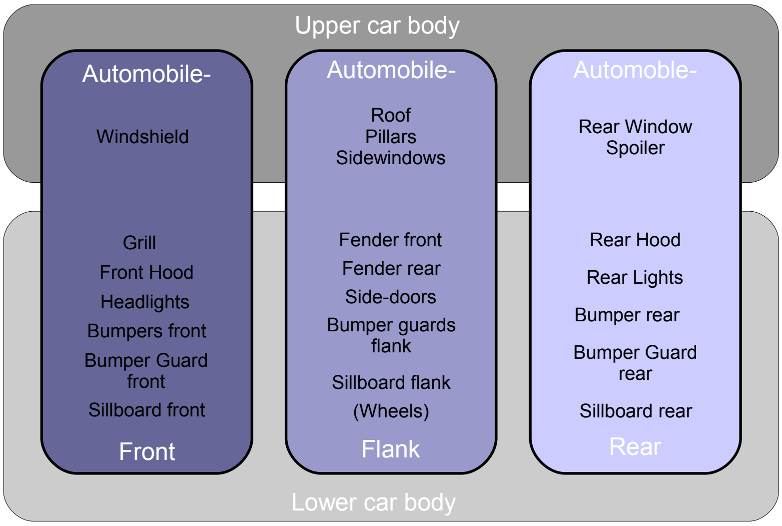


*Figure 6. Formal Differentiation of an Auto-mobile [18]*

In order to convert the scheme shown above in a graphical form the first vocable have to be defined. These are called *auto-mobile, upper-car, lower-car, front, flank* and *rear parts*. The part vocabulary contains a parameter called id (identifier). Using this id parameter, it is possible to greatly decrease the vocabulary number, as most parts can be represented by association of a certain part with a certain id. Figure 7 visualises the parts and id on the auto-mobile's front, rear and flank (colour-coded in accordance to Figure 6). Their borderlines will later serve to automatically generate the surfaces.

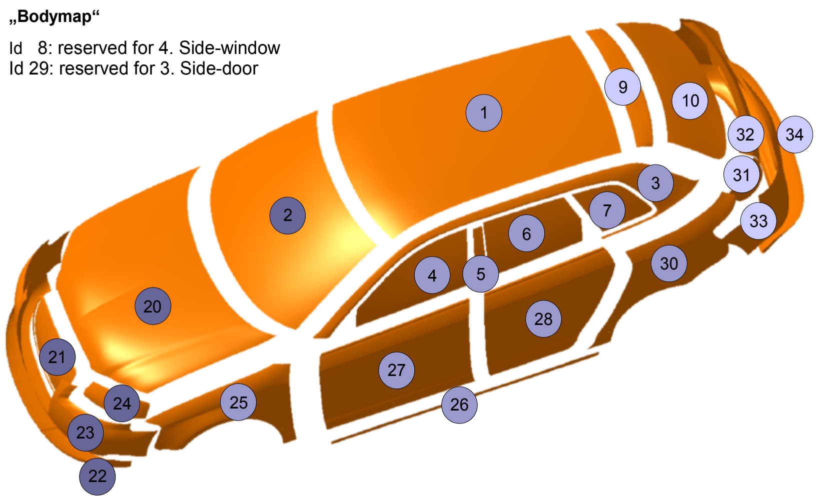


*Figure 7. Body map of an Auto-mobile [18]*

Using the vocabulary and executing design rules defined as graph transformations, a graph-based design representation of Figure 6 is created. This is being shown in Figure 8 for the upper car body. In addition, the characteristic lines defined in Section 3.2.2 have been added to the graph, leading to a general design graph representation. A single graph node with a variable id-parameter may contain additional parameters, such as the starting/ending points of a spline, as well as all the base-point, tangent and curvature information. This information may also be stored in an external file related to their id (identity), which is automatically triggered as the information becomes necessary.

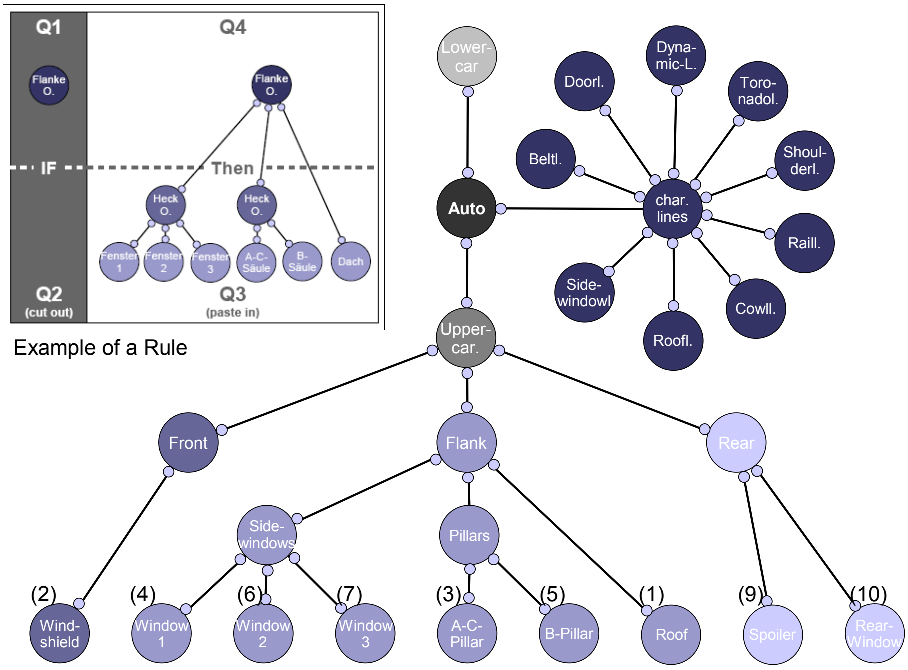


*Figure 8. General Design Graph for an Audi-type Car [18]*

This way it is possible to relate the line information directly to the vocable and at the same time use external data as provided by third party applications [12]. Therefore it would be easily possible to use predefined lines and interchange them for quick modifications of the exterior design.

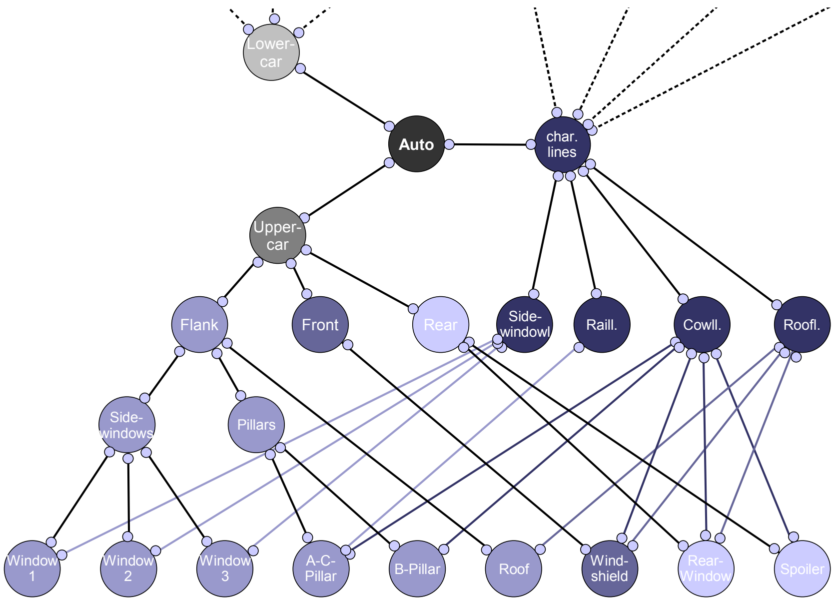


*Figure 9. Specialized Design Graph for an Audi-type Car [18]*

### 4.3 Conduction of the specialised exterior design graph

With the completion of the general design graph, it is now possible to create a more specialised one based on the additional information of the characteristic lines. As has been shown, all these lines are always connected to exactly the same auto-mobile parts of the exterior. Therefore the graph can be extended as shown in Figure 9, by introducing relationships between these characteristic lines and the parts. This is accomplished through the usage of rules, which trigger transformations of the original graph which contains then all the information necessary for the automatic generation of the exterior surfaces and for its 3 dimensional presentation, using a CAD program (like Catia V5).

### 4.4 Automatic surface reconstruction

The graph shown in Figure 9 can now be used to automate the surface reconstruction. Before this can be done, additional lines have to be integrated. This is accomplished by defining a new vocabulary called *spline*. This vocabulary is almost identical to the characteristic line vocabulary except for its name and the way its id is handled. Here the id is not defined but computed, as the line gets its id from the *part* vocabulary and adds its own id number to it. This way the ids are unique and in the Catia model later it is visible to which part the line belongs to. A spline can then be added via rule *A* shown in Figure 10 to an already existing part. The rules parameters are the part-id and the line-id, which can later be adjusted in the program. This way different lines are created by one single rule.

After the lines the surfaces introduced by the *surface* vocabulary may be created. Its basic ability is to gather the identities of other lines and refer to them. As these identities are also the line ids in the Catia model, it is possible for the surface vocable to use them as a parent-element and create a smooth surface. Next to its own unique id parameter it has two additional ones, namely the function parameter and the mirror parameter. The function parameter is used to define the surface-function used, as Catia V5 offers different possibilities of creating surfaces. The mirror parameter defines if the created surface should be mirrored along the cars plane of symmetry.

The surface vocabulary may be manipulated in a set of rules. As an example for such rules, rule A is presented in figure 10 and creates surface node. This surface vocabulary could take any number of lines to create a surface, so rules for different combinations may be created. As one example, rule B in Figure 10 defines a specific surface creation based on four borderlines and without intersection.

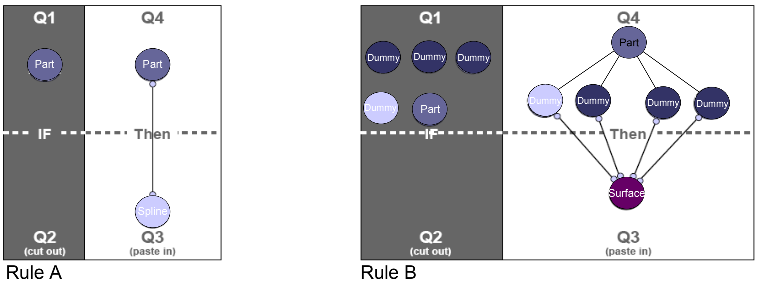


*Figure 10. Rules A and B [18]*

During rule execution, a defined rule searches design graph whether it matches. If a match is found, the rule is applied on the design graph and the surface is automatically created. Otherwise no modification to the design graph is being made. Figure 11 shows a small portion of the design graph after execution of rules A and B, as well as the surface created in Catia V5 after their execution.

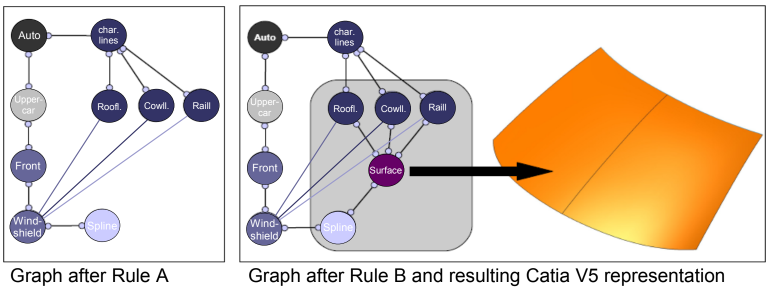


*Figure 11. Automated Surface Reconstruction [18]*

### 4.5 Resulting car exterior

Using the definitions of the surface rules, it is possible to re-engineer an auto-mobile exterior. This has been done for an Audi A3 Sportsback, using exact curvature information from measurement data licensed from Autograph Dimensions [12]. The quality of the resulting surfaces is shown in Figure 11, where both the exterior surfaces generated and the result of the isophotic analysis in Catia is presented.

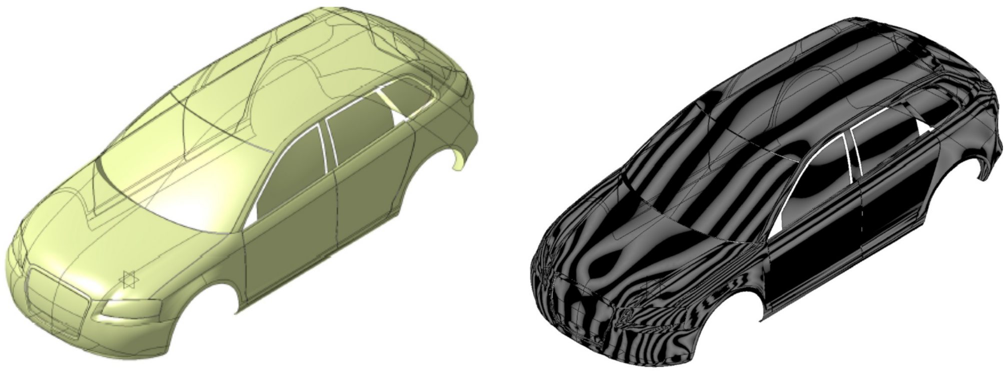

*Figure 11. Re-engineered Exterior and Surface Analysis of an Audi-type Car [18]*

Smaller details (side and rear mirrors, door and window seals, etc.) have been omitted, though it would easily be possible to extend the design graph and incorporate these additional elements. In order to do so, additional geometric information concerning these parts has to be obtained.

Subsequently to the automatic re-engineering of the car exterior, an isophotic analysis was triggered manually. It is commonly used by designers to judge the surface quality and although the surface generation information was rather poor, the surfaces created are of surprisingly good quality.

### 4.6 Discussion

In this work, the general design methodology using a formal graph-based design language for compilation in the design compiler 43 has been shown. It was exemplified using the creation of a rule-based design language for re-engineering the exterior design of an Audi A3 Sportsback. In the following, some benefits as well as some drawbacks of the procedure presented will be discussed. Furthermore, additional suggestions of improvements and enhancements will be made which could be incorporated in future versions of the design language.

As has been seen beforehand generating a design language for the re-engineering of exterior design seems to be quiet tedious the first time. Of course, the whole vocabulary, all the design rules and finally the production system has to be developed. Furthermore, an in-depth domain knowledge about the styling process itself and the complex interactions between the characteristic lines and parts involved is obligatory. Finally, generic scripts in order to trigger the Catia plug-in have to be created. As an alternative to all these programming considerations, one could instantly start designing manually, just by paper and pen. Once the design language is created however, the automatic replay capability boosts the productivity of the designer. Rule modifications are then almost effortless and the compiler does the rest of the detail work.

It is easy to change rules and thus the existence and the coupling of certain lines to mimic the designs already defined by different manufacturers. Furthermore, scaling changes the character of a line. A line's acceleration, lead-in and lead-out would be examples for these criteria. According to [1], a mathematical representation for these parameters has to be found, and the lines would have to be translated accordingly using this representation instead of explicit points. This would then allow for more interactivity and in its conclusion in the creation of completely new exteriors.

Surface quality and approximation could also be further improved by incorporating additional surface information. In contradiction to simply defining the surfaces by their borderlines and profiles, measured points could be integrated. This additional surface information could be obtained using a 3D scanner. Parallel to this additional point information profiles could be defined. This approach would also benefit by the definition of line characteristics.

Finally, it is necessary to state that although it is possible to re-engineer exterior designs it is still impossible creating exterior designs from scratch. This is due to the lacking mathematical theory for styling validation and the fact, that humans are better, more creative and adaptive in such a case.

## 5 CONCLUSION

It has been shown how to re-engineer the exterior of a car using a graph-based design language. By applying graph-based design rules, the design language generates a complete exterior representation of an Audi A3 Sportsback. The design language allows the administration of all the data involved, an automatic actualisation of the geometry model following modification of the design graph. The language can be reliably re-executed to regenerate the model geometry at any moment in time.
Additionally the design graph represented could be a reliable source of surface information used for further work, extending it by additional domains, such as aerodynamics, statics and dynamics of automobiles. The possibility to feedback quantitative information of these additional domains to the design graph could then lead to an overall improvement of the exterior design in general.

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