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Research on Automotive Front Face Styling Based on Shape Grammar

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Abstract. Automotive front face styling design needs to satisfy both innovative aesthetics and the recognition of brand identity. Under the dual drivers and constraints, this research focuses on the design method for inheriting brand identity in automotive front face styling. A design process combining shape grammar and product family DNA is proposed. The Audi sedan series front face is selected as the research object. Firstly, the dominant styling features and implicit design intentions of the brand DNA are extracted, and a mapping is established between the two. Then, the initial shape is determined based on user expectations and constraints. Finally, suitable grammar rules are selected based on shape grammar theory to derive and generate design solutions. The automotive front face styling designed through this method exhibits excellent brand recognition and matches the users' design intentions. This design process can effectively reduce deviations between conceptual design and final products in the early stage of automotive front face styling design, minimize repetitive design, and thus shorten the development cycle, reduce costs, and enhance market competitiveness.

Keywords. Shape grammar; Product family DNA; Automotive front face; Styling design

1. Introduction

Consumers place a much higher emphasis on styling when purchasing cars compared to other products, and this tendency is gradually increasing. With the development of diversified consumer behavior, consumers have a greater aesthetic perception and attention to automotive styling. They pay more attention to the image and symbolism of luxury, craftsmanship, and contemporaneity conveyed by automotive styling. Currently, scholars both domestically and internationally have explored automotive styling design and proposed innovative practical methods. For example, Lu Zhaolin et al. [1] studied the thinking mechanism of automotive designers in the fuzzy early design stage through verbal report experiments and mathematical statistical analysis, and summarized corresponding patterns. Zhao Jing et al. [2] applied shape grammar theory and derivation rules to existing brand styling features, generating new electric vehicle styling that meets brand inheritance requirements. However, automotive styling design needs to consider multiple factors, including brand DNA, user demands, and feature innovation. Therefore, this paper proposes a method that combines shape grammar with product family DNA for research on automotive front face styling design. When determining the constraints

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of shape grammar, product family DNA is introduced to determine genetic constraints and guide the design process.

2. Research methods

2.1. Overview of shape grammar

Shape Grammar (SG) is a shape manipulation theory proposed by George Stiny and James Gips in the early 1970s. It is based on previous research and has been innovated upon [3]. Deoxyribonucleic Acid (DNA) was originally a concept in molecular biology used to store genetic information [4]. In the field of industrial design, DNA is metaphorically used to refer to the design genes that represent the brand inheritance of a product, indicating the design features that have been retained after multiple iterations of innovation. Shape Grammar, as a formalized method in the stage of conceptual design, can effectively inherit existing features and evolve from prototypes, generating a large number of innovative designs.

2.2. The law of use of shape grammar

The core idea of shape grammar in design practice is to combine the design subject with design elements. Basic element styles are extracted from existing products and design elements and generalized into geometric shapes. Then, these geometric shapes are derived according to the rules of shape grammar to generate a series of new patterns. Finally, these new patterns are recombined and assembled to form new design styles and structural forms. The definition of shape grammar can be represented as SG = (S, L, R, I), where S is a finite set of derived shapes that are generated according to the rules R after being symbolically labeled. L is a finite set of symbols for derivation rules, R is a finite set of rules for derivation, and I is the initial shape for derivation [5].

2.3. Design and research process

The research on automotive front-end styling design based on shape grammar can be roughly divided into five stages: product form analysis, extraction of brand styling genes, determination of constraints, selection of grammar rules, and generation and selection of design solutions [6].

In Stage 1, the product form analysis stage, the elements of automotive front-end styling design are identified through literature research. In Stage 2, a specific automotive brand is selected, and its styling genes are collected to establish a gene library. In Stage 3, constraints are determined based on factors such as user needs and brand positioning. In Stage 4, suitable derivation rules are selected from a set of shape grammar rules to guide the design process. In Stage 5, the front-end styling solutions derived in the previous stage are evaluated using the 5-stage SD method through a questionnaire. The solution with the highest score is considered the optimal solution. The research process for automotive front-end styling design is illustrated in Figure 1.

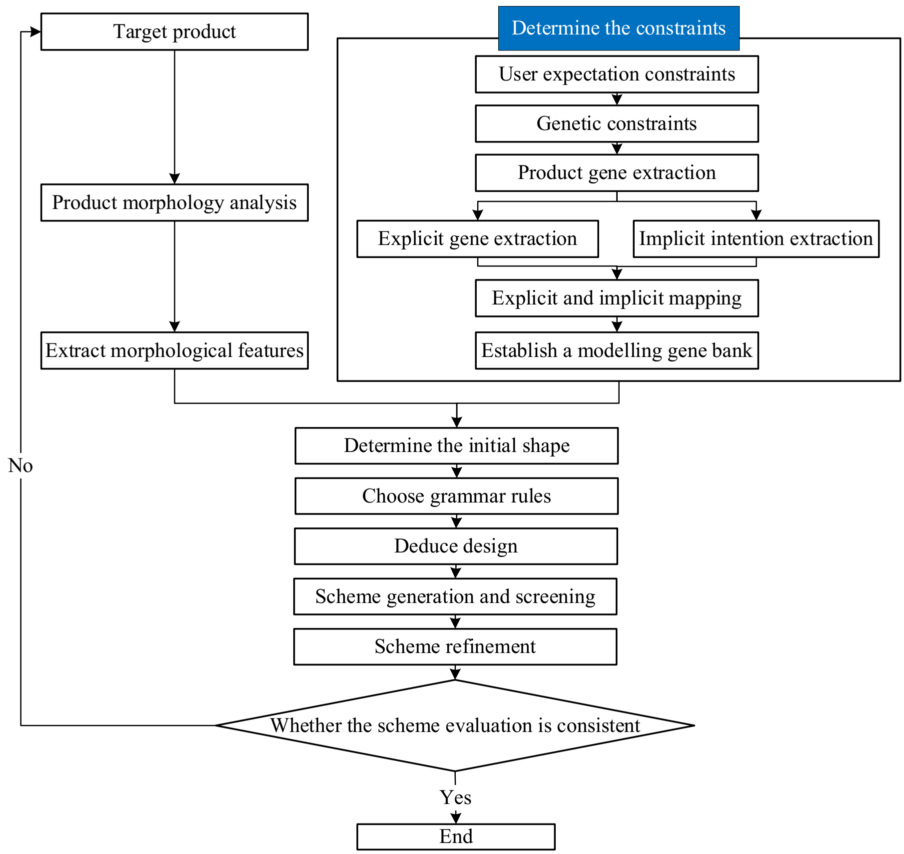


Figure 1. Shape grammar research model

3. Case verification

The Audi A3 is a flagship model under the Audi brand. Since its introduction in 1996, it has undergone three generations of updates and has launched more than 20 different models. As a luxury car brand from Germany, the Audi A3 has enjoyed great popularity in both domestic and international markets, making it one of the most representative models of the Audi brand. This makes the Audi A3 an ideal choice for research purposes. Detailed information about the research samples can be found in Table 1.

3.1. Product morphology analysis

The styling features of passenger cars mainly include overall vehicle design, front-end styling, body waistline, interior CMF (color, material, finish), and rear-end styling. Among them, the front-end styling is the most representative design element that reflects the brand characteristics, making it the key focus of shape grammar-based morphological extraction. When designing the front-end of a car, it is typically divided into four parts: front headlamp assembly, hood curve, grille, and fog lamps. Shape grammar is applied to extract and evolve these parts individually.

3.2. Brand modelling gene extraction

3.2.1. Product family DNA dominant modelling feature extraction

To extract the front-end styling features of the Audi A3 series using shape grammar, first, the contour of the Audi A3 series front-end styling is depicted using Bessel curves. Then, the feature lines of the front-end, headlamp contour lines, hood curve, grille, and fog lamp contour lines are depicted, as shown in Table 2. Next, following the principles of morphological decomposition in shape grammar, the front-end styling features of the Audi A3 series are deconstructed, and important styling elements are summarized to establish the Audi A3 product family's front-end styling element encoding library, as shown in Table 3. Using this encoding library, each Audi A3 series front-end styling sample can be represented using a combination of styling element codes. For example, the sample 09-A3 (2019 model) can be expressed using the styling elements [a3, b3, c2, d3][7].

Table 1. Audi A3 car front face modeling sample

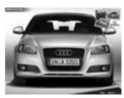
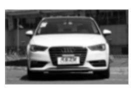
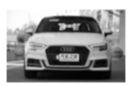
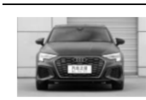
The first generation				
	01-A3(1998-model)	**02-A3(2003-model)**		
The second generation				
	03-A3(2006-model)	**04-A3(2009-model)**	**05-A3(2012-model)**	
The third generation				
	06-A3(2013-model)	**07-A3(2015-model)**	**08-A3(2017-model)**	**09-A3(2019-model)**
				
	10-A3(2021-model)	**11-A3(2022-model)**		

Table 2. Audi A3 sample front face modeling contour extraction

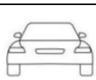
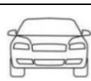
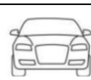
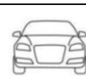
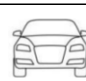
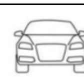
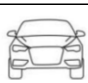
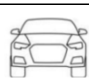
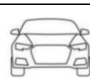
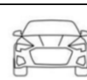
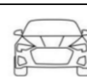
					
A3(1998)	**A3(2003)**	**A3(2006)**	**A3(2009)**	**A3(2012)**	**A3(2013)**
					
A3(2015)	**A3(2017)**	**A3(2019)**	**A3(2021)**	**A3(2022)**	

Table 3. The main modelling elements of the front face of Audi A3 series product family coding library

Styling features	Styling elements			
X_1:Headlight group	A_{11}:Simple geometry	A_{12}:Simple and irregular shape	A_{13}:Complex and irregular shape	
				
X_2:Enter the style gate	A_{21}:Flattening	A_{22}:Rounded trapezoid	A_{23}:Hexagon	A_{24}:Flat hexagonal
				
X_3:Hood curves	A_{31}:Outer convex arc	A_{32}:Inner concave arc	A_{33}:Short straight arc	A_{34}:Long straight arc
				
X_4:Fog lamp	A_{41}:Class parallelograms	A_{42}:Inverted trapezoid	A_{43}:Regular trapezoid	A_{44}:Irregular pentagon
				

3.2.2. *Product family DNA recessive modelling intention extraction*

From a perceptual perspective, the semantic differential method was used to select styling intention vocabulary [8], the Richter scale method was used to rate the intention vocabulary, and the Delphi method was used to statistically analyze the ratings, as shown in Figure 2.

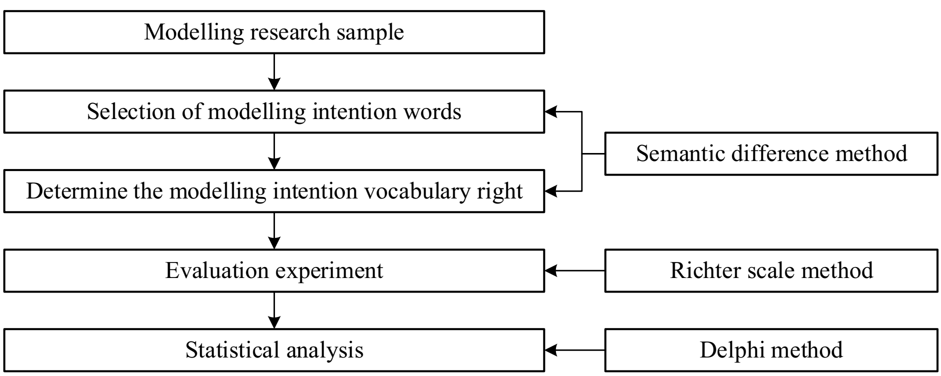


Figure 2. Implicit modelling intention extraction model

By referring to Audi's brand-related materials, core feature terminologies were extracted. At the same time, a large amount of imagery vocabulary related to car styling was collected through various means such as literature, interviews, and questionnaires. Through expert interviews, vocabulary that had similar meanings or was not suitable for evaluating car styling was eliminated. Following the principles of the semantic differential method, opposite-meaning words were paired, resulting in a final selection of 60 sets of styling imagery vocabulary. These imagery words were combined with the primary styling element encoding library of the Audi A3 product family's front-end styling to create a survey questionnaire. Ten professional car styling designers and 20 design professionals, including teachers and students, were invited to participate in the questionnaire survey. Based on the frequency of selection of the imagery vocabulary, the top six sets of vocabulary were chosen as representative styling imagery for the Audi A3 front-end samples. The specific results are shown in Table 4.

Table 4. Six groups of modelling intention vocabulary

Modelling intention vocabulary		
S1 Straight line - Short line	S2 Heavy - Lightweight	S3 High end - Low end
S4 Ample - Compact	S5 Smooth - Dynamic	S6 Majestic - Shabby

Using an imagery vocabulary combined with a coding library of the main styling elements of the Audi A3 series front face, a 7-level imagery vocabulary SD scale was created, with scores of 3, 2, 1, 0, -1, -2, -3, as shown in Table 5. The Delphi method was employed to invite 10 automotive design experts to rate the SD scale. Positive values were used to represent the imagery vocabulary on the left side, while negative values represented the imagery vocabulary on the right side. The absolute value of the score indicates the strength of the imagery represented by the sample. A total of 10 valid survey responses were collected. The SPSS software was used to obtain the mean values for each group of imagery vocabulary for each sample vehicle. The specific results are shown in Table 6.

Table 5. Example of Audi A3 front face modelling SD intention vocabulary table

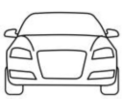
Sample model	Intentional vocabulary	Corresponding score	Intentional vocabulary
	Straight line	3、2、1、0、-1、-2、-3	Short line
	Heavy	3、2、1、0、-1、-2、-3	Lightweight
	High end	3、2、1、0、-1、-2、-3	Low end
	Ample	3、2、1、0、-1、-2、-3	Compact
	Smooth	3、2、1、0、-1、-2、-3	Dynamic
	Majestic	3、2、1、0、-1、-2、-3	Shabby

Table 6. Average score of sample perceptual intention

Intentional vocabulary	01	02	03	04	05	06	07	08	09	10	11
S1 Straight line-Short line	2.33	1.75	1.86	0.56	0.85	-0.69	-1.02	-1.53	-1.86	-2.05	-1.96
S2 Heavy-Lightweight	1.75	1.58	1.65	0.25	0.96	-0.02	-0.53	-0.87	-1.86	-2.23	-2.06
S3 High end-Low end	-2.02	-1.05	-1.25	0.59	0.26	-0.05	0.58	1.28	1.69	1.88	2.06
S4 Ample-Compact	-0.58	-1.56	-0.85	-0.26	-0.64	-0.26	0.06	0.59	1.06	1.28	1.59
S5 Smooth-Dynamic	2.05	1.85	1.92	-0.65	0.74	1.05	-0.06	-1.05	-1.56	-2.05	-1.69
S6 Majestic-Shabby	-1.05	-0.74	-0.58	0.68	0.55	0.85	1.06	1.28	1.69	2.26	2.56

3.2.3. Mapping analysis between modelling features and modelling intentions

Based on the extraction of explicit styling features and evaluation of implicit styling imagery from samples of the Audi A3 car's front face, it is determined that the styling imagery depends on the external styling features of the product. Therefore, the genetic makeup of the product family's styling is formed by the mapping relationship between the explicit styling features and implicit styling imagery of the product family.

Subsequently, a joint analysis of the Audi A3 car's front face styling features and styling imagery is conducted to construct a mapping model between the product family's styling features and styling imagery evaluations.

Multiple regression analysis was conducted using SPSS 26.0 software [9]. The explicit styling elements were set as independent variables, and the implicit styling imagery was set as the dependent variable. A linear regression analysis equation was established to analyze the partial correlation coefficients between the various feature elements of the car's front face and the imagery vocabulary. Taking the example of the "S3 high-end to low-end" imagery vocabulary, the results of the partial correlation coefficients are shown in Table 7.

Table 7. Analyse results of 'High end - Low end'

	Unstandardized coefficients		**Standardized coefficients**			**Collinearity statistics**	
Model	**B**	**Standard error**	**Beta**	**t**	**Significance**	**Allowance**	**VIF**
(Constant)	-4.041	0.992		-4.075	0.007		
Headlight group	1.600	0.534	0.797	2.995	0.024	0.447	2.237
Enter the style gate	-0.068	0.252	-0.060	-0.269	0.797	0.646	1.547
Hood curves	0.232	0.413	0.159	0.562	0.594	0.398	2.511
Fog lamp	0.093	0.155	0.112	0.605	0.568	0.928	1.078

The influence of various design elements in the front face of a car on the aesthetic perception is related to the magnitude of the partial correlation coefficient. A larger partial correlation coefficient indicates a stronger impact of the design element on the aesthetic perception. The partial correlation coefficient can be positive or negative, with positive values indicating a positive influence and negative values indicating a negative influence. Based on the research findings, it is possible to identify the design elements with larger absolute values of the partial correlation coefficient as the key design genes in the front face design of automobiles.

3.3. Determine the constraints

The design of the front face of a car needs to consider both brand genes and user expectations. For the Audi A3, which targets young people, the body shape needs to highlight a sense of fashion and high-end. User expectations include factors such as social trends and consumer aesthetic psychology, establishing constraints and associations between constraints and perceptual images. User expectation images are obtained through sensory engineering methods, and 60 sets of adjective pairs describing car images were collected through data collection and expert evaluations. The adjective pairs were rated using a Likert scale, with scores ranging from 3 to -3. Adjectives with an average score above 1.5 were extracted as user expectation images. These adjectives, ranked from highest to lowest score, are: high-end (2.12), technological (2.08), elegant (1.99), open (1.93), flowing (1.68), and individual (1.56).

In summary, considering both brand genes and user expectations, we have determined the final intended vocabulary as "high-end" and "imposing". Based on the mapping relationship between the design features and the desired image, we can determine that the larger the values of the four prominent features: front headlights A13, grille A24, hood curve A33, and fog lights A43, the more the front face of the car will exhibit the characteristics of "high-end" and "imposing". In particular, the front headlights A13 (with a partial regression coefficient of 1.600) have a significant impact on the "high-end vs low-end" desired image. Based on this information, we can determine the initial shape, as shown in Table 8.

Table 8. Initial shape

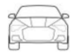
Headlight group	Enter the style gate	Hood curves	Fog lamp
			

3.4. Scheme generation

Based on the previous constraints, suitable grammar rules were selected to deduce the confirmed initial shape. The deduced solutions are shown in Table 9. A 5-point SD method was used to evaluate 81 new solutions through a questionnaire. The evaluation results showed that the new solutions scored above average for the "high-end" and "imposing" image words, indicating that the new solutions performed well in these image aspects. Solution 21 had the highest score, indicating that this method can effectively continue the brand features and meet user needs.

Table 9. 81 preliminary front face design proposals for cars

01	02	03	04	05	06	07	08	09
								
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
								
19	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
								
28	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
								
37	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
								
46	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**
								
55	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**

								
64	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**
								
73	**74**	**75**	**76**	**77**	**78**	**79**	**80**	**81**
								

4. Conclusions

This study takes the design of the front face of the Audi A3 as an example and explores the application of shape grammar guided by product DNA in automotive front face design. By quantifying the design variables of explicit design features and implicit design intentions, and applying them to solution deducing and optimization, the feasibility of the proposed design method has been validated. However, automotive design is a complex integrated design process, and when applying this method to design cars, it must be based on a unified overall style. In future research, it is necessary to combine the front face design with other genetic factors in automotive design, improve the establishment of the genetic library for automotive product families, and integrate shape grammar to form a comprehensive and systematic analysis and design method.

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