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On the Avant-Garde IDeS Method for the Future of Car Design Applied to an SUV Project

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Abstract: This case study aims to develop a new innovative SUV (Sport Utility Vehicle) model exploiting IDeS (Industrial Design Structure), which is an engineering approach conceived to optimize car design projects in the automotive industry like never before. A compact SUV was chosen because it is a type of vehicle that is highly requested by customers, and it is extremely successful in the market due to its versatility. In fact, compact SUVs are mixed vehicles that combine the pragmatism of a car with the typical robustness of an off-road vehicle making them suitable both for urban and off-road scenarios. The following pages will illustrate the steps followed for the realization of the final product using the SDE (Stylistic Design Engineering) method and other various design technologies, such as Quality Function Deployment (QFD), Benchmarking (BM) and Top Flop Analysis (TPA). In the final part of this project, the virtual prototyping of the product is carried out using Additive Manufacturing (AM) with an FDM 3D printer. The combination of these methods forms, to all intents and purposes, the IDeS, a newly developed innovative and cutting-edge discipline capable of schematically guiding the new product development process in companies with unprecedented efficiency.

Keywords: IDeS; SDE; car design; CAD modelling; innovation; QFD

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1. Introduction

The Sport Utility Vehicle (SUV) is a type of motor vehicle derived from offroad cars adapted to an urban use, which became popular around the world in the early 1970s when the British Land Rover introduced the first Range Rover model. SUVs resemble MPVs and station wagons while keeping off-road characteristics like high ground clearance and 4-wheel drive. SUVs, unlike other types of cars, are more comfortable due to having plenty of space for passengers, softer suspension and a higher driver's seat position, which brings a concrete advantage in increasing the driver's visibility while reducing the psychological stress caused by traffic. However, the center of gravity's height, suboptimal aerodynamics and the high weight of the vehicle could worsen the road holding, the emissions and the performance.

Regarding the regulations, the European Union (EU) has developed an extensive body of legislation which establishes standards and objectives for several pollutants emitted by motor vehicles [1]. Those new regulations will provide a 15% decrease of the CO2 emissions within 2025 and a 37% decrease within 2030 influencing the production's choices of the car manufacturers, who will be forced to adapt and redirect the production's strategy on ecological cars with zero detectable emission [2]. Although in the last ten years, the automotive market has seen an incredible increase in the SUVs' sales, reaching almost 50% of the European market share in 2021 and near 45% of the total market share, SUVs remain mostly powered by ICE (internal combustion engines) [3]. Additionally, considering their big dimensions in respect to other urban vehicles, SUVs are the second largest contributor of the vehicle market to an increase in global carbon emissions [4]. According to EU regulations, future SUVs will have to be powered by either an electric or hybrid engine in order to avoid high fees and therefore, a huge rise in SUV prices for customers. SUVs can be classified in 5 different categories:

- Mini SUVs: they are the smallest ones of the SUV segment, and they are shorter than 4200 mm. Current models are built with a load-bearing body frame with small off-road capabilities and interesting decorative features such as large bumpers and lowered suspension. In this class, we find vehicles like Fiat Sedici (Italy) and Suzuki SX4 (Japan).
- Compact SUVs: the medium-sized class with lengths between 4250 and 4600 mm. They can be either low-priced like Toyota RAV4 (Japan), or expensive, such as Mercedes-Benz GLC (Germany), Audi Q3 (Germany) and Range Rover Evoque (Great Britain).
- Crossover SUVs: (either called CUV or coupé-SUVs): they are born from the combination of compact SUVs' size with the sporting design of the coupé cars. In this category there are the BMW X4 (Germany), the Alfa Romeo Stelvio (Italy) and the Audi Q3 Sportback.
- Mid-size SUVs: the large size class, with a length between 4800 and 5000 mm. They are typically sold at a very high price, and they are considered the big brothers of compact SUVs, such as the Audi Q7, Mercedes-Benz GLE and Land Rover Defender (Great Britain). Inside the mid-size SUV segment, they develop the sport SUV concept, with vehicles such as the Porsche Cayenne (Germany), Range Rover Sport and Mercedes-Benz GLE AMG 63.
- Full-size SUV: the most luxurious and expensive class, with a length between 4800 and 5300 mm. This category includes Luxury SUVs, born from the starting idea that materialized with the launch of the Range Rover and followed by another model like BMW X7 and Mercedes-Benz G-Class; Sport Luxury, a new concept that includes Lamborghini Urus (Italy) and Aston Martin DBX (Great Britain); Super Luxury, much more expensive niche passenger cars, such as Mercedes-Mayback GLS-Class, Rolls-Royce Cullinan (Great Britain) and Bentley Bentayga (Great Britain).

A car model as ergonomic and unique as the SUV is certainly not going to disappear from the automotive market scene within a few years [5]. Therefore, even companies which have always been involved in producing racing cars such as Ferrari and Lamborghini have introduced this new vehicle model to their target market. For this reason, an innovative methodology such as IDeS is perfectly suited for applications in this field.

2. Materials and Methods

IDeS (Industrial Design Structure) is a new methodology designed to optimally guide the development process of a new product within a company. Its efficiency is such that several companies could also reorganize the subdivision of their departments and the tasks assigned to the various internal core teams according to the IDeS schematization itself. The main advantage, as will become clear, lies in the fact that each stage of product development, from market analysis and concept realization to prototyping, is described by the IDeS in such a way that the list of tasks to be performed and their allocation to the various employees of the company is clear in advance. Ideally, then, an efficient methodology such as IDeS should be flanked by good planning of internal activities (typically, using a Gantt chart). Very often, technical gaps in the project development are realized too late [6]. At other times, it occurs that the lack of innovation brought to the market by the new product is noticed too late [7]. Errors in the virtual prototypes of the product made in CAD, in the design calculations, and flaws in the manufacture of the model are all delicate aspects at the root of the greatest loss of time and money that companies incur. IDeS's main objective is to minimize the possibility of them happening as much as possible. It is composed of three main phases:

- Product Set-up: this is the industrial project's phase in which a new product's idea is conceived. The Product Set-up is composed of the Quality Function Deployment (QFD), which surveys the market to accurately understand the customer needs [8]. Subsequently, a study of competitors is achieved by Benchmarking Analysis. Afterwards, the Product Set-up ends with the definition of the innovative aspects of the new product, through the Product Architecture, and with an aesthetic analysis according to Stylistic Design Engineering (SDE).
- Project Development: in this phase, the product is developed by building a 3D model based on the functional and aesthetical details chosen in the earlier steps. Then, the 3D model is used to create the final rendering before going ahead with prototyping.
- Production Set-up: if the prototype satisfies all the previous criteria (both QFD and SDE), then production can take place. This topic will not be covered in the present article.

2.1. Quality Function Deployment (QFD)

The concept of the QFD method was firstly introduced in Japan in the late 1960s and actively developed at Mitsubishi's Kobe Shipyard (Japan) in 1972 [9]. This method is used to help manufacturers to develop market-oriented products by linking customers' needs with technical characteristics, gaining an advantage in the market due to higher satisfaction rate [10]. The QFD is based on two main parts: the first one concerns the "Six Questions" analysis and the second one the use of two matrices: the "Importance" and the "Independence" matrix [11].

2.1.1. Six Questions

The Six Questions are used here to define the necessary characteristics or requirements for a brand-new compact SUV according to allegedly future customers. The questions listed below can be answered both by members of the company (engineers, designers, research and development staff, etc.) and by people outside the company. Among the latter, it is possible to recognize a particular class of future buyers of the product under development. These opinions, if obtained on both sides, ensure that the investigation of the degree of innovation to be offered to the market can be extended to many interviewed samples. Furthermore, they help at an early stage to assess the degree of feasibility of the product by the company investing in its development.

- Who buys it: the product is targeted at the upper-middle class, in particular adult workers (35+ years old) who may have family but will not give up the sporting appeal of the car. The requirements the product must have in order to satisfy the needs investigated with the first question are: appealing design, passenger and load compartment, versatility, security, performance.
- What is it for: the product serves to supply a comfortable travel experience for all the passengers and provides plenty of space for any loads, like suitcases or bags. Requirements: comfort, passenger, and load compartment.
- Where is it employed: the product can be used both on urban roads and on suburban roads due to its electrical power engine, its compact size, its comfort, and the high batteries' autonomy. Requirements: dimensions, comfort, autonomy, versatility.
- When is it used: the product can be used in all seasons and on all occasions, which makes it perfect for daily use due to the product's versatility. Requirements: emissions, comfort, versatility.
- Why is it chosen: the product provides reliable performance, best comfort, high security, infotainment, sporting and elegant design, and it is highly customizable. Requirements: security, comfort, performance, design, versatility, customization, technology.

- How is it used: the product's characteristics can be varied according to the driving situation, road condition, or personal needs. Requirements: versatility, comfort, performance.

Requirements are expression of the needs of the client; therefore, a deep understanding of those needs might be a key in order to design a high-selling car:

- Design: aesthetics is still one of the most influential points in selling products, in particular cars. A good-looking car will outsell an average-looking car even if the last one has better performances. The design of a vehicle is the first thing customers look at in a car; therefore, it should be appealing and intriguing.
- Interior space: even if compact SUVs try to shrink the dimensions as much as possible, they are still SUV. The person who buys an SUV is one looking for plenty of habitability for himself and his passenger.
- Load compartment: along the interior space, an SUV should provide large load compartments, meaning a large trunk in the back and in the front that might be available in case the vehicle is electrically powered. However, load compartments should not worsen the cockpit.
- Versatility: a key characteristic increasingly searched for by customers that have the need to adapt their vehicle to multiple functions supplying as much as possible a flawless experience.
- Safety: due to the COVID-19 pandemic, which negatively influenced public transportation, private cars became the main form of transportation. SUVs, given their dimensions, provide more space for manufacturers to work on safety systems like multiple airbags or a bulkier chassis to ensure a safe environment for the cockpit [12].
- Performance: significant not only in terms of maximum velocity and acceleration but also for the optimization of energy and fuel consumption.
- Price: surely what most of the clients look for. It depends on production and R&D costs as well as the brand name and prestige of the product. Every technical and qualitative aspect of the vehicle affects the final price.
- Visibility: one of the main pros of an SUV is road and obstacle visibility given by the large dimensions and thanks to the high height of the car.
- Comfort: given the large dimensions and the available interior space, one can expect to find in SUVs a quite comfortable experience for both long travels, allowing also huge luggage capability in the trunk, and short urban trips.
- Emissions: the 21st century challenge is climate change. The level of emissions that humanity have kept for the last thirty years is unsustainable; therefore, we need to improve our emission rates in all aspects of our lives, which means also in the transport market. All the regulations on emissions of the nations as well as worldwide agreements, like the Parigi agreements of 2015, are set to guide us to a more sustainable transportation in the next future [13].
- Customization: the compact SUV market is spread over a wide range of prices, from EUR 30,000 to more than EUR 70,000 due to customization options. When a customer is willing to spend such an amount of money, he would also like to be able to personalize his car according to his taste and preferences.
- Technology: the last fifteen years have seen an exponential growth in technology applied to vehicles, from infotainment to safety systems, fuel and energy consumptions and, in the most recent years, autonomous driving.

2.1.2. Matrices

Once an initial market analysis (including the six typical questions) reveals the general requirements that the vehicle must have, it is useful to understand which ones are the most important and for what reasons. The two tables constructed to identify them are the "Importance matrix" and the "Independence matrix". The first one is filled by numerical values given by the relative importance between the row and the column requirement:

- 0 if the row element is less important than the column one's.
- 1 if they are both equally important.
- 2 if the column element the more important than the row one's.

The total importance value is given by the sum of the row values. Lastly, in order to figure out the relative relationships between the requirements, the independence matrix is constructed by values given by the relative dependence of the row requirement respect to the column one:

- 1 if the dependence is weak.
- 3 if the dependence average.
- 9 if the dependence is strong.

The total dependence grade is given by the sum of the row values, while the total influence grade is given by the sum of the column values. As can be appreciated in Figure 1, the most important requirements are: Design, Price, Visibility, Comfort, Emissions, and Technology.

	Ghvljq	Lqwhulru#vsdfh	Ordg#frp sduwp hqw	Yhuvdwlolw|	Vdihw|	Shuirup dqfh	Sulfh	Frp iruw	Hdvh#ri#xvh	Fxvwrp l}dwlrq	Whfkqrorj|	G lp hqvlrqv	Wrwdo	Lp sruwdqfh
Ghvljq	4	4	5	4	5	5	4	4	4	4	4	5	49	;17
Lqwhulru#vsdfh	4	4	5	3	4	4	3	4	3	4	4	4	43	816
Ordg#frp sduwp hqw	3	3	4	3	4	3	3	3	3	3	3	3	5	414
Yhuvdwlolw|	4	5	5	4	5	4	4	3	3	5	4	4	47	:17
Vdihw|	3	4	4	3	4	4	4	4	3	5	4	5	44	81;
Shuirup dqfh	3	4	5	4	4	4	4	4	3	5	4	4	45	916
Sulfh	4	5	5	4	4	4	4	4	4	5	4	5	49	;17
Frp iruw	4	4	5	5	4	4	4	4	4	4	4	5	48	:1k
Hdhfwulf	4	5	5	5	5	5	4	4	4	5	4	5	4<	4313
Fxvwrp l}dwlrq	4	4	5	3	3	3	3	4	3	4	3	5	;	715
Whfkqrorj|	4	4	5	4	4	4	4	4	4	5	4	5	48	:1k
G lp hqvlrqv	3	4	5	4	3	4	3	3	3	3	3	4	9	615

Figure 1. Importance Matrix.

As can be appreciated in Figure 2, the most dependent requirements are versatility, performance, and price, while the most influential ones are interior space, technology, and dimensions.

	Ghvljq	Lqwhulru#vsdfh	Ordg#frp sduwp hqw	Yhuvdwlolw|	Vdihw|	Shuirup dqfh	Sulfh	Frp iruw	Hohfwulf	Fxvwrp l}dwlrq	Whfkqrorj|	Glp hqvlrqv	Wrwdo
Ghvljq		4	4		4		4			4	6		;
Lqwhulru#vsdfh	6									6	6	<	4;
Ordg#frp sduwp hqw	6								6	6		<	4;
Yhuvdwlolw|		6	6		6	4		6	6		<	6	5;
Vdihw|		6				4	4	4			<	6	4;
Shuirup dqfh					4		6	4	<	4	<	<	66
Sulfh	<	6	6	6	6	<		6	<	6	<	4	88
Frp iruw		<	6	6	4	4	4		6		6	4	58
Hohfwulf				6		6					4		:
Fxvwrp l}dwlrq	4						6				6		:
Whfkqrorj|							6						6
Glp hqvlrqv	4	<	<			4		4					54
Wrwdo	4:	5;	4<	<	<	49	45	<	5:	44	7<	68	

Figure 2. Independence Matrix.

2.2. Benchmarking Analysis

A direct comparison with the company's main competitors, in relation to the various products already marketed by them, is ideal for two main reasons. Firstly, it allows one to understand what strategies they have devised to meet customers' needs by offering highly innovative solutions [14]. Furthermore, it is necessary to understand in which technical-quality aspects it is necessary to invest more time and money to obtain a product which is better than the others and therefore, highly competitive on the market. This type of comparison is called "benchmarking analysis". In this sample work, nine vehicles are considered as competitors:

- Alfa Romeo Stelvio: from the Italian automotive industry, equipped with an internal combustion engine (ICE), it combines the dynamism of a sports car with the comfort of an SUV.
- Range Rover Evoque P300E: the Evoque P300E employs the PTA platform of Land Rover, specially designed to accommodate the plug-in hybrid electric vehicle (PHEV) propulsion system.
- BMW X2: the compact SUV of the Bavarian car manufacturer, equipped with a PHEV propulsion system that provides an exceptionally low electric consumption.
- Audi Q3 SB TFSI: the compact SUV of the German automotive industry, which combines sportive and elegant aspect with a PHEV propulsion system.
- Mercedes-Benz EQA: this model of EQA was born in 2021 and it is a full electric "sister" of the GLA with two motors that provide zero emission.
- Ford Mustang Mach-e (USA): the first fully electric SUV by Ford, inspired by the muscle Mustang model. It is extraordinarily strong on the market thanks to its small dimensions.
- Kia EV6 (Corea): a fully electric crossover SUV that shows a modern and distinctive design, with an EV autonomy up to 450 km.

- Volkswagen ID.4 GTX (Germany): the first fully electric crossover SUV of the German car manufacturer shows itself with a natural and elegant design and a top electric engine.
- Lexus UX FE (Japan): a fully electric crossover SUV that has a sporty appearance and combines speed, fluidity, and silent drive.

In Figure 3 are shown all the competitors and to each of them are linked nineteen technical specifics in order to have a total vision of the fundamental characteristics of the cars.

Brand Model	Alfa Romeo Stelvio	Range Rover Evoque P300E	BMW X2	Audi Q3 SB TFSI	Mercedes-Benz EQA	Ford Mustang Mach-E	Kia EV6	Volkswagen ID.4 GTX	Lexus UX FE	TOP VALUES
Powertrain	Diesel	PHEV Gasoline	PHEV Gasoline	PHEV Gasoline	Full Electric	Full Electric	Full Electric	Full Electric	Full Electric	
Consumption [L/100km]	4.8	2	1.7	1.6	-	-	-	-	-	-
Consumption [kWh/100km]	-	18	15	16	17.7	17.2	16.9	18.1	17.8	< 15
EV Autonomy [km]	-	55	53	51	426	440	480	480	305	>480
Emissions [g/km]	128	44	40	36	-	-	-	-	-	-
Length [mm]	4690	4370	4360	4484	4460	4655	4680	4582	4490	< 4360
Width [mm]	1900	1990	1820	1849	1850	1790	1880	1852	1840	< 1790
Height [mm]	1670	1640	1520	1616	1620	1460	1550	1637	1540	< 1460
Weight [Kg]	1660	1787	1500	1740	1965	1969	1985	2224	1860	< 1500
Load Capacity [L]	525	472	470	380	340	402	490	534	367	> 534
Displacement [cc]	2143	1497	1499	1395	-	-	-	-	-	-
Power [kW/CV]	118/160	227/309	162/220	180/245	140/190	198/269	168/228	220/299	150/200	> 227/309
Max Speed [km/h]	220	213	193	210	160	190	185	180	160	> 220
Acceleration 0-100km/h [s]	8.1	6.4	6.8	7.3	8.9	6.2	7.5	6.2	7.5	< 6.2
Maximum Torque [Nm]	450	260	220	400	373	430	350	460	300	> 460
Number of Seats	5	5	5	5	5	5	5	5	5	5
Number of Doors	5	5	5	5	5	5	5	5	5	5
Recharge time [km/10min]		22	40	20	68	73	64	77	49	> 77
Price [€]	53,500	57,850	49,950	55,000	55,000	52,000	49,500	54,700	57,000	< 48,680
TOP	1	1	3	1	1	4	2	6	1	
FLOP	5	2	1	2	3	0	0	2	1	
DELTA	-4	-1	2	-1	-2	4	2	4	0	

Figure 3. Benchmarking matrix with a comparison between different competitors.

The first thing to do is to recognize for each characteristic which is the best and the worst car that satisfies it. For example, the Audi Q3 seems to be the best car by looking at the estimated average fuel consumption per 100 km. The Alfa Romeo Stelvio, on the other hand, seems to be the most fuel-consuming car among those under investigation. It is important to remember that data for benchmarking analysis are generally taken from the literature. Their reliability should be investigated. However, even data that are not perfectly correct can fit into this table as the objective is to delineate a list of characteristics on which innovation should be made and not a simple ranking between cars. it is convenient to compare models belonging to the same market segment. Comparing very different vehicles, such as a city car and a racing car, obviously does not make the slightest sense.

The last column of Figure 3 is the Innovation Column, which highlights the best value in a row for each different feature, preceded by “<” or “>” depending on whether they need to be decreased or increased in the new product.

In the last rows of the same figure, the “top-flop analysis” appears, which is useful to define the level of innovation to provide to the future customers. For each car, a difference is made between the number of characteristics in which it is the best and those in which it is the worst. The difference can even be negative in some cases. This is done to calculate the “Delta” value, which is equal to the greatest difference between those calculated for each brand. This parameter is particularly important as it represents the theoretical number of features in which the new SUV model will have to be better than the others in order to be a success.

2.3. What-How Matrix

The What–How matrix allows one to compare the requirements of the customers (What) with the designer’s answers (How). Therefore, Figure 4 shows in the rows the requirements of the customers (obtained in the Importance matrix) and in the columns, the parameters used in the Benchmarking Analysis. To set the type of relationship between the customer requirements and the performance of the car, a numerical evaluation was used: non present (0), weak (2), medium (4–6), and strong (8–10). Finally, all the values in each column were summed up and chosen as the many highest values as Delta of Innovation (5) imposed: Type of powertrain system, EV autonomy, General dimensions, Number of seats, Recharge time.

	Srzhuwudlq	Frqvxpswlrq	HY#Dxwrqrp|	Hplvvlrqv	Glphqvlrqv	Zhljkw	Ordg#fdsdflw|	Srzhu	Pd{#vshhg	Dffhohudwlrq	Pd{#Wrutxh	Qxp1#ri#Vhdwv	Qxp1#ri#Grruv	Uhfkdujh#Wlph	Sulfh	Wrwdo
Ghvljq	7	5	5	3	43	7	9	3	7	3	3	7	;	3	9	83
Sulfh	9	7	7	5	5	3	5	9	7	7	7	5	5	;	3	83
Ylvlelolw|	3	3	3	3	43	3	7	3	3	3	3	;	7	3	5	5;
Frpiruw	5	3	7	3	7	5	5	5	3	3	3	;	;	43	7	79
Hohfwulf	43	43	43	43	7	9	9	7	7	;	;	3	3	43	;	<;
Whfkqrorj|	9	7	7	7	3	3	3	7	3	7	3	3	3	9	5	67
Wrwdo	5;	53	57	49	63	45	53	49	45	49	45	55	55	67	55	

Figure 4. What–How matrix.

3. Case Study

3.1. Product Architecture

The next step in the IDeS "to-do list" is the study of product architecture. It concerns the schematization of the various components that are part of the finished assembly, placed in a conceptual framework. In the case of an automobile, this phase is particularly complex, and it is not intended to be investigated in depth; it is not the purpose of this article. Only a summarized example containing some salient aspects is provided. The schematization starts from the features to innovate in order to make the SUV competitive in the market.

(a) General dimensions: looking up at the Benchmarking Analysis, the target dimensions were the height and the width of the Ford Mustang Mach-E (1460 mm, 1790 mm) and the length of the BMW X2 (4360 mm). With the aim of improving the habitability of passengers, the height of the Mustang is neglected by setting the new height at 1550 mm.

(b) Type of powertrain system: the powertrain choice has been made following the rules of the What–How Matrix in Figure 4. The main categories analyzed were price derived (fuel cost, vehicle cost, cost/km), performances (acceleration, top speed, weight, tested technology) and generality (autonomy, emissions, tax benefits).

- Fuel cost: electric is surely the cheapest source of power right now and PHEV, being powered up by both electric power and liquid fuels, can be placed in an intermediate price range.
- Vehicle cost: diesel and gasoline engines are already technologically advanced and optimized while electric motors are still in optimization phase and therefore, also considering the cost of the battery pack, pricier.
- Cost/Km: this parameter takes into consideration all the fixed and variable costs and according to ACI, the average cost is EUR 0.51–0.60/km for gasoline, EUR 0.35–0.65/km for diesel, EUR 0.37–0.55/km for hybrids and EUR 0.28–0.41/km for the electric vehicle.
- Acceleration: electric engines characteristics allow them to provide top acceleration better than ICE thanks to the max torque which can be provided since the start of the engine, while ICE needs to reach high rpm to provide maximum torque.

- Top speed: in this case, the weight of the car needs to be considered and an EV needs huge battery packs which slow down the car in reaching the top speed. Therefore, ICEs are more capable of reaching higher speeds.
- Weight: as said before, the battery of the EV is not neglectable making them the heaviest.
- Tested technology: ICEs are already deeply tested and reliable while hybrids and electric are still in development and optimization and their performances and reliability are improving yearly.
- Autonomy: ICEs are still the best choice for long travels, but the energy density of the batteries is growing as well as the range of EVs.
- Emissions: opposite to autonomy, the EV guarantees zero emissions (if the electric energy used to recharge the battery is obtained at zero emissions).
- Tax benefits: hybrids and EVs still have price incentives, tax relief and, according to the city's regulation, different privileges (free parking, access to limited traffic zones, and so on).

As shown in Figure 5, the most suitable powertrain was the electric one.

	Jdvrolqh	Glhvho	SKHY	HY	Wrwdo
Ixho#frvw	5	7	;	43	57
Yhklfoh#frvw	43	43	9	7	63
Frvw2np	7	7	;	43	59
Dffhohudwlrq	9	7	;	43	5;
Pd{#vshhg	43	43	9	7	63
Zhljkw	;	;	5	5	53
Whvwhg#whfkqrorj|	43	43	;	9	67
Dxwrqrp|	;	;	;	9	63
Hplvvlrqv	5	5	9	43	53
Wd{#ehqhilw	5	5	43	43	57
Wrwdo	95	95	:3	:5	

Figure 5. What–How matrix for powertrain choice.

Given the nature of the powertrain, the vehicle was equipped with 4 electric motors, one for each wheel, to provide different torque depending on the driving situation to enhance performances, drivability, and safety.

(c) EV Autonomy: Currently on the market, there are various kinds of batteries available: cylindrical, prismatic, and pouch. The decision was to use multiple cylindrical solid-state batteries to increase the energy density and to provide a reliable functioning and to make the maintenance easier. The type of cell was a solid-state cell 4680 with graphene which may provide autonomy up to 500 km.

(d) Recharge time: The output of a charge is measured considering amperage and voltage. Amperage is the amount of electricity that flows from the battery to the connected device, while voltage indicates the strength of the electric current. Multiplying volts by amps gives the total power measured in watts. Graphene solid-state batteries can provide up to 550 kW of fast charging which means an average of 150 km/10 min. The main problem of graphene batteries is the price, which can be reduced at 1/10 of the standard production cost thanks to the 3D graphene technology.

(e) Number of seats: The goal is to take the market share of large families by allowing customers to choose different options for the number of seats: the classical 5 seats supplying a huge space for the trunk and plenty of habitability in the back seats; the 6 seats configuration reducing the load compartment by offering the maximum available habitability for the passengers; the 7 seats configuration which offers the greatest number of seats for large families.

3.2. Sketches

With the Stylistic Design Engineering (SDE), the vehicle design process is defined in a rigorous and rather new way. In fact, while up until the 2000s, this important phase in the development of a new vehicle was entrusted solely to great experts in the field, such as Pininfarina, Zagato, Giugiaro, Bertone, thanks to the revolutionary initial approach offered by engineer Lorenzo Ramacciotti, former CEO of Pininfarina Spa, and thanks to the research activities of the University of Bologna, things have changed considerably. By applying in detail the steps briefly described below, it is possible even for small companies to devise and create great design results that offer innovation and uniqueness to the new product being developed. In this case, we will refer to an SUV. The first point is to study different stylistic trends (Retro, Stone, Natural, and Advanced) and draw different sketches, one for each trend.

(a) Retro: the term Retro pays homage to the past with recent elements. In the automotive world, the Retro style is inspired by the 1970s, 1980s, and 1990s: for example, the Fiat 500 model is a new city car that takes the style of the old 500 model.
(b) Stone: as the name suggests, the Stone style calls for a robust, gritty, and massive design. Stone style is particularly present in the automotive world of the last years, and it is the typical design adopted by SUV models but also for luxury sports cars like Rolls Royce. The robust characteristics of the Stone trend are seen as a safer product by the customers.
(c) Natural: nature has always been a source of inspiration for designers, and it plays a key role in modern concepts. The Natural style looks to reinterpret tradition in a modern way, based on the lightness, strength, and elegance of nature.
(d) Advance: Nowadays, new and extravagant style trends that can convey the idea of future to people are highly appreciated. The Advanced style was born in the 20th century, bringing an avant-garde vision to the new product. The key features of this trend are completely new, revolutionary, minimal, and geometrically regular forms.

In Figure 6, the sketches (made on Sketchbook) of the four analyzed trends are proposed in three different views: ¾ front, ¾ retro, and lateral.

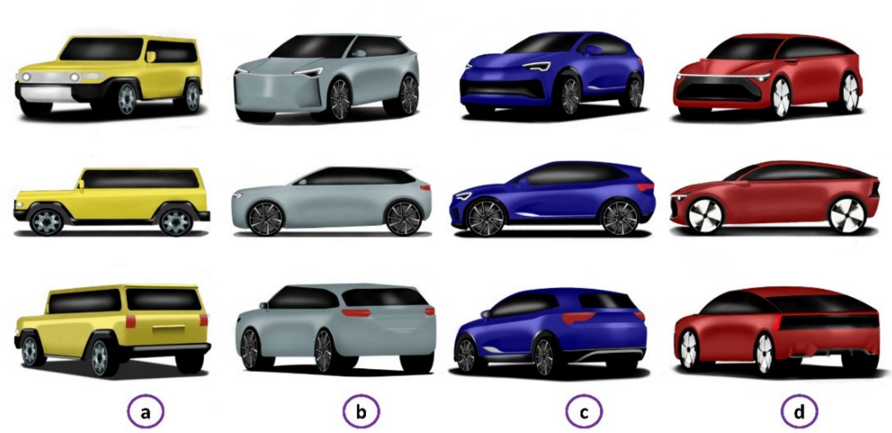

Figure 6. Colored sketches: (**a**) Retro; (**b**) Stone; (**c**) Natural; (**d**) Advanced.

3.3. 2D Drawings

The 2D drawings convert the approximate shapes of the sketches into an orthogonal design (on software such as AutoCAD) making the lines more realistic, so it will be possible to have a clearer overview of dimensions and proportions. Orthogonal projections (Figure 7) were set up as blueprint views starting from the digital sketches, with four projections planes, according to the lateral view, the top view, the back view, and the front view. For each style, the lateral view was drawn into a 4360 mm (length) × 1550 mm (height) square, the top view into a 4360 mm (length) × 1790 mm (width) square, the front, and the back view into a 1790 mm (width) × 1550 mm (height) and the wheelbase was equal to 2680 mm.

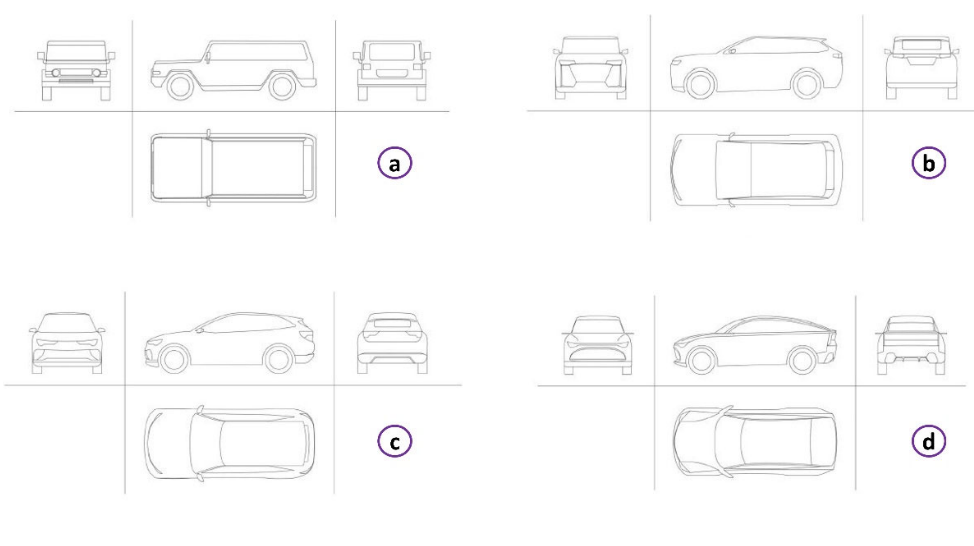

Figure 7. (**a**) Retro views; (**b**) Stone views; (**c**) Natural views; (**d**) Advance views.

3.4. Volumetric and Aerodynamic Analysis

The volumetric analysis shown in Figure 8 allows to understand the interior space, one of the most important features a SUV can have to increase the level of passengers' comfort. It was carried out using AutoCAD and superimposing the lateral shapes of each trend.

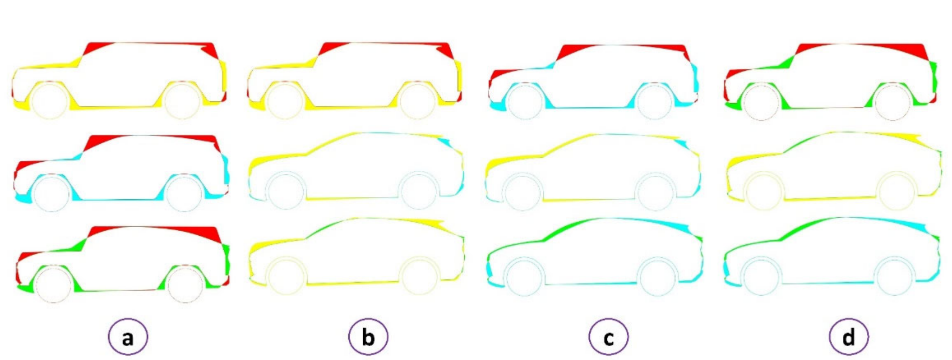

Figure 8. Volumetric analysis for each style against the others: (**a**) Retro; (**b**) Stone; (**c**) Natural; (**d**) Advanced.

The idea was to create a ranking, in which all the four styles competed against each other. The model with the most internal space earns 2 points, while the loser earns 0 points. All the comparisons are summarized below:

- First comparison: Advanced (0 points) vs. Natural (2 points); Retro (2 points) vs. Stone (0 points);
- Second comparison: Advanced (0 points) vs. Retro (2 points); Natural (0 points) vs. Stone (2 points);
- Third comparison: Advanced (0 points) vs. Stone (2 points); Retro (2 points) vs. Natural (0 points).

The most successful result came from the Retro style, followed by the Stone one and the Natural one. The last one, in this case, is the Advanced style. Through the aerodynamic analysis, it is possible to evaluate the Cd (drag coefficient) performed on Ansys. This value shows the ability of the car to break through the air, as it is a dimensionless coefficient useful to measure the aerodynamic resistance of a moving body in a fluid: the higher the coefficient is, the greater is the resistance offered by the air and the worse is the aerodynamics of the car [15]. The drag coefficients were calculated imposing a standard speed of 100 km/h on simplified shapes for each car style. The results obtained were: 1.161 for Retro; 0.838 for Stone; 0.776 for Natural; 0.813 for the Advanced Style. As can be seen from the Cds values, the shape of the Natural and Advance presented a less resistance to the forward motion. However, it is essential to highlight how the results are all remarkably close and oscillate around a Cd equal to 0.8, apart from the Retro.

4. Results

The final design was created combining distinct characteristics of the previous proposals: the upper part was taken from the Stone in order to provide more interior space, the front and the rear of the car from the Advanced to give a more futuristic design with a fair aerodynamic resistance, while the lateral part was taken from the Natural style for stylistic reasons. Therefore, the final proposal contains three of the four trends shown before. The final sketch and blueprints are shown in Figure 9.

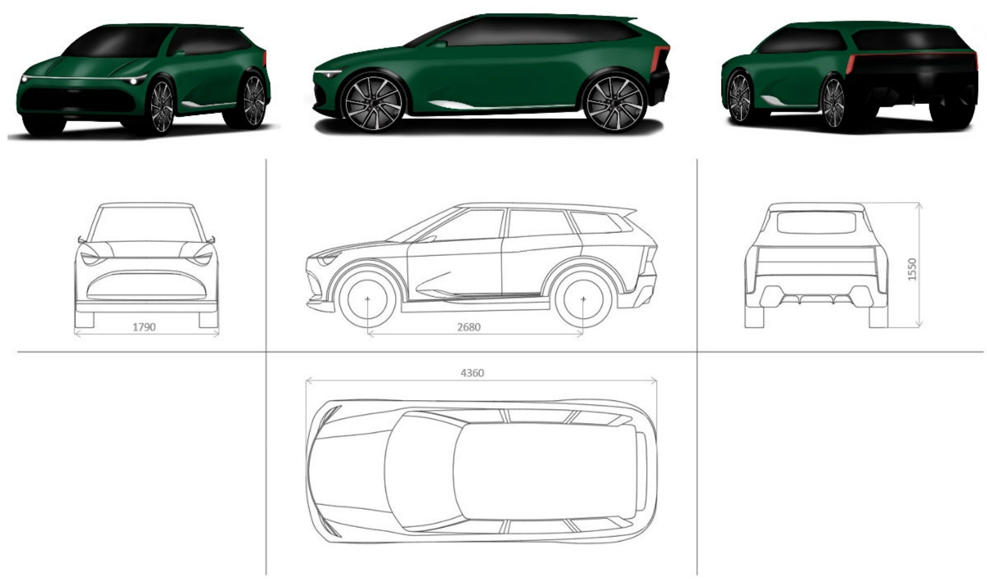

Figure 9. Final sketches with different views of the model and final blueprints with the main dimensions of the vehicle.

4.1. Chassis Modelling and Optimization

The purely engineering side concerning the design of a vehicle comes into play, for example, when the first CAD model of the chassis is made. The procedure is time-consuming and particularly complex, so an extremely simplified example of building the chassis (with a structural simulation applied to it to test its mechanical behavior) will be shown here. The first step in the modelling of the frame was to create its structure by considering two hypothetical different configurations. This should not come across as an unnecessary complication. Very often the study of several possible configurations is tackled during the course of a project in order to obtain a better chance of the optimal solution emerging, in terms of aesthetics, functionality, and product performance.

Both configurations were made with the consideration of providing sufficient space for the electric motor mounts, suspension, battery pack, and cable management. This was done assuming a forward-shifted battery position, which would require longer cables to connect all devices. Subsequently, both chassis were validated using structural steel as material in order to guarantee high resistance values while implementing a static structural analysis on Ansys. A vertical load of 13 kN representing the weight of the car's parts supported by the chassis was applied on the center of mass (CoM), then five remote points were set: (a) Center of Mass (CoM) (for the vehicle load force application); (b) Rear left wheel (pin constraint); (c) Rear right wheel (roller constraint); (d) Front right wheel (roller constraint); (e) Front left wheel (pin constraint). A safety factor of 18.94 was evaluated. Otherwise, considering the chassis without a structural battery, 6 remote points were set because the battery weight was considered as a vertical force to be added to the 13 kN, and they were: (a) Center of Mass (CoM) (vehicle load force application); (b) CoM of the battery (battery load force application); (c) Rear left wheel (pin constraint); (d) Rear right wheel (roller constraint); (e) Front right wheel (roller constraint); (f) Front left wheel (pin constraint). Figure 10 shows the result of the simulation in terms of stresses and total deformation (mm). A safety factor equals to 8.85 was evaluated.

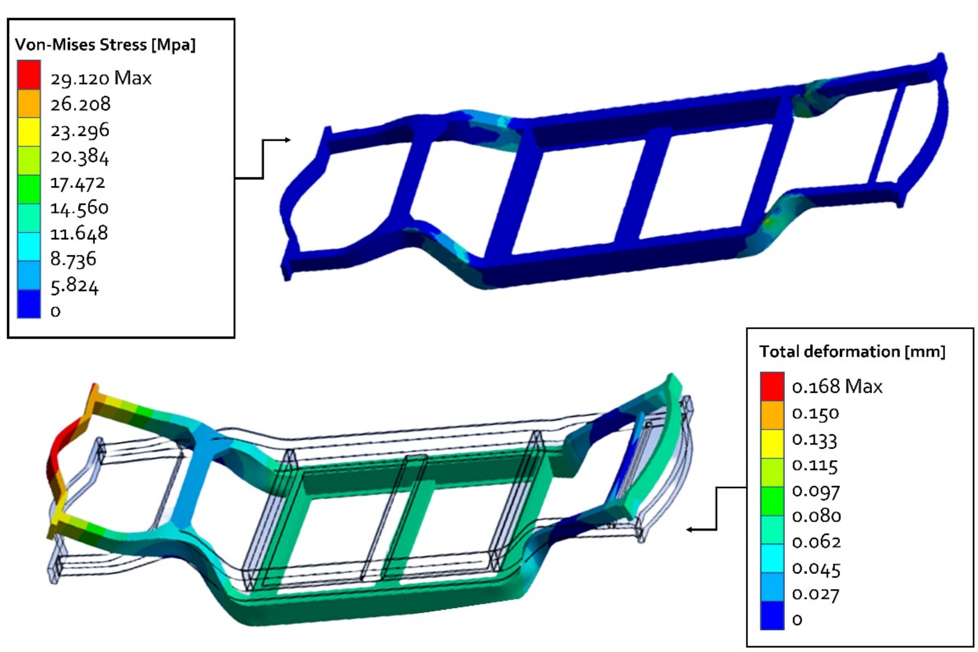

Figure 10. Max stress values and max deformation (scale × 1000) evaluated for the second configuration.

Finally, the upper part was modelled according to the dimensions of the final blueprint. In Figure 11, the final mock-up is shown. With the aim of contextualizing the chassis together with the other elements inside the car, there was created a more complex assembly by also adding wheels, four electric motors, seats in the 7-seat configuration and a hypothetical driver with an average height of 185 cm. This part of the project is particularly useful for an initial assessment of the ergonomics of the vehicle. Possible issues related to incorrect dimensioning of the interior volume or lack of visibility to the outside should already emerge at this design stage. The simplified model of a driver helps even more in making these assessments.

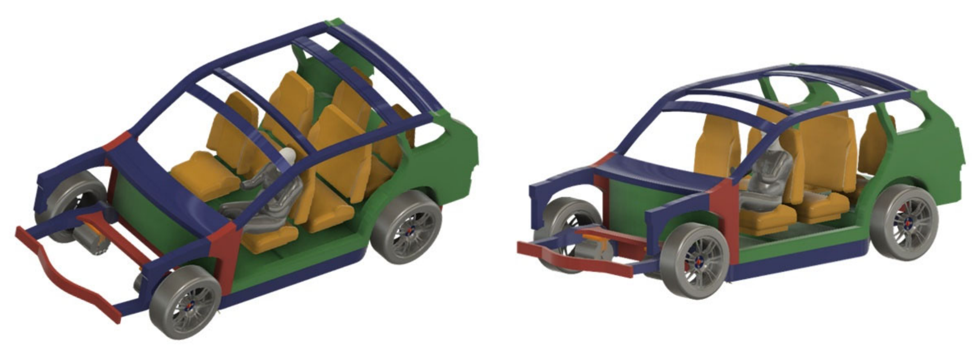

Figure 11. Final mock-up with an integrated driver model. Castings are visible in red, sheets in green, and extrusions in blue.

4.2. Surface Modelling and Aerodynamic Validation

3D body-surface modelling is used to create a 3D drawing where the designers can interact in a more dynamic way. In this phase, it is possible to introduce accurate details with more refined and precise shapes, which cannot be obtained with sketches and blueprints [16]. Starting from the blueprints of the car, the external body of the vehicle was modelled on Blender using subdivisions surfaces using the blueprints as a guide. The modelling of the car body is critical and requires months of work in a specialized company. The quality of the model must be faultless or defects in it will be reflected in dents and blemishes that will appear on the physical model of the vehicle. The use of subdivision surfaces is excellent to ensure a continuity of curvature even in the most geometrically complex areas; they are also very quick to implement. However, neither this type of surface nor the use of software such as Blender is adequate for a product that is to be engineered. Blender is not a CAD, like NX or Catia, software used in high-class companies like Mercedes and BMW. However, the methodology described here is excellent if applied with the aim of obtaining an initial styling result of the finished SUV in a short time. The final 3D model is shown in Figure 12.

Figure 12. 3D model design on Blender.

Once the external shape of the final model of the car was obtained, the entire series of aerodynamic tests designed for the model had to be re-performed. As can be seen in Figures 13 and 14, a considerable improvement was obtained, demonstrating that the stylistic choices were also appropriate from an engineering point of view. To perform the fluid dynamic analysis, the first thing to do is to derive a negative of the vehicle that is as simplified as possible. This means that small shape details (door handles, vehicle logo, style lines on the body, and so on) should be removed so as not to unduly lengthen the time of mesh computation and analysis resolution by the software (Ansys Fluent in this case). Moreover, such details do not have a major influence on the final value of the vehicle drag coefficient and the distribution of air velocity flow around it. It was chosen to work with a k-epsilon model (settable on Fluent) and a vehicle speed of 130 km/h. The outlet pressure of the air flow was set equal to atmospheric pressure for obvious reasons.

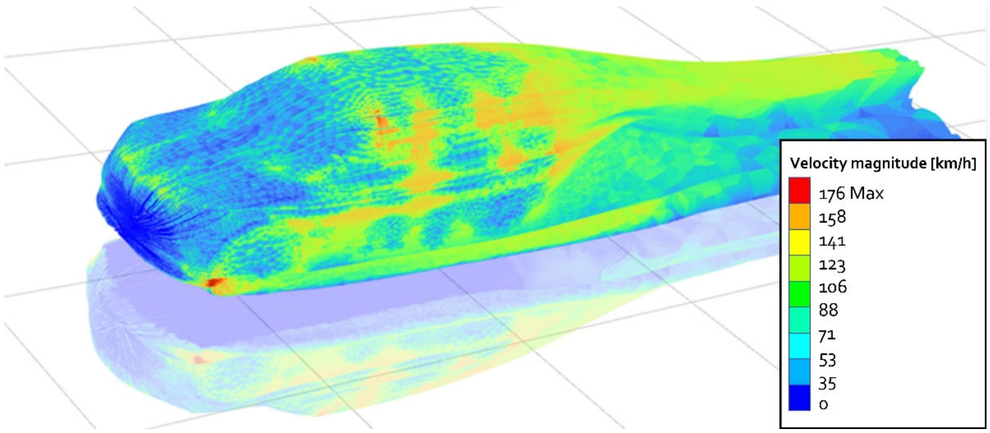

Figure 13. Final aerodynamic analysis with air flow.

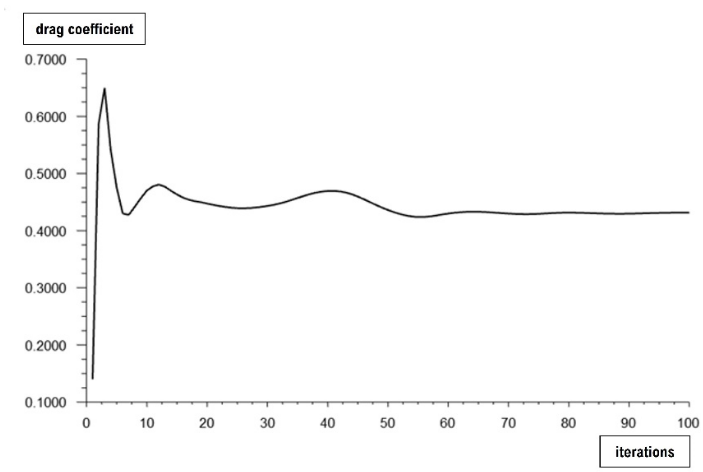

Figure 14. Chart on the convergence to the exact value of Cd obtained with Ansys Fluent with increasing number of iterations.

4.3. Rendering

The rendering phase, performed here both on Blender (for the cloth reveal) and Keyshot (preferred for the static rendering to show more realistic colors in distinct environments), is used to have realistic images of the final product and it is an important phase because it transmits to customers the coherence, the aesthetic beauty of the product and the same sensations that they would feel if the product would have been right in front of them. Rendering is the digital representation that simulates materials of the product components in different realistic environments that can enhance all the characteristics of the product. Therefore, it is possible to make distinct color choices and aesthetic combinations, assuming real life scenarios. In Figure 15, two outdoor renderings of the final car are shown.

Figure 15. Rendering performed using Keyshot.

4.4. 3D Prototyping

Thanks to 3D printing, it was possible to obtain the digitally designed shapes of Voyager in a three-dimensional model. This process is fundamental for rapid prototyping, it is in fact able to create objects starting exclusively from the 3D model without the need for demanding knowledge [17]. The most-used printing technology is FDM, which uses a filament that is extruded into a nozzle at elevated temperatures, the material that comes out is deposited on a moving plate and defines the final shapes layer by layer. This type of printing is very versatile because it can work with multiple materials, like metallic and polymeric ones, while providing a high quality of printed objects. However, to create cantilevered surfaces, it is necessary to create supports which reduce the cleanliness of the model. The Voyager prototype was made by FDM with a black PET-G filament and printed in a temperature range of 233–243 °C for the extruder and 65–72 °C for the plate. In order to enhance all the details of the car and avoid losing definition due to the support, the decision was made to print the model by dividing it into two halves and assembling them later. Once the printing was completed, the model was assembled and colored by hand with realistic colors in order to improve the final aesthetic (Figure 16).

Figure 16. 3D printed model.

5. Conclusions

This project was intended to describe the stylistic development of an electric and innovative SUV. Starting from a preliminary analysis, through the Quality Function Development, the main requests of customers were highlighted and, through the Stylistic Design Engineering, they were converted into sketches, creating five total proposals for the aesthetic configuration of the new SUV, called Voyager: one for each trend studied, and subsequently, a final proposal that merged three of the four trends. The application of the method led afterwards to the creation of orthogonal projections (2D CAD) and finally, to the body surface modelling (3D CAD) of the car, achieving the objectives of the SDE. A further goal was achieved by placing the Voyager SUV into real environments in the rendering phase, which confirmed the validity of the idea and enhanced the aesthetic qualities of the product. As a result of the project, it was possible to view the car created in the model produced with the FDM 3D Printing technology (Additive manufacturing). The applications of the Stylistic Design Engineering method have therefore achieved the subsequent objectives:

(a) A merger of the best features of the different stylistic trends was carried out through Digital Sketching.
(b) Two different approximate analysis, volumetric and aerodynamic, were processed to reach the best possible final design, with the aim of quickly simulating the process of some in-depth analysis of vehicle performance in the automotive field.
(c) Accurate 3D body-surface modelling was developed.
(d) As a first result, it was possible to view the car in the environment, using the renderings.
(e) As a second result, two different prototypes were created, a virtual one, through CAD modelling, and a physical one (Maquette), through Additive Manufacturing (AM).

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