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Blitz Vision: Development of a New Full-Electric Sports Sedan Using QFD, SDE and Virtual Prototyping

Leonardo Frizziero , Ludovico Galletti , Lorenzo Magnani, Edoardo Gaetano Meazza and Marco Freddi *

Department of Industrial Engineering, Alma Mater Studiorum-University of Bologna, Viale Risorgimento, 2, 40136 Bologna, Italy; leonardo.frizziero@unibo.it (L.F.); ludovico.galletti@studio.unibo.it (L.G.); lorenzo.magnani7@studio.unibo.it (L.M.); edoardo.meazza@studio.unibo.it (E.G.M.)
* Correspondence: marco.freddi2@unibo.it

Abstract: In this paper, industrial design structure (IDeS) is applied for the development of two new full-electric sports sedan car proposals that go by the names *Blitz Vision AS* and *Retro*. With a deep analysis of the trends dominating the automotive industry, a series of product requirements was identified using quality function deployment (QFD). The results of such analysis led to the definition of the technical specifications of the product via benchmarking (BM) and top-flop analysis (TFA). The product architecture was then defined by making use of a modular platform chassis capable of housing a variety of vehicle bodyworks. The structured methodology of stylistic design engineering (SDE) was used. This can be divided in six phases: (1) stylistic trends analysis; (2) sketches; (3) 2D CAD drawings; (4) 3D CAD models; (5) virtual prototyping; (6) solid stylistic model. The chassis of the CAD model was verified structurally by means of FEM analysis, whereas the drag coefficients of the two vehicle proposals were compared with one of the main competitor's vehicles via CFD simulations. The resulting car models are both aesthetically appealing and can be further developed, leading eventually to the production stage. This proves the effectiveness of IDeS and SDE in car design.

Keywords: virtual product development; vehicle virtual design; stylistic design engineering (SDE); car design; industrial design; design engineering; quality function deployment (QFD); additive manufacturing; augmented reality

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1. Introduction

The design of a new vehicle generally involves hundreds of people within a company, from designers to R&D experts, from CAD modellers to engineers specialising in chassis and fluid dynamics, and to those who will present and sell the model to future customers. We are talking about major investments that leave no room for failure. The car is among the most important, useful and expensive tangible good owned by a person. That is why automotive manufacturers have to operate at very high-quality standards. Despite this, one still hears very often about "flops", i.e., models that have sold poorly. Manufacturing or design faults realized too late, disappointing and unadvanced aesthetics and a lack of innovation in the vehicle are among the main causes of the biggest failures in this field. We could cite the Maserati Chubasco (1990), which was deemed too expensive when the development phase was at an already very advanced design level. Other examples could be the Ford Th!nk (1999), the Cadillac XLR (2003), the Ford Contour (1995), the Audi Quattro Spyder (1991), the Citroen Karin (1980), the Alfa Romeo Scighera (1997), the Porsche Panamericana (1989), the Saturn Curve (2004), the Audi Rosemeyer (2000), the Bentley Hunaudières (1999), and so on. The concepts of the last two mentioned represent the basis of the well-known Bugatti Veyron.

Over the years, many have attempted to define, first, an effective and schematic design methodology capable of laying a solid foundation for the development of new products. An example of this is the "Kano method", which focuses entirely on the recognition of the characteristics the product should possess and their classification. Its application is useful for defining a list of the most important features to be offered to the consumer, but it is weak in many respects [1,2]. For example, it does not provide for a comparison with competitors and does not methodically define how one should proceed to be sure that all possible variants have been considered. In many companies, the only real methodology applied is "benchmarking", i.e., a comparison with competitors operating in the same market segment [3]. Even if one spends a lot of time understanding how many and which aspects are appreciated by consumers and who succeeds best, one does not create innovation by limiting oneself to this application alone. Another method that is particularly well known in the literature is the "Taguchi" method, which aims to shift the focus on improving product quality from the later stages (production stages) to the initial stages (concept and design) [4,5]. Its application lays the foundations for the so-called "robust design", a design methodology capable of providing an idea of the "cost of quality", which can help the designer to find the best solution among those that can be considered for the implementation of the project relatively quickly [6]. Not to be outdone is "quality function deployment", a methodology developed in the 1960s to translate customer needs into technical project requirements in a few steps [7–9]. It is regarded as the method capable of "giving a voice to consumers", which suggests why its application is valid in a variety of industries. TRIZ ("theory of inventive problem solving"), top-flop analysis and ABC analysis are other methodologies only mentioned here in order not to lengthen the discourse. More recently, defined methodologies have been implemented to complete the existing ones, each applicable mainly to a specific phase of product development and, therefore, are weak in other respects. Mention may be made of Design for Six Sigma (DFSS), together with its possible sub-definitions [10,11], or IDeS (industrial design structure), developed by the University of Bologna in relation to a revolutionary first approach to the industrial design method developed by Ramaciotti (CEO of Pininfarina). An articulated method capable of drawing on the most advantageous aspects of the previous ones already described, IDeS finds application in a multitude of sectors with reference to the automotive industry. It includes the definition of stylistic design engineering (SDE), a methodology comprising the sketching phase in relation to the study of the stylistic trends most appropriate to the new vehicle being built. The importance of the SDE lies in the fact that at this stage, the first idea of product aesthetics is conceived. For the same reason, it is only from there onwards that the opportunity arises to communicate the product idea and all the necessary information to the company departments responsible for vehicle engineering and manufacture.

According to the IDSA definition, industrial design (ID) is the professional service of creating products and systems that optimize function, value and appearance for the mutual benefit of user and manufacturer [12]. The development of products starts with the analysis and synthesis of data gained by surveying the requirements of potential clients and manufacturers alike. Every new product released to the market has to meet stringent innovative requirements [13]. For that reason, industrial design is an inherently multidisciplinary activity that must dialogue intensively with management, marketing, engineering and manufacturing sectors [14]. Designing is an activity that by its own nature arises from both industrial experience and deterministic approaches. Choosing which method is better suited for a specific industrial sector is often quite hard due to the heterogeneity of the product and the processes involved in its production.

This paper presents a case study of industrial design structure (IDeS) applied to the development of a new motor vehicle belonging to the sports sedan segment. In IDeS, the project is deconstructed into a series of phases each with a specific goal, leading to the production stage at the end. As known in the literature, this methodology is best suited to be applied in the industrial field since it creates a link between the design structure and the company organization. IDeS divides the product development into three macrophases, represented by design setting, product development and production (Figure 1). This paper focuses mostly on the design setting and product development phases of IDeS. The application of IDeS for automotive product development has already been explored in the literature, but without going into detail in the area of product development. The present work wants to fill this gap by proposing a new product for the automotive industry and giving a deeper insight into the design engineering and prototyping phases [15], verifying the applicability of the method and underlining its efficiency and potentials, especially when the product development phase comes into play.

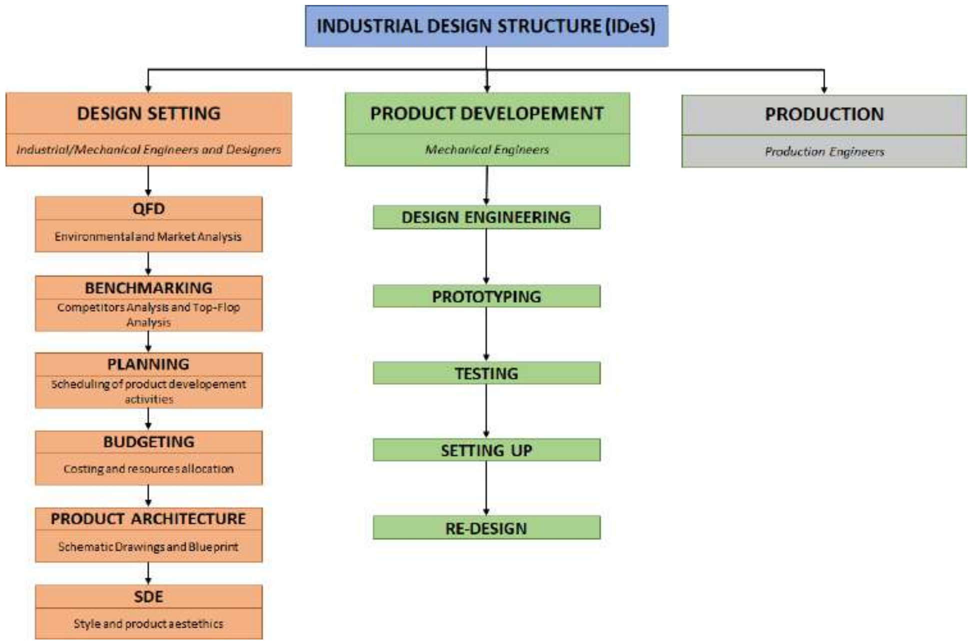

Figure 1. Logical diagram of the IDeS methodology's various subphases, from market analysis to final product prototyping.

2. Materials and Methods

2.1. Environmental Analysis

In Molex's January 2021 report on the future of automotives [12], a survey of a total of 230 decision makers working in automobile companies with at least 1000 employees was presented. Several key factors were identified. Firstly, 91% of respondents said that the "car of the future" will be powered by electricity, either fully electric (64%) or hybrid (27%). Autonomous driving is believed to be in reach by 94%, although only 28% said that cars will be fully self-driving, whereas the majority believes that automation will come in the form of safety support systems for human drivers. All these innovations are believed to come at a significant cost, as 56% stated that the car of the future will be at least 50% more expensive than today's equivalents. Finally, 97% believe that range anxiety (that is, the fear that a vehicle has insufficient range to reach its destination and would thus strand the vehicle's occupants) will no longer be a problem in ten years for three main reasons: better battery life duration, wider spread of charging stations and drivers becoming accustomed to the new limitations of electric vehicles. As to which of the many trends of the sector will carry the most weight in defining the future car, many intriguing responses were given that underline clearly the characteristics needed for the next automotive product. The important innovation areas for the industry in the next 10 years appear to be electrification (38%), followed by connectivity (33%) and passenger safety (29%). This clearly suggests that the future of the car is either full-electric or full-hybrid, and that customers may require a "smart" car, possibly capable of autonomous driving, but still demand the highest standards of safety [16].

The hardest obstacle to innovation is believed to be technology: the primary concern is battery duration still being too scarce, followed by software and advanced electronics. As for the industry challenges, costs are the main burden, as well as the much-needed infrastructures developing too slowly (e.g., charging stations, traffic light sensors, etc.).

Concerning the customer, the fundamental difficulty is related to the sensitiveness to cost increases, which is believed to be an inevitable consequence of electrification of the automotive industry in the next years. Other hurdles include unease about AI and self-driving technologies when it comes to safety of the passenger and the general hesitation to change existing behaviours and habits. The top trends driving the "car of the future" will thus be electrification and connectivity, whereas technological innovation will be the element of major disruption. From the survey, it can be concluded that decision makers working in the automotive industry have a clear idea of the trends, challenges and needs of customers. In addition, all automakers agree that their customers demand a green or socially responsible initiative, starting with a zero-emission vehicle.

Of course, 2020 has been an exceptional year due to the COVID-19 pandemic. This has not left the automotive sector unharmed, as it experienced a decline in sales all throughout the year, reaching −14.6% from 2019 year-end totals. However, it seems that the pandemic has made customers rethink the priority of car ownership, as people tend to consider it more important than it was before the pandemic. What is generally thought is that as the pandemic recedes, this expectation will fall back somewhat, though the perceived significance of possessing a car overall will remain high. Looking at the electric vehicle (EV) sector alone, sales returned to pre-pandemic levels. The IEA 2021 report [17] shows that, despite the pandemic, new electric car registrations have gained more than a 10% market share in China and are close to reaching the same digits in Europe. The year of 2020 saw the global electric car stock reach the 10 million mark, thus reaching a 43% increase over the previous year. Two-thirds of new electric car registrations belong to battery electric vehicles (BEVs). The largest fleet of electric cars is in China, with 4.5 million electric vehicles, though in 2020 Europe's fleet had the largest annual increase, reaching 3.2 million, and leading with 1.4 million new registrations despite a 22% contraction of the automotive market. China followed with 1.2 million registrations, whereas the United States saw 295,000 new electric cars.

2.2. Quality Function Deployment

Quality function deployment (QFD) is a method developed in Japan beginning in 1966 that, according to the words of its inventor [18], is able to "*transform qualitative user demands into quantitative parameters, to deploy the functions forming quality and methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process*". In other words, QFD is aimed at creating a link between the customer's needs and the full set of technical specifications on which to build the development of a new product. The procedure, although being extremely simple in nature, provides the users with a set of general rules that have to be continuously applied in product development. With the QFD method, the user is at first able to define the environment in which the product is going to be used and, consequently, identify and classify its needs in a logical order. Once the needs are clear, an assessment on their relative importance can be performed and, therefore, the developer is able to understand what the actual customer requirements are. Finally, this information can be translated into technical characteristics and a full list of the product specifications is obtained. QFD begins with the *six-questions report*, through which customers' needs can be identified. The next step requires the logical classification of the key customer requirements. This is obtained through the *dependency matrix* and the *importance matrix*. These three phases are presented in the following sections.

2.2.1. Six-Questions Report

Information gathering is the first action that follows the environmental analysis. Usually, this phase is carried through a series of interviews of individuals selected inside a market segment footnote (that is, an identifiable group of individuals, families, businesses or organizations, sharing one or more characteristics or needs in an otherwise homogeneous market). A simple way to carry out this task is by the so-called six-questions method. This method requires either interviewees or product developers on their behalf—as it is in this case—to answer to the following questions, and the results are summarized in Table 1:

- *Who uses/buy the product?* As for most sports sedans, the product is intended for a middle-upper class individual, either single or with a family of a maximum of five people. The typical clients would be adult males starting from 40 years of age, employed, and having duties that require medium-to-long distance transfers. The ideal use of the car would be either for daily commutes to work or for business travel as a company vehicle. Thanks to it slick design, the car may be appealing even to people in their early 30s who are particularly interested in avant-garde technologies and have unique personalities. Families of a maximum of five people may find comfort and safety using the car for medium-short-duration travel with medium baggage. In addition, lovers of the sporty driving sensation may find the car as the golden mean between performance and pleasure. Finally, cars of this kind are also attractive in regard to the company car or taxi-limousine market.
- *What are the uses of the product?* The product will be identifiable as an example of innovation in the automotive industry. Its cutting-edge design will have to meet the highest standards of quality and style, although not being so disruptive as to appear tacky. A particular emphasis will be directed towards providing state-of-the-art technologies for the electric powertrain in order to minimize energy consumption. An adequate battery pack shall be selected in order to acquire a range equivalent to several hours of continuous driving. Necessary in this regard is the implementation of energy recovery systems during braking. As for the interior, it will have five seats capable of comfortably sitting four people and satisfactorily sitting up to five.
- *Where is the product used?* The car would mainly be used outside of towns and city centres. Its dimensions and performance are the quintessential characteristics for sub-urban and highway driving, where high-speed cruising and low-energy consumption is needed. Moreover, in these conditions it would be ideal for the driver to be assisted by an ADAS (advanced driver-assistance system), either in the form of autonomous driving or just to improve safety. Thanks to the quiet electrical drive, the car may also be ideal for people living in low-noise and low-traffic neighbourhoods.
- *When is the product used?* As most modern cars, its use is predicted to be daily and remain almost constant throughout the year. A daily fast recharge of the battery pack would be ideal for long-duration daily journeys. Moreover, it should be safe to drive under all but extreme weather conditions, even when cruising at high speeds and with the ADAS engaged.
- *Why would the product be chosen?* The car is chosen thanks to its good overall performance, security and comfort. Its innovative and elegant design will be appealing for both middle-aged and younger customers. It will guarantee wide independence and freedom of movement to the owner without them having to fear too short ranges typical of other EVs. Finally, it is a green alternative as it will be a zero-emission vehicle and, therefore, it allows the owner to save on fuel, road tax, insurance and parking, and also allowing access to any low-traffic neighbourhoods.
- *How is the product used?* It can be used in a "classic" way, in which the driver enjoys the journey by being active and focused on driving the vehicle. Otherwise, in a more "futuristic" version, the driver may take advantage of the technology of autonomous driving by diverting some of their energy to socialising with other passengers or conducting business using other devices all while having the security of being in a safe environment. Finally, thanks to its performance, the driver may fully immerse in the action, taking advantage of the superior performance and driving characteristics of the vehicle.

Table 1. QFD—six questions and identification of key customer requirements.

Six Questions	Key Elements
Who uses/buy the product?	Comfort, Design, Medium price, Safety
What are the uses of the product?	Comfort, Design, Electric drive, Low consumption, Energy recovery systems, Performances, Safety
Where is the product used?	ADAS, Electric drive, Low consumption, Performances
When is the product used?	ADAS, Electric drive, Fast recharge
Why would it be chosen?	Comfort, Design, Eco-friendliness, Performances
How is the product used?	ADAS, Connectivity, Performances, Safety

2.2.2. Dependency Matrix

The dependency matrix is a simple tool through which it is possible to quantify the logical relationship between the different requirements obtained from the six-questions report. By placing the requisites as the first row and column of a square matrix, for each pair it is possible to answer the question: "*how much does the element in the row depend on the elements in the columns?*" The dependency is defined by associating judgments to a specific numerical value summarized in Table 2. With the filled matrix, the numerical values for each row and for each column can be added to define a global dependency value for each requirement. Afterwards, it is possible to rank the most dependent and the most independent needs. This method applied to the development of a future sports sedan car is presented in Table 3. In the case of a very strong dependence of the requirement in the row on that in the column, a 9 must be entered as a value in the matrix; in the totally opposite case, a 1 is entered. A middle way (moderate dependence) is represented by the value 3. A total absence of dependency is represented by 0.

Table 2. Judgment values in the dependency matrix.

Value	Dependency Judgement
Empty	No dependency between the two requirements
1	Weak dependency between the two requirements
3	Medium dependency between the two requirements
9	Strong dependency between the two requirements

Table 3. Final dependency matrix considered for the project.

Dependence Matrix	Price	Performances	Comfort	Electrification	Safety	Design	Efficiency	Low Consumption	ADAS	Fast Recharge	Eco Friendliness	Connectivity	Total
Price		9	3	9	1	1	3		3		1	9	**39**
Performances	9			3		3		9					**24**
Comfort	3			1					9			3	**16**
Electrification	3						9	9		9		3	**33**
Safety	1		3			1			9			3	**17**
Design	3	3			3						3		**12**
Efficiency	1			3				3					**7**
Low consumption		9		9			3			1	3	3	**28**
ADAS	1		3	1	3							9	**17**
Fast recharge			3	9				3				1	**16**
Eco-friendliness	1		1	9			3	9		3		1	**27**
Connectivity	1								9				**10**
Total	**23**	**21**	**13**	**44**	**7**	**5**	**18**	**33**	**30**	**13**	**7**	**32**	

The analysis indicates that the requirements most sensitive are “Price” (39), “Electric drive” (33), “Low Consumption” (28) and “Eco-Friendliness” (27). The matrix provides information on what requirements are most influential: “Electric drive” (44), “Low Consumption” (33), “Connectivity” (32) and “ADAS” (30). These results are perfectly coherent to the environmental analysis. Indeed, electrification, ADAS and connectivity have been presented as top priorities for the future of the automotive industry, whereas needs such as low consumption and eco-friendliness are two of the customer-driven challenges facing the industry.

2.2.3. Importance Matrix

Once the dependency matrix is defined, there is the need to define the relative importance of the various requirements. To gain this type of information, the importance matrix (or relative importance matrix) has to be built. This is conducted through a similar method as the aforementioned dependency matrix; however, a different question needs to be answered: “*is the item in the row more important than the one in the column?*” By asserting a judgment of relative importance between pairs of items, the matrix can be filled using the numerical values presented in Table 4. After assigning the numerical values to each box of the matrix, the sums for each row are calculated to classify the absolute importance of the quantities. The last column of the matrix contains the “Normalized Importance” values, i.e., the total values normalized to the maximum value of the “Total” column. If the requisite on the row is arguably less important than the column with which it is compared, a 0 is entered. The value 1 is used for equal levels of importance, whereas the value 2 is applied in the opposing case to the first.

Table 4. Judgments and their value in the importance matrix.

Value	Importance
0	The row item is less important than the column item
1	The row item and the column item have equal importance
2	The row item is more important than the column item

The result of applying this method to the current case study is summarized in Table 5. The analysis has shown that the most important requirement for the sports sedan segment is “Safety”, as it has the highest relative importance. Following that, “Price”, “Comfort” and “Electric drive” all have similar relative importance.

Table 5. Importance matrix.

Dependence Matrix	Price	Performances	Comfort	Electrification	Safety	Design	Efficiency	Low Consumption	ADAS	Fast Recharge	Eco Friendliness	Connectivity	Total	Importance
Price	1	2	1	1	1	2	1	1	2	1	1	2	16	7.6
Performances	0	1	0	0	0	1	2	2	1	2	2	1	12	5.7
Comfort	1	2	1	1	1	2	1	0	2	1	1	2	15	7.1
Electrification	1	2	1	1	0	2	1	1	2	1	1	2	15	7.1
Safety	1	2	1	2	1	2	2	2	2	2	2	2	21	10.0
Design	0	1	0	0	0	1	0	0	1	0	0	1	4	1.9
Efficiency	1	0	1	1	0	2	1	1	2	1	1	2	13	6.2
Low consumption	1	0	2	1	0	2	1	1	2	1	1	2	14	6.7
ADAS	0	1	0	0	0	1	0	0	1	0	0	1	4	1.9
Fast recharge	1	0	1	1	0	2	1	1	2	1	1	2	13	6.2
Eco-friendliness	1	0	1	1	0	2	1	1	2	1	1	2	13	6.2
Connectivity	0	1	0	0	0	1	0	0	1	0	0	1	4	1.9

2.3. Benchmarking and Technical Requirements Definition

The analysis of the market is a precious way to identify the level of innovation of the competition and, subsequently, develop a product able to impose itself on the market [19]. The process of comparison between the various products on the market is called benchmarking and its aim is to discover strengths and weaknesses of models already existing in order to improve on them. Despite its simplicity, this approach has been proven to be able to sharply reduce development cost whilst facilitating preliminary phases of development [20]. The following project development phase requires the identification of the technical requirements of the product [21]. In benchmarking this is performed by creating the so-called "innovation column" and with the top-flop analysis. Finally, in order to identify what is the most significant subset of requirements, the tool of the what-how matrix is used, and from that will arise the full list of technical/innovation requirements the new product ought have.

2.3.1. Benchmarking

Benchmarking begins with an analysis of the products belonging to the competition. This is carried out by searching for the technical data sheets, general information and performances of the products similar to the one that is under development. Through this comparison, a list of the ideal requirements for a future and innovative product can be obtained. This takes shape in the form of the innovation column. These data, although not all of them, are taken as a reference during the development phases. Regarding the case study, twelve competitors' sports sedan models that either dominate or are destined to dominate the European market were chosen. A total of twenty-six terms for comparison were used. These were clustered in three main groups: dimensions, vehicle performance and battery characteristics. This process is summarized in Figure 2.

			Audi		BMW	Kia	Lightyear	Lucid	Mercedes		Polestar	Porsche	Tesla		*Innovation column*
	Model		e-tron 55	e-tron Gt	i4 eDrive40	EV6 GT	One	Air	EQS 580	EQE	2 Long Range	Taycan 4S	Model 3	Model S plaid	
	Release year		2019	2021	2022	2022	2022	2022	2022	2023	2021	2020	2019	2022	
DIMENSIONS	Lenght	*mm*	4901	4990	4783	4695	5057	4970	5216	4946	4607	4963	4694	4970	< 4607
	Width	*mm*	1935	1960	1852	1890	1898	1950	1926	1961	1800	1966	1849	1964	> 1800
	Height	*mm*	1616	1410	1448	1550	1426	1410	1512	1512	1479	1379	1443	1445	< 1379
	Weelbase	*mm*	2928	2900	2856	2900	2950	nd	3210	3120	2735	2900	2875	2960	> 3210
	Weight	*kg*	2595	2350	2125	2175	1300	2300	2585	2100	2188	2215	1825	2162	< 1300
	Cargo volume	*l*	660	405	470	490	780	nd	610	430	405	407	542	793	> 793
	Seats	-	5	4	5	5	5	5	5	5	5	4	5	5	5
	Doors	-	4	4	4	4	4	4	4	4	4	4	4	4	4
PERFORMANCES	Power supply	-	E	E	E	E	E	E	E	E	E	E	E	E	E
	Total power	*kW*	300	390	250	430	100	597	385	215	300	390	239	760	> 760
	Total torque	*Nm*	664	640	430	740	1200	nd	855	530	660	640	420	nd	> 1200
	Acceleration 0-100	*s*	5.7	4.1	5.7	3.5	10	3.2	4.3	6	4.7	4	5.6	2.1	> 2.1
	Top speed	*km/h*	200	245	190	260	150	270	210	160	205	250	225	322	> 322
	Drive	-	AWD	AWD	Rear	AWD	AWD	AWD	AWD	Rear	AWD	AWD	Rear	AWD	AWD
	Drag coefficient	-	0.25	0.24	0.24	0.25	0.2	0.21	0.2	0.23	0.28	0.22	0.23	0.21	< 0.20
BATTERY	Battery capacity	*kWh*	95	93.4	83.9	82.5	60	113	120	100	78	79.2	55	95	> 120
	Net battery capacity	*kWh*	86.5	85	80.7	77.4	60	110	107.8	90	75	71	52.5	90	>110
	Theoretical range	*km*	365	420	475	395	575	660	610	535	395	375	350	535	>660
	Estimated range	*km*	310	355	400	335	460	555	510	450	335	315	290	445	> 555
	Consumption	*Wh/km*	237	202	170	196	104	167	177	168	190	189	150	168	< 104
	Charging time (2.3 kW)	-	44h 15min	43h 30min	41h 30min	39h 45min	30h 45min	56h 15min	55h 15min	46h 15min	38h 30min	36h 30min	27h	46h 15min	< 27h
	Fast-charging time (50 kW)	-	76min	75min	71min	68min	66min	97min	95min	80min	66min	63min	52min	nd	< 52min
	Max charging power	*kW*	155	270	200	250	75	300	200	170	151	225	170	250	> 300
	Fastest carging time	-	26min	21min	30min	18min	44min	20min	32min	33min	32min	21min	23min	28min	< 18min
	Price	*€*	79.445	99.800	58.300	65.990	149.000	140.000	135.529	70.000	52.500	106.487	43.560	126.990	< 43.560
	Top number		2	1	1	3	6	6	5	1	3	3	3	6	
	Flop number		2	2	0	0	5	2	1	0	4	1	5	0	
	Delta		0	−1	1	3	1	4	4	1	−1	2	−2	6	

Figure 2. Benchmarking and top-flop analysis tables.

2.3.2. Top-Flop Analysis

Since it would be neither feasible nor economical to achieve all the objectives identified in the innovation column, a subset of them must be chosen; this is conducted by identifying the top-competitor through the top-flop analysis. This analysis requires the identification of each feature to compare which product has the best and worst values. Then, a balance can be made weighting equally tops and flops, and a score can be associated to each competitor.

The one with the best score represents the model with the higher degree of innovation. This analysis is presented in the bottom of Figure 2.

It is necessary to underline what criteria were used to define the "most favourable" characteristics for the new vehicle, especially when it comes to qualitative elements. Having a large wheelbase and width were considered preferable since it would mean having more pitching stability. For the same reason, limited height and length were considered positive characteristics. As for comfort, being able to accommodate a larger number of passengers and having more cargo volume were identified as positive traits. The analysis showed that the main competitor is Tesla's S Plaid, as it achieved the highest score in the top-flop analysis. The features for which Tesla beats or matches the competition when it comes to dimensions are cargo volume and number of seats. As for performance, this model is the best when it comes to power, acceleration and top speed. On the other hand, Tesla's Model S Plaid does not match competitors in any of the battery performance parameters. As to this subset of specifications, Lucid's Air comes out clearly on top beating the competition in 4 out of 10 parameters. Interestingly, all top competitors' models belong to the executive segment, and for this reason prices exceed the EUR 100,000 mark. This represents an interesting challenge since all previous analyses have shown that price is one of the most important requirements. In order to improve on competitors, further developments in battery capacity and safety have to be prioritized.

2.3.3. What-How Matrix

Through the analysis carried out with the interrelation matrices it has been possible to identify the requirements of the new product. Moreover, with the benchmarking it was possible to study the technical requirements of a possible competitor's product. However, no technical specifications have been defined thus far in order to achieve these objectives. For this purpose, one can use the what-how matrix (relationship matrix) presented in Table 6 This matrix is built by placing the main customer requirements in the rows and the technical features in the columns. Whereas the first were defined during QFD, the process of choosing the right technical parameters to insert in the matrix is up to the designer who, knowing the sector to which he belongs, is required to understand what the product needs in order to beat the competition. These parameters are, therefore, those already used during benchmarking. The matrix is then filled using numerical values assigned, as in the case of the dependency matrix (Table 3). Beginning with the requirement that achieved the highest score, one is required to choose a number of them that match and possibly exceed the difference of tops and flops of the main competitor described in the top-flop analysis. The results shown in Table 6 underline that the main requirements to be improved are battery capacity, price and comfort, as they obtained the highest scores in the last column.

2.4. Product Architecture

The architecture describes how a product's functions are realized by its physical elements. Defining the product architecture therefore means assigning functional elements to physical elements and defining their mutual interfaces [22]. The vehicle architecture describes the physical layout of the vehicle underlining which modules realize specific functions. In the automotive industry, the definition of the vehicle architecture is often not limited to a single product but spans multiple models (if this is the case, it is usually referred to as a *modular architecture*). This choice has the fundamental advantage of making the development product-variants more efficient and profitable [21]. The *platform* is a neutral architectural basis for all variants consisting of a defined core of standardized elements.

Table 6. What-how matrix.

What-How Matrix	Length	Width	Height	Wheelbase	Weight	Cargo Volume	Power Supply	Total Power	Total Torque	Acceleration 0–100	Top Speed	Drive	Drag Coefficient	Battery Usable	Theoretical Range	Consumption	Max Charging Power	Fastest Charging Time	Price	Total
Price	1	1	1	1			9	9	9	3	3	3	1	9	3		1	1	9	**64**
Comfort	9	9	9	9	3	9	1	1	1	1		3			9		9	9	3	**85**
Electrification							9							9	9	9	3	3	3	**45**
Safety	3	3	3	3	3														3	**18**
Efficiency					9	1	9	3	3	3	3	3	9	1	3	9	1	1		**58**
Low Consumption					3		9	3	3	3	3		9	3	9	9	3	3		**60**
Fast Recharge							9							3	3		9	9	1	**34**
Eco Friendliness					1		9	1	1	1	1			3	3	9	1	1	1	**32**
Total	**13**	**13**	**13**	**13**	**19**	**10**	**55**	**17**	**17**	**11**	**10**	**9**	**19**	**28**	**39**	**36**	**27**	**27**	**20**	

2.4.1. 2D Architecture

In order to define the general dimensions of the vehicle, the Tesla Model 3 was taken as a reference since it has proved to have a reliable architecture with a high standard of safety and driveability, making it one of the most popular EVs on the global market. The general dimensions are shown in Figure 3.

An important element of the architecture of the vehicle lies in the drivetrain that implements the kinetic energy recovery system. In this case, the KERS includes a CVT-flywheel design (Figure 4). Although more complex than a purely electrical KERS, this solution can provide up to 20% efficiency gain. Moreover, the presence of a continuously variable transmission results in higher efficiency and acceleration during normal operation. Thanks to these advantages, one could choose to either reduce the electric units or the battery-pack size. Since the customer requirements have underlined the importance of high battery duration, it was decided to downsize the motors while maintaining the battery capacity. This decision was justified by the fact that despite a smaller engine, the CVT would be able to compensate fully for the performance reduction, especially when it comes to acceleration and top speed.

2.4.2. 3D Architecture

Most full-electric vehicles adopt a so-called "skateboard platform". It is based on a *ladder type chassis* that functions as a platform for the vehicle and hosts the batteries, electric motors and other fundamental electronic components. All components are fastened to the chassis via specialized substructures. Usually, it is also provided with removable and replaceable corner units at the wheels, into which the suspension, steering, powertrain and braking functions are embedded (Figure 5). The vehicle developed for this case study was indeed created around a skateboard platform. In addition, the battery pack functions as an integrated structural element. In order to achieve 4WD, two identical electric units are present: one powering the frontal and the other powering the rear one. They are mechanically decoupled from one another, although they function in synergy being coordinated by a common power control unit.

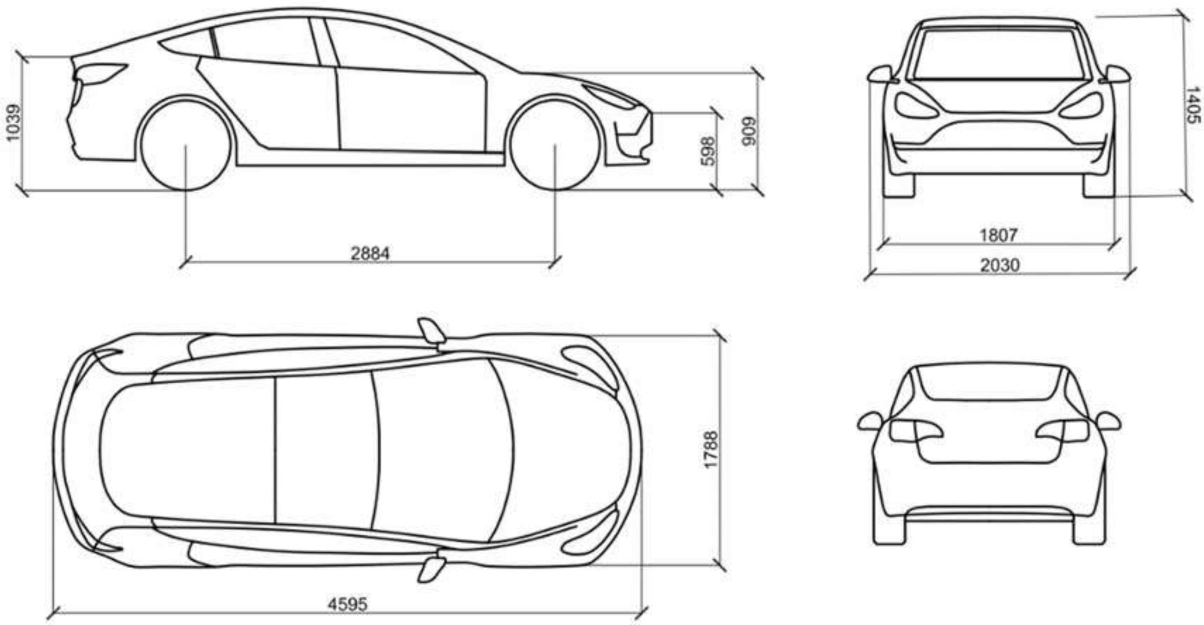

Figure 3. Vehicle dimensions.

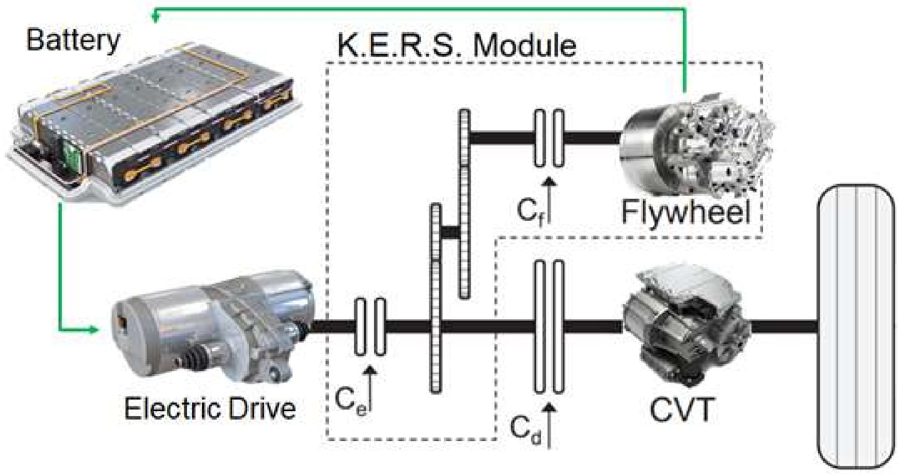

Figure 4. Powertrain architecture.

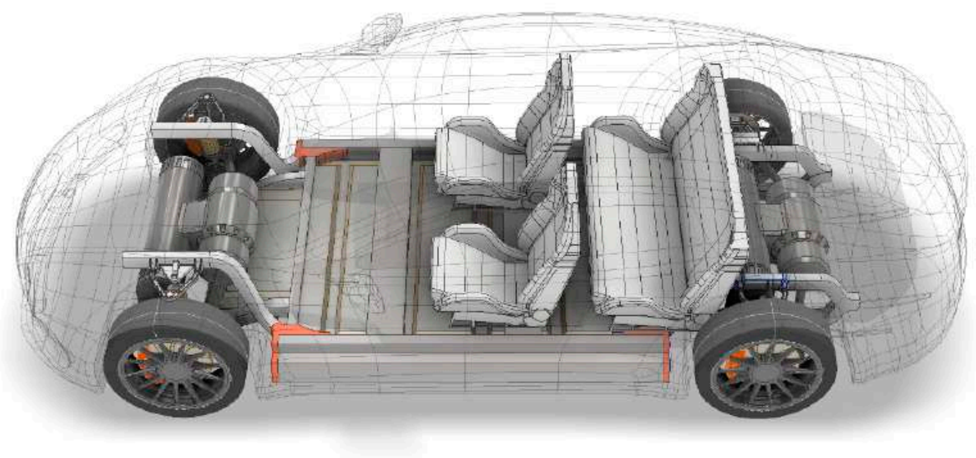

Figure 5. Vehicle 3D architecture.

2.5. *Stylistic Design Engineering*

Stylistic design engineering (SDE) is a design methodology aimed at analysing compelling stylistic trends and providing a new stylistic idea for the product. This procedure starts with the creation of sketches and leads to the complete stylistic technical study; for example, producing a maquette as the final result. This design method is known in the industrial world as the "Pininfarina method" and was developed and perfected by Eng. Lorenzo Ramaciotti, the former CEO of *Pininfarina SPA*.

2.5.1. Stylistic Trend Analysis

The goal of the stylistic trend analysis is to identify the stylistic and aesthetic requirements of the vehicle. Usually, this step requires not only analysing competitors, but also the history of the brand the vehicle belongs to. In this case study, the brand was identified as BMW. In this stage, the name "Blitz Vision" was chosen for the project and, therefore, for the final product.

Since 1933, BMWs had a radiator grille in the so-called "double kidney" configuration, that is, a grill divided in two symmetrical intakes [23]. Being an iconic and distinctive element associated to the brand, the kidney grill can be adopted as a stylistic reference for the evolution of the BMW's stylistic design philosophy. As a matter of fact, the shape of the grill has evolved over time, evolving from a purely technical feature to an intelligent and iconic element [24]. Despite the numerous metamorphoses, the famous double kidney has never lost its role as the brand's signature style. In the following subsection, we present some of the most known and iconic BMW models, exploring their main stylistic features.

The BMW 303 was the first model to be equipped with that stylistic signature that still distinguishes BMWs almost 90 years later: the air intake in the form of a double kidney. The rounded shape above and below the grille of the BMW 303 and the BMW emblem positioned between the upper arches of the car's radiator resulted in a highly recognizable whole. In the period up to WWII, the BMW double kidney became smaller and smaller, favouring elegance, on all BMW models, but always respecting the shape it had on the BMW 303.

In 1956, the BMW 503 entered the market, in which the radiator of the 1930s gave way to a fully chromed double kidney of medium height. The reduced size was made possible by the fact that the double kidney was no longer the only component that ensured engine cooling, but was supported by two side air intakes. The BMW 3200 CS (1962) and BMW 2000 CS (1965) still had a similarly shaped kidney grille. In the same year as the BMW 503 came the BMW 507 Roadster, the first BMW with two large horizontal air intakes. The BMW 507's large air intakes were necessary because they were the only source of fresh air for the engine's radiator pulsing under the ultra-flat engine hood. The appearance of the grille was also relevant for another reason: the BMW 507 was the brand's first model to feature the so-called "shark nose", which makes the hood appear longer and suggests a dynamic push forward. This feature was definitively adopted with the "new class" of the 1960s and characterized the vehicles of the 3, 5 and 7 Series until the 1990s.

The grille of the BMW 1500 (and its 1600, 1800 and 2000 sisters) resembled that of the BMW 503, but for the first time the kidneys were connected, thinner than in previous BMW models and positioned between two horizontal grids as wide as the car. With its configuration of primary grille and secondary grille, this ensemble was the copy of the front of the main BMW models up to the 1980s, including the 2 Series (starting from 1966), the BMW 2500 and 2800 sedans (starting from 1968), the related BMW 2800 CS coupe (also from 1968) and its legendary heirs BMW 3.0 CS, CSi and CSL.

A special case in the history of the double kidney is the 1978 BMW M1 sports car. Its lowered front required ultra-flat air intakes, but without sacrificing the presence of the double kidney. The air intakes were the smallest a BMW had ever sported. The double kidney design in the M1 was taken up in the front configuration of later models, such as the BMW Z1 (1988) and BMW 8 Series (1989).

The year 1990 marked a new evolutionary leap with the third generation of the BMW 3 Series: in this design, the BMW double kidney was flat and horizontal, but not very wide. Unlike the first generations of the Series 3, the two halves of the radiator were separated. The double kidney was markedly rectangular with slightly rounded edges and was separated from the headlights by surfaces in body colour. This configuration remained present on several models starting from the 1990s, from the BMW 7 Series (1994) and 5 Series (1995), through the BMW Z3 (1995) and the next generation of the 3 Series (1998) up to the first two generations of the BMW X5 (1999).

Three generations of the BMW 3 Series later, a new evolution: in the BMW 3 Series (F30), the detached, relatively large double kidney appeared for the first time on the surface of the headlights and was not separated by grilles or body-coloured side surfaces from the headlights. Configurations such as the BMW radiator grille were also found on the 2015 BMW 7 Series, the current generation of the BMW 5 Series and BMW 6 Series (both from 2017). In the current BMW 3 Series, the modern grille configuration combines some well-known features (joined kidneys, directly connected headlight surfaces and pentagonal shape) with new elements. For example, the double kidney is located much higher than the upper edge of the headlights, as it rises slightly on the hood. In the M variants, the classic vertical bars of the double kidney were replaced by a reticulated structure formed by the so-called "nuggets", small wedge-shaped elements integrated into the reticulate.

With two visionary cars, BMW is looking at what the brand's main stylistic signature might look like in future models: On the BMW Vision iNEXT, the centre bar has been modified as an evolution of the BMW i3 kidney. Behind the surface are housed a video camera, sensors and other technological solutions aimed at assisting the driver and autonomous driving. In the BMW Vision M NEXT hybrid sports car, the grille is sculpted and closed by glass, extending widely across the front. The lighting of the double kidney and the touch of colour inside increase the three-dimensional effect.

2.5.2. Sketching

Having identified the most famous stylistic trends of BMW, the sketching phase can begin. Sketches represent the first step of the creative process. They serve the purpose of defining the main stylistic features of the vehicle [25]. One view of the purpose of concept sketches in the engineering domain is that they are intended to provide quicker communication and retrieval at the early stages of design by providing combined visual and factual descriptions for improved evaluation and concept selection [26].

Usually, more than one proposal is made according to the general stylistic trends that can be observed in the automotive design. Generally speaking, there are four trends that nowadays dominate the market: advanced, natural, stone and retro. Sketches do not need to be strictly realistic as the following SDE phases tackle these problems; however, in this phase the designer should provide a complete picture of the appearance of the product and possibly integrate these innovations that influence the aesthetic of the vehicle.

Advanced: As for the advanced version (*Blitz-Advance*), the inspiration comes from the future, manifesting itself in sinuous curves that close each other in the rear of the car. The height and width of the vehicle play a fundamental role, capable of creating a feeling of attachment to the ground. The bodywork is completed by a new horizontal and recessed grille and, once again, the final shooting brake physiognomy to take advantage of the air flows (Figure 6).

Natural: The proposal belonging to the natural stylistic trend (*Blitz-Nature*) is inspired by the new models such as the 4 Series, M3, M4 and, above all, I4 sharing the same kidney grille. This new trend, which has divided the critics, will certainly remain a historic icon in terms of revolution of the BMW house and that is why it was important to include as an innovative starting point. In addition to this, the natural sketch is defined by precise and sharp lines that do not follow curved geometries and break the classic harmony presented on many modern cars. The bodywork is completed by the shooting brake physiognomy, the large front air intakes that cool the braking system and a very marked extractor capable of conveying the air flows that cross the bottom of the car in order to create depression and keep the car attached to the ground (Figure 7).

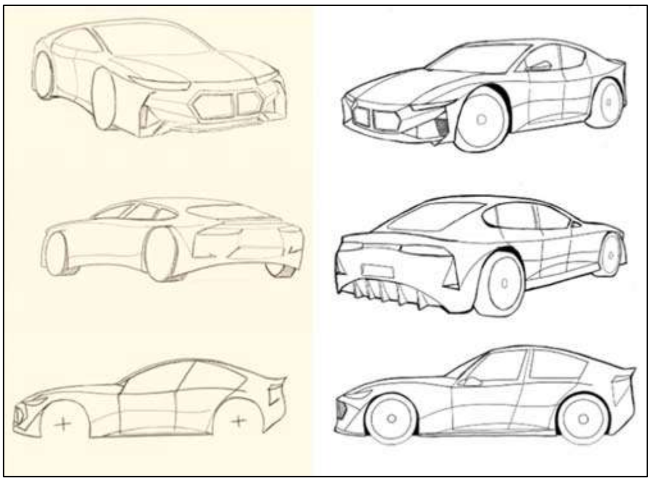

Figure 6. Sketches of the advanced proposal.

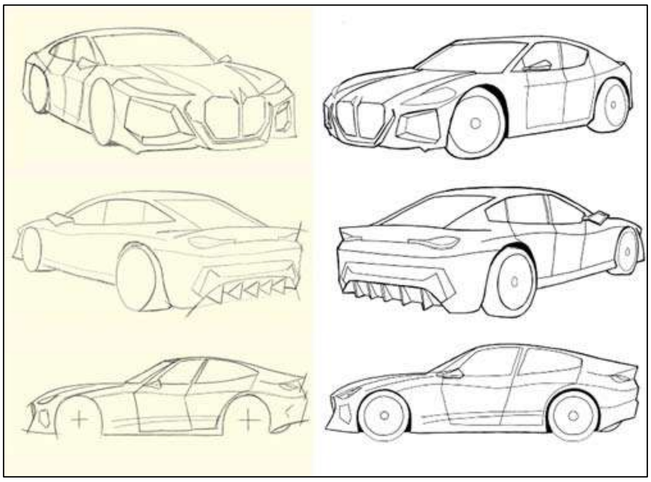

Figure 7. Sketches of the nature proposal.

Stone: For the realization of the stone version (*Blitz-Stone*), various vehicles between the end of the 1990s and 2019 were taken as sources of inspiration. For the definition of the overall shape, it was decided to take as example the BMW 5 series e60, which went into production in 2003 and marked a breaking point compared to previous BMW models. The front was influenced by various models and styles. In order to obtain a sports vehicle, it was decided to rely on Grand Turismo type vehicles that can provide high performance with elegant shapes. The cars analysed were the Ferrari 599 GTB Fiorano (2006), where ideas for the bonnet were taken, and the more recent Jaguar F-Type (2019), using its fenders and optical groups. The classic double kidney grille was developed starting from the late 1990s models of the Bavarian group, opting for a narrow configuration in the vertical direction, aware of this as the only aesthetic function since our project is an electric vehicle. For the sides, the idea was to implement a three-volume style with very sporty features, such as the hollowed bellies and the presence of an air intake placed behind the front wheel, whose position was inspired by BMW's 2000s models. Finally, for the rear, inspiration was taken from the Japanese automotive world. In particular, the Lexus IS (2017) encouraged the shape of the trunk. The presence of the extractor is aimed at emphasizing the sporty soul of the car, even in an elegant context (Figure 8).

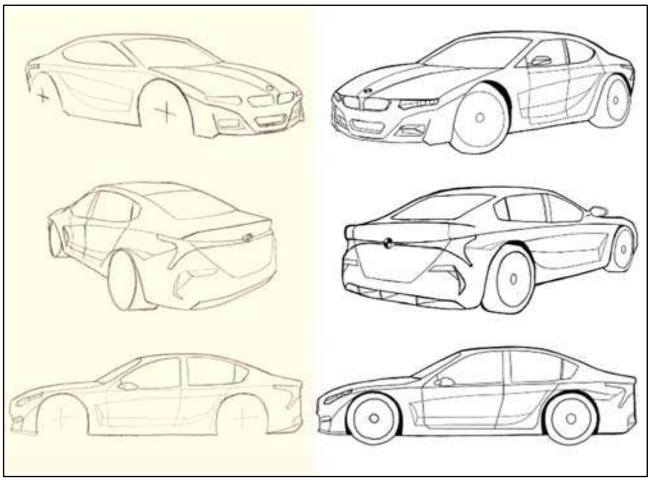

Figure 8. Sketches of the stone proposal.

Retrò: The retrò variant (*Blitz-Retrò*) wants to be an homage to the iconic BMW models of the 1950s and to the BMW 507. The 507 model of BMW was initially intended to fulfil the demand of roadsters in the American market and its production was strongly pushed by Max Hoffman, a well-known importer of luxury European automobiles in the USA, famous for the success of models such as the Mercedes 300 L and Porsche 356 overseas. Due to the production costs, only 252 units of this model were produced, and it was dismissed after just 3 years. The most striking feature of BMW 507 is the wavy shoulder line, typical in 1950s roadsters, yet rarely seen in modern BMW sports sedans. Other models were considered during the sketching phase of the Blitz Retrò, such as the Aston Martin Rapide, Jaguar XJ and Porsche Panamera. All these vehicles share a style that recalls historic models of their respective brands and are examples of contemporary sports sedan models. The sketching started by defining the general shape of the kidney grille, directly inspired by BMW 507 with an elongated and semi-oval shape. Then, the distinctive shoulder line was sketched and, starting from it, the rest of the car was created. Since the vehicle is an homage to the 1950s car, a shooting brake physiognomy was chosen instead of the common three-volume configuration that defined BMW since the 1960s (Figure 9).

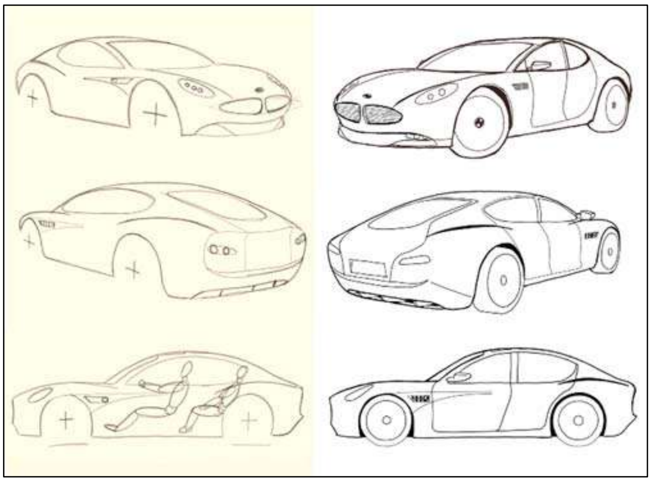

Figure 9. Sketches of the retro proposal.

In order to decide which proposal to develop, both stylistic and technical parameters derived from the four sketched models were taken into account (Figure 10). This led to the decision to pursue two different vehicle bodyworks sharing the same chassis architecture. The first model arises from the combination of the stone and advanced proposals with the name ***Blitz Vision AS***. It would therefore be in continuity with existing BMW models that share the three-volume configuration and hard surface transitions. However, instead of adopting a hard three-volume configuration, the trunk and the rear of the roof would blend, achieving both an increment in the internal space and a more gradual body transition capable of improving the aerodynamics of the vehicle. The second proposal would carry on from the Retrò version and would therefore be called ***Blitz Vision Retrò***. Although not new for BMW, the idea of renovating a previous model with a more suitable car configuration, such as the sports sedan, is an interesting option. This version would make use of a “shooting brake” body design in order to improve habitability and at the same time pay homage to the classical style of 1950s European executive and coupe cars.

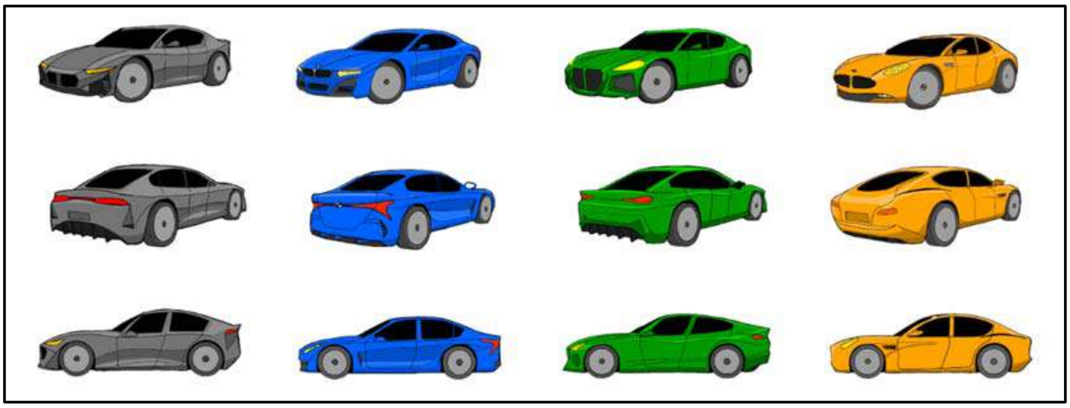

Figure 10. Sketches of the four proposals. From the left: advance, stone, nature and retro.

2.6. Product Development: Design Engineering

2.6.1. Orthogonal Drawings

The first step of design engineering consists in the definition of a rigorous 2D drawing starting from the sketching obtained as a result of SDE. The 2D drawings could also be realized during SDE based on the different proposals. However, during product development all dimensions must be precisely defined, and the drawings are to be meticulously updated to fit the vehicle requirements that emerged during the product architecture definition. Since some changes may still be necessary, the procedure that leads to the 2D drawings can be repeated several times until a satisfactory result is obtained in terms of both aesthetics and dimensions. The 2D drawings of the two proposals are presented in Figures 11 and 12.

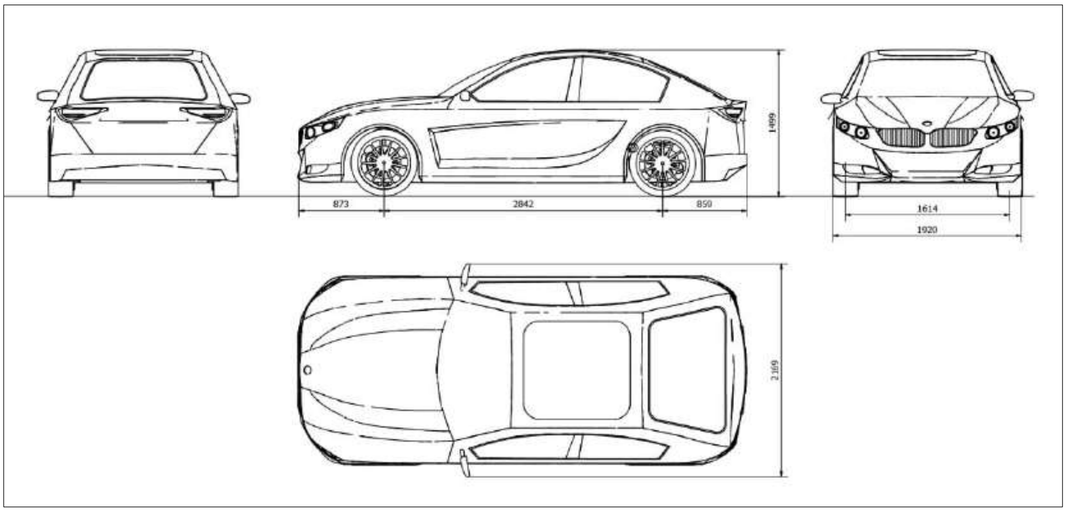

Figure 11. Orthogonal projections of Blitz Vision AS.

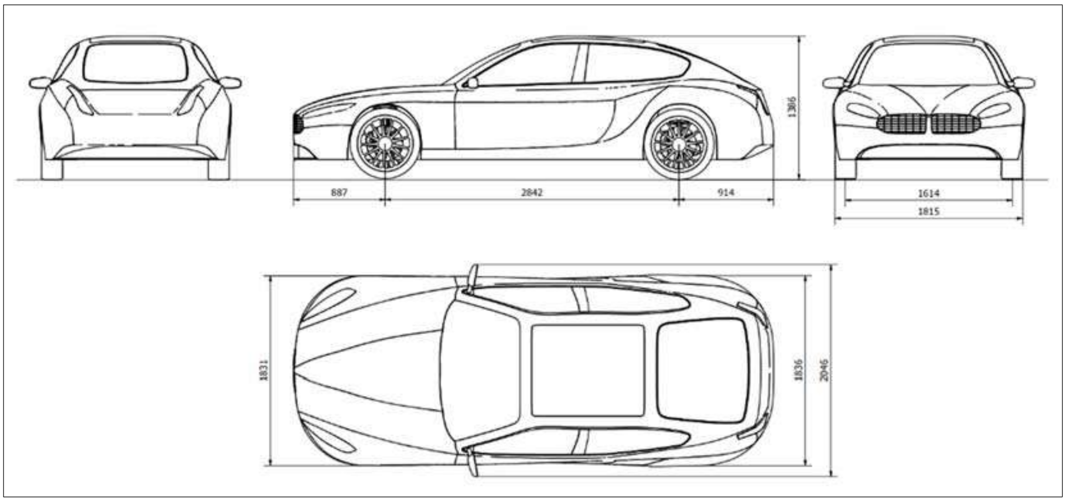

Figure 12. Orthogonal projections of Blitz Vision Retro.

2.6.2. Chassis Modelling

The frame, also known as the chassis, is the main structural subsystem of the vehicle as it guarantees the integrity and the base platform on which all parts are connected. The body also defines the eventual use of the vehicle since during its design, requirements such as noise and vibrations, durability and safety are considered. Generally speaking, the chassis falls in a series of four types of structure:

- *Space Frame*: It consists of a framework of beams connected at nodes in a truss structure. Usually, the process used in order to produce this kind of body structure is roll forming and hydro-form, ideal for low production volumes.
- *Ladder Chassis*: It consists of two longitudinal beams connected by a series of transverse struts. This chassis structure has the advantages of easy manufacturing and low price. On the other hand, not being a three-dimensional structure reduces torsional stiffness of the vehicle. The vehicles that adopt this kind of chassis are usually referred to as adopting a *body-on-frame* architecture.
- *Central close tunnel*: It is similar to the ladder chassis except for the fact that the structural integrity of the vehicle lies in a singular large member running down the centre of the vehicle. This kind of architecture has the problem of limiting the overall size of the vehicle.
- *Integral Frame*: This chassis type consists of one main strong structure that integrates both frame and body. This solution offers high resistance to loads. Other advantages include space saving and weight reduction. Minimizing wasted material and production processes are valid reasons for mass production.

From the considerations above, two possible types of chassis designs can be considered for a sports sedan: either a ladder chassis or an integral frame, considering that both solutions offer the same advantages for the capability of mass production. Since in most electric vehicles the mass is concentrated near the undercarriage where the battery pack is positioned, a ladder chassis was chosen. This also offers the possibility of sharing the same chassis along multiple vehicles with just minor adjustments as it is already common in the automotive industry. The integrity of the chassis in torsional and flexural loads can be augmented with the addition of the battery tray as a structural element of the vehicle, given that this is an essential element needed for the vehicle to function. As to the manufacturing techniques involved during the production of the chassis, three main types of structural elements dominate the production: extrusions, metal sheets and castings. Incidentally, the manufacturing techniques will be close-die extrusion (typical of a straight structural element), metal sheet bending and metal forging/casting. In the case of the chassis and especially in the automotive field, hydroforming is often used not only for metal sheet deformation, but also for truss manufacturing. A general classification of the main elements of the chassis in these categories is presented in Figure 13. With the chassis, the definitive 3D architecture of the vehicle can be defined (Figure 14). Other than the chassis, other mechanical elements were modelled such as the front and rear suspensions.

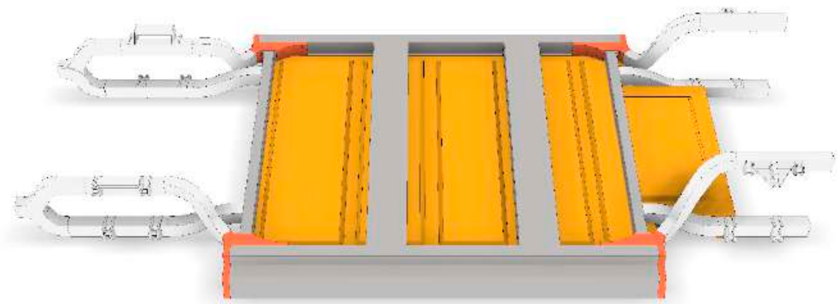

Figure 13. Vehicle chassis with colours corresponding to different manufacturing techniques: castings in red, extrusions in grey, hydro-formed metal in white and sheets in orange.

Figure 14. Vehicle 3D architecture CAD model.

2.6.3. FEM Analysis and Optimization

The simulations were carried out with the aid of Ansys 2021 R2. The first analysis carried out on the complete chassis was the static one, in which the resistance of the chassis to the weight force of the whole vehicle was verified. The frame was constrained to the ground, taking as reference the position of each wheel centre. As to the torsional analysis of the chassis, a force F was applied to the frontal left wheel centre and the rear. In this way a pure torque was applied to the chassis. The value of the F load was defined in order to obtain a torque equal to 4000 Nm. The relationship between the torque applied and the relative rotation between the front and rear axles made it possible to derive the value of the stiffness of the frame, excluding the effect of the suspensions. Next, a flexural analysis was carried out by constraining the wheel centres and loading the structure in its centre of mass. Similar to the torsional test, the bending stiffness can be expressed as the ratio of the applied force to the deflection at the point of application of the load. Idealizing the chassis as a beam undergoing torsion, a load equal to 4000 N was applied in the middle of the pitch of the side sills. The chassis was verified in all three simulations with wide margins of safety (Figure 15).

2.6.4. Surface Modelling

Surface modelling is the first step towards the realization of the CAD model of the product. In fields such as automotive design, high standards of quality are to be achieved during surface modelling given that the final product must meet both the expectation of the customer and the feasibility requirement of the production. In the industry, surfaces are rarely created from a purely 2D drawing. In fact, clay models either to scale or full size are usually realized and then scanned, producing a preliminary surface on which the CAD department can work. The aim of surface modelling is to achieve a so-called "class A surface". This term does not have a unique definition, but generally refers to a set of surfaces that are high quality and usually obtained from free-form modelling.

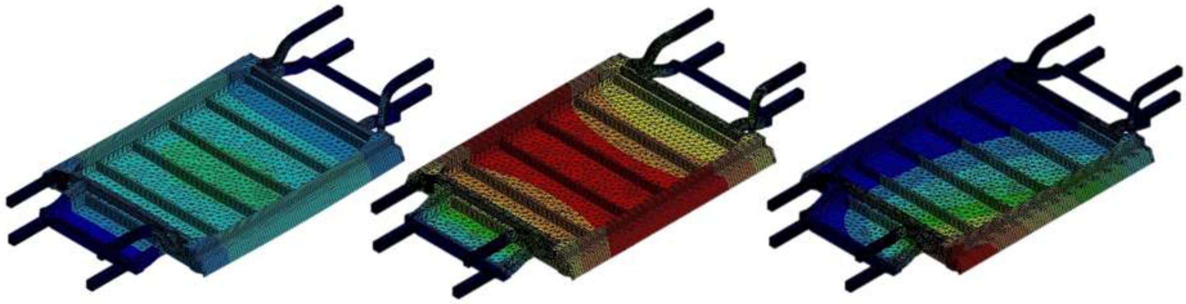

Figure 15. FEM simulation of the chassis. From the left: static, flexural and torsional test.

Since no clay model was available, a method consisting of both free-surface modelling and patching was used. The first step consisted of the creation of a 3D sketch made using NURBS (non-uniform rational basis spline (NURBS) is a mathematical model using basis splines (B-splines) that is commonly used in computer graphics for representing curves and surfaces), obtained by intersecting contour lines of the vehicle created during the sketching phase. For parts such as fenders, side-skirts and bumpers, the "patch" tool was used to create a surface starting from a close 3D sketch. For elements such as doors, roof and hood, free-form modelling was used. This procedure led to a preliminary surface work that defined the preliminary shape of the car. At this point the existing surfaces were refined and patched together, as to obtain a water-tight surface complete of all stylistic features. The deliberate decision to adopt a single software for modelling both surfaces and the chassis gave the possibility of direct integration between the structure and the bodywork during the final definition of the latter. In this way, a superior refinement of the design of the vehicle was possible by having surfaces that perfectly matched the existing frame. The main stages of the surface modelling stage are presented in Figure 16. Both vehicle proposals underwent this procedure.

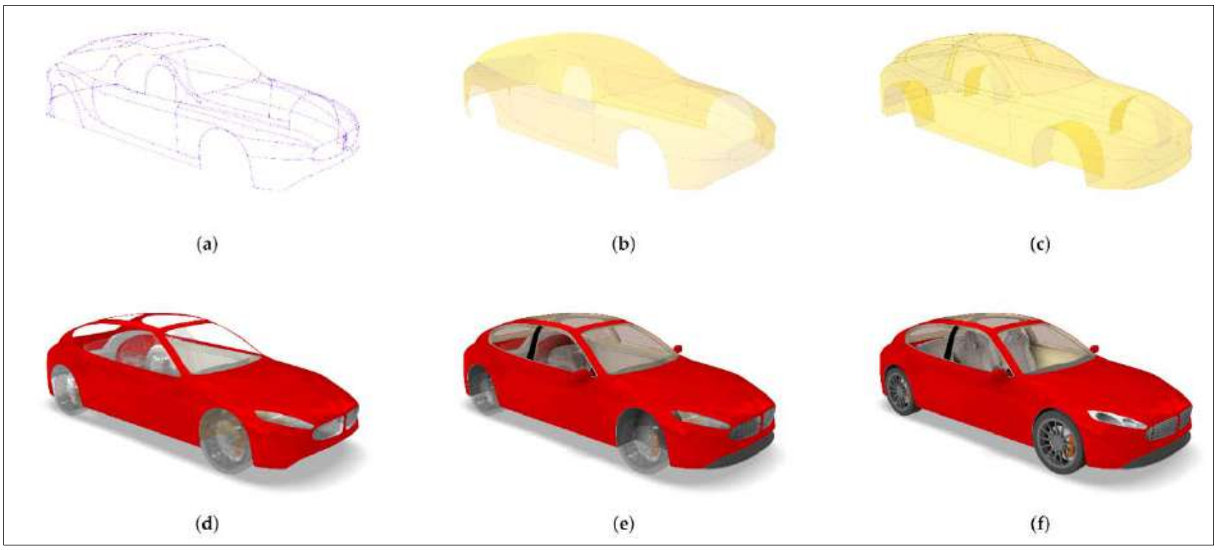

Figure 16. Stages of surface modelling for the Retrò version: (**a**) 3D sketching according to 2D drawings; (**b**) preliminary surface modelling; (**c**) watertight surface; (**d**) surface thickening and integration with chassis; (**e**) frame modelling; (**f**) final CAD model.

2.6.5. CFD Analysis and Optimization

Once the surface model was created, the aerodynamic performances of the vehicle could be analysed. In fact, forces and moments the vehicle receives from the surrounding air depend more on the shape of the body than on the characteristics of the chassis. Vehicle aerodynamics tackles a wide range of objectives; still, its main goal is often considered to be the reduction of aerodynamic drag. Traditionally, the aerodynamic performance of motor vehicles is performed experimentally, and the wind tunnel is the main tool used. However, especially during the design phase, computational fluid dynamics can be used for an initial estimate of the aerodynamic loads, although it can be extremely demanding in terms of computational power and time. Incidentally, blunt bodies' aerodynamics, such as that of vehicles, is very difficult to simulate given their large, detached zones and wake. For that reason, numerical and experimental results hardly coincide perfectly.

Computational fluid dynamic analysis was performed on both vehicles using the CAE software SimScale that uses open-source code OpenFOAM for CFD analysis. This verification is aimed at estimating the value of the drag coefficient of the car (C_D or C_x). The general definition of the drag coefficient of a body invested by a fluid is defined by the following equation:

$$C_D = \frac{D}{\frac{1}{2} \cdot \rho \cdot v^2 \cdot A}$$

where D, ρ, v and A are the drag force (drag is generally defined as that force measured on an object laying in the direction of the fluid flow, i.e., the force measured in the direction of the fluid flow), the fluid density, the fluid speed and the reference area (SAE recommendation states that the frontal projected area including the tires and the under-body parts must be used) of the body invested by the fluid, respectively. The purpose of this coefficient is to associate the aerodynamic performance of the vehicle to a dimensionless parameter depending not just on the fluid characteristic, but also on its geometry.

Both Blitz Vision AS and Retrò models were simulated in a uniform flow of air moving at 130 m/s at standard temperature and pressure conditions. To compute turbulence effects the standard K-epsilon model was used. Given the aforementioned uncertainty of blunt body numerical aerodynamics, a third simulation was performed on a CAD model of the Tesla Model S Plaid as a reference for the measured C_x of the two vehicles (this was necessary to obtain confrontable values given that the C_x seen in benchmarking are significantly different). The numerical results are presented in Figure 17. The results are valid considering that the values of C_x lie between 0.35 and 0.45, with it being a rare exception to be lower than 0.35. Moreover, the models simulated do not consider the permeability of elements such as the intakes. The C_x of the two proposals are encouraging considering that with few adjustments, they already match one of the main competitors, the Tesla Model S Plaid. Interestingly, the Blitz Vision Retrò has the lowest C_x in spite of the similar overall dimensions with other models. This is possibly due to a more streamlined body and a lower maximum height.

Model	$D[N]$	$S\ [m^2]$	C_X
Tesla Model S Plaid	788	2.19	0.4498
Blitz Vision AS	872	2.47	0.4428
Blitz Vision Retrò	678	2	0.4244

Figure 17. Numerical results of the CFD simulations.

Improvements in the aerodynamic performances can be suggested by observing the streamlines around the vehicle and the pressure fields on the different surfaces, which can be seen in Figure 18.

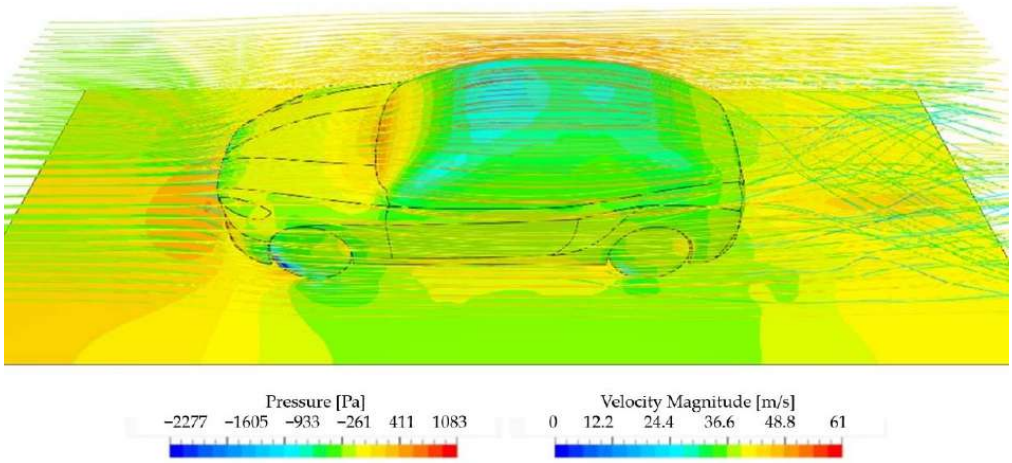

Figure 18. Pressure contour and streamlines around the vehicle.

As typically happens in vehicles, a separation bubble is formed where the hood and the windshield meet. In this region high turbulence and pressure are present, and for that reason it is common to locate the intakes for ventilation of the passenger compartment here. In order to reduce the entity of such a turbulence region, both models were modified in order to reduce as much as possible the inclination of the windshield. This solution, although being aerodynamically positive, reduces visibility. Since both vehicles surpassed the CFD analysis, the final model can be defined (Figure 19).

Figure 19. Final CAD models. Above row: Blitz Vision Retro. Lower row: Blitz Vision AS.

2.7. Prototyping

2.7.1. Rendering

The first stage of virtual prototyping is the rendering. In product design, rendering serves a fundamental purpose as it can provide the designer and the project team with a concrete idea of what their product will look like in a real environment. Therefore, this phase serves a communication aim as well as an engineering one. In a broader sense, rendering refers to the process of generating an image from a 2D or 3D model by means of a computer program. Usually this is performed to achieve a photorealistic representation of the CAD model which serves a purely engineering purpose (Figure 20). To achieve this result, elements apart from the actual model are considered, such as lights, reflection, shadows and external environment. The software used during this phase was Autodesk VRED.

Figure 20. First rendering of Blitz Vision AS and Blitz Vision Retrò.

2.7.2. Augmented Reality

As stated in the previous section, the representation of the product in a realistic environment has a fundamental role in the design work as well as in marketing, as it can provide the viewer with a clear idea of what the product will look like once out of the factory. In this process, an important tool that could be implemented is the one of augmented reality. Now, since rendering and augmented reality serve somewhat the same purpose, it is necessary to define what the two are. Rendering is just an implementation of virtual reality, that is, a virtual representation of either a fictional or real environment, whereas augmented reality allows the viewer to experience the interaction between a virtual model and the real environment through a series of interfaces. In other words, if virtual reality excludes any direct references to the real world, augmented realty exploits a real environment as the background for the representation of a virtual object. We can therefore understand that the basis of augmented reality lies in a software capable of recognizing objects in a real environment and tracking their relative position in a virtual reference frame. This is achieved by using cameras with more sophisticated devices such as AR visors worn by the user. Other than being an ideal for the customer, the visualization of the product in a real environment offers significant advantages during the prototyping phase. For example, production of physical models (maquettes) can be avoided all together or can simply be postponed until a more definitive design has been decided.

Augmented reality implementation of this project was made possible by the use of *Vuforia* and *Unity*. Vuforia is an augmented reality software development kit for mobile devices that enables the user to register a 2D or 3D object that can later be tracked precisely from a real to a virtual environment. Once the image target was decided, the actual implementation of AR was possible using Unity, that is, a cross-platform game engine that, among its various features, gives the possibility of realizing an augmented reality project. Being fairly easy to master, Unity is often used in industries outside video gaming, such as film, automotive, architecture, engineering and construction. Once in Unity, the Vuforia database containing the chosen image target was imported and placed in the virtual environment. Then, an *.obj* file of the CAD model was imported as the "hierarchical son" of the image target. After minor adjustments to colours and materials it was possible to start the AR simulation. Just before that, the image target was printed on a sheet of paper and then placed in a well-lit room. Thanks to the hierarchical nature of Unity, as soon as the image is in the frame of a camera, the model is automatically projected into the virtual environment. The final result for both models is presented in Figure 21.

2.7.3. Solid Stylistic Model (Maquette)

The final development of the project was represented by the creation of the *maquette* of the product. In industrial design, a maquette is a scale model of the final product. Maquettes are realized in various steps of the design project and are usually the main mean through which the product is presented to the management. In this case study, a scale model Blitz Vision Retro was 3D printed using FDM technology. In order to facilitate this procedure, the model ought to be simplified to minimize the number of surfaces. Various geometrical elements need to be either modified for the purpose or eliminated altogether, including sidemirrors, brakes, frontal grills and rear diffusers. The maquette is presented in Figure 22.

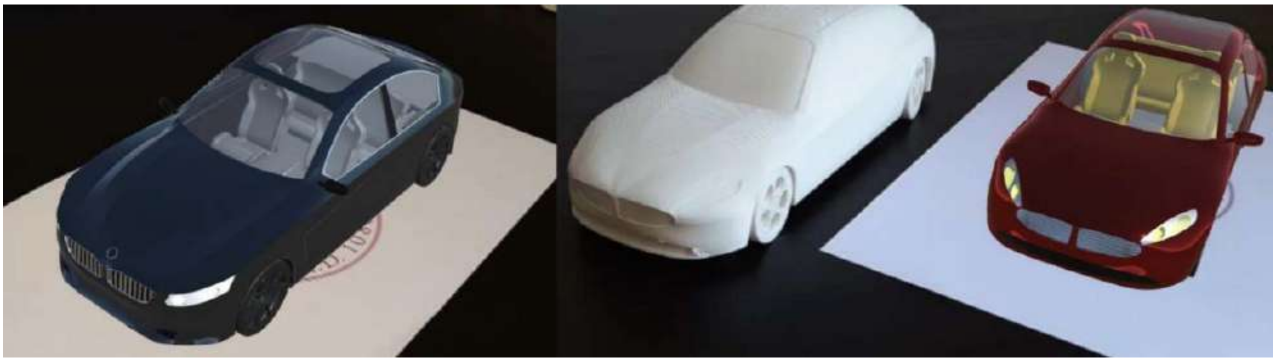

Figure 21. Augmented reality implementation of the two models.

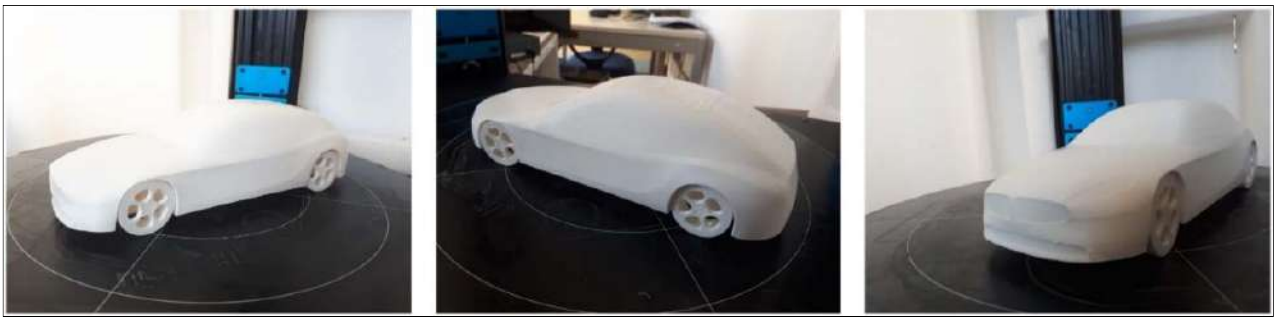

Figure 22. Additive manufacturing moquette of Blitz Vision Retro.

3. Results

The design stages of the two new BMW full-electric sports sedans are schematized in Figure 23. The final result, represented virtually by the CAD model and physically by the maquette, could be further developed into a full-scale prototype by an accurate engineering study of all parts and functions as a state of the example of the capabilities of QFD, SD and virtual prototyping combined in the field of automotive design.

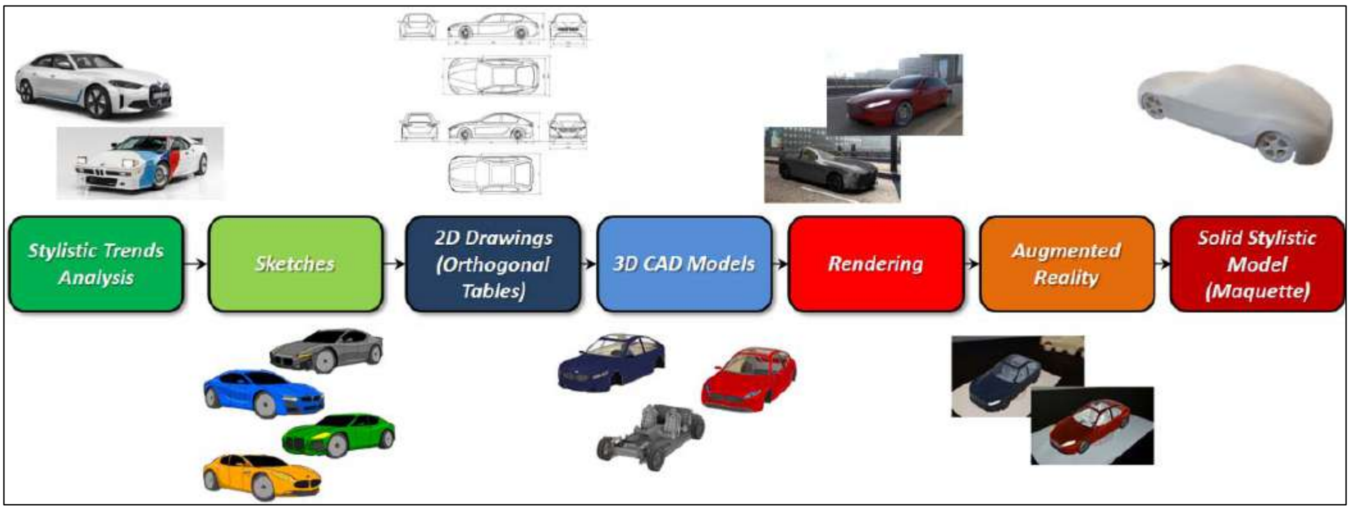

Figure 23. Stylistic design engineering diagram.

4. Discussion

Using IDeS, it was possible to describe in detail the procedure leading to the development of new automotive products with particular emphasis on the design setting and product development phases. Firstly, a deep environmental and market trend analysis was performed, considering both customer expectations and manufacturers' opinions. Customer requirements were identified and examined using quality function deployment (QFD), leading to benchmarking and technical specification definitions where 12 different competitor models were considered. The product architecture was finalized in a modular skateboard platform specifically designed for a full-electric vehicle and capable of housing various frames. By means of stylistic design engineering (SDE), the aesthetics of the vehicle were decided using four different stylistic proposals. In the end, it was decided to show the modular platform potential by developing two different model proposals, which were then created via CAD and validated using CFD. As for the prototyping, using state-of-the-art software and technology, it was possible to implement three different forms of virtual maquettes. Firstly, artificial reality was implemented in the form of renderings in virtual environments. Then, augmented reality was used by projecting the virtual CAD model into a real environment. Finally, using additive manufacturing, a physical maquette was created. The design process used in this work proved to be both effective and efficient as it is capable of borrowing specific elements from other methods known in the literature and, in some instances, it manages to overcome some of their limitations with relatively low effort. When compared to the Kano model, IDeS is much more time-saving and complete since it is not purely based on the data collection from potential customers. The Kano model still has the benefit of providing a useful insight into the customer's perception regarding the importance of the different product attributes; however, it is much more prone to skewing the relative weighting of the product characteristics. This drawback is prevented in IDeS as the initial surveying is not necessarily limited to potential customers, but it may also include experts from the industrial world. Another important aspect of IDeS is the fact that it does not use benchmarking alone in order to define the general requirements of the product, as often happens in real industrial applications. By following benchmarking with top-flop analysis it is possible to identify, select and prioritise specifications of greatest impact. This approach has the benefit of being both robust, as it is based on a quantitative ranking process, and flexible, as the selection of the most important parameters is up to the designer who is free to tailor them both to their own creative thinking process or to the quality requirements of the industry. IDeS shares with the Taguchi method the so-called "off-line quality control" approach. This is based on the assumption that during the design phase lies the potential of minimizing variation in the final product quality. As a matter of fact, this same approach can be seen from the first stages of IDeS, and thus, during the conceptual design phase that eventually leads to the definition of the technical requirements of the product. In these same stages, one could think of further improving the effectiveness of IDeS by involving Taguchi's robustification process, thanks to which a product is made less sensitive to those variables that result in higher parameter variability in the final product.

5. Future Developments

The three technologies used during the prototyping phase (rendering, augmented reality and additive manufacturing), being necessary to improve the design phase before a final physical prototype is produced and therefore tested, bear the potential of avoiding redesigns in later stages of the product development that result in unexpected costs peaks, and potentially avoid the induction of a later redesign step, which would produce high costs for the total project management. They also serve a fundamental role in helping technical and styling product developers during the design stage while maintaining high-quality standards. For these reasons, it would be interesting to investigate how the following phases of product development can be positively influenced by these prototyping techniques.

6. Conclusions

In this case study, a state-of-the-art application of IDeS was presented, describing in detail all the phases, procedures and tools used for the development of a new sports sedan car. The following goals were achieved:

- A thorough and complete analysis of the stylistic trends dominating the sports sedan market.
- Two innovative stylistic proposals for new BMW sports sedans using digital sketching techniques.
- CAD modelling and FEM validation of the modular platform-chassis.
- Surface modelling of the vehicle and validation via CFD analysis.
- Augmented reality application for both proposals.
- A solid model (maquette) produced via additive manufacturing (AM).

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