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Industrial Design Structure (IDeS) For A New Hybrid Sport Coupé Car

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Abstract

This case study aims to develop a proposal for the future sport coupé (Frizziero *et al.*, 2021) using the IDeS (Frizziero *et al.*, 2022) (Industrial Design Structure) method for testing and validation. IDeS method is a blend of innovative and advanced systematic approaches used in setting up a new industrial design. The method includes several sequential phases: quality function deployment (QFD), benchmarking (BM), top-flop analysis (TFA) and stylistic design engineering (SDE). The development of the sports coupé will progress through these phases, guiding the definition of technical and stylistic choices essential to compete in the market share. The ultimate goal is to validate the obtained result using this innovative methodology. This involves confirming that the product aligns with its segment (S-segment), meets QFD-defined requirements, outperforms competitors from the BM in TFA, and follows the stylistic requirements outlined in the SDE.

Keywords
Industrial Design Structure (IDeS), Stylistic Design Engineering (SDE), Quality Function Deployment (QFD), Sportscar, Hybrid.

1. Introduction

Our exploration into the S-Segment aims to distill key characteristics and design principles, focusing on performance attributes. However, the main goal is to use these insights to conceive an innovative next-generation sports coupé (Pagliari, 2023). Inspired by both contemporary and classic vehicles (Figure 1), we seek to push the boundaries of innovation, reimagining features from seating arrangements to powertrain solutions. This endeavor aspires to contribute to the evolution of sports car classification, envisioning a vehicle that embodies performance while reflecting the changing landscape of automotive design and technology.

Figure 1. List of S-segment cars used for benchmark.

1.1 Objectives

This work aims to show the application of the IDeS (Mascitelli *et al.*, 2023) method in the development of a new hybrid vehicle within the S segment. The goal is to create an innovative product with a distinctive and a futuristic style. Simultaneously, it is crucial to define and fulfill market demands and, so, meet consumer expectations through meticulous and targeted analysis. This approach aims to streamline the process, reduce time, resource consumption and explore avenues to expedite the acceptance of the final product.

2. Materials

Various materials were employed in the execution of the current project, categorized into two main groups: Software and Machinery. Focusing on the software aspects crucial for the research, the tools utilized include:

- Autodesk Sketchbook (used for drawing sketches).
- Autodesk AutoCAD (used to draw 2D blueprints).
- Blender (used to create the 3D model of the vehicle and some of the static renders).
- PTC Creo (used to create the chassis and for studies of the various styling proposals).
- SolidWorks (used for aerodynamic and structural analyses).

A 3D FDM printer (Fused Deposition Method) was additionally employed as part of the machinery to validate the project, specifically for generating a styling maquette.

3. Methods

IDeS (Galiè *et al.*, 2023) is an effective method designed to guide the development of new products within a company. It requires a specific organization of company departments to optimize its application. The method's efficiency lies in the detailed description of each step, reducing intervention costs by predicting or avoiding errors. The three main phases of IDeS are (Figure 2):

1. **Project Set-up:**
    - Conception phase defining customer needs through QFD (Frizziero, 2014) and finding competitors via BM.
    - Establishing innovative aspects through Product Architecture and aesthetic analysis using SDE.
2. **Product Development:**
    - Creating a 3D model based on functional and aesthetic details chosen in earlier phases.
    - Utilizing the 3D model for final rendering before prototyping.
3. **Prototyping/Production:**
    - Proceeding to production if the prototype aligns with established criteria from QFD and SDE.

The IDeS method, combined with effective planning, aids in making informed choices throughout the development process, contributing to the product's success in the market.

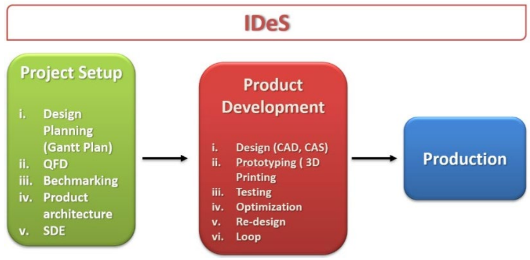


Figure 2. IDeS Scheme

3.1 Environmental Analysis

Environmental analysis, a first phase in IDeS (Industrial Design Setting), involves creating a document that outlines the current state and potential development of the intended product. IDeS, widely used in vehicle design, guides the systematic creation of new products. The analysis document serves as a comprehensive dossier, detailing the reference environment and key characteristics, including cultural, productive, and commercial contexts. Enhanced with visual elements, such as figures and diagrams, the document ensures easy comprehension of essential concepts.

3.1.1 Definition of the S-Segment

The S-Segment (REGULATION (EEC) No 4064/89 MERGER PROCEDURE, 1999) in European car classification is dedicated to sports coupés, denoting passenger vehicles with a sloping or truncated rear roofline and two doors. Known as "roadster sport" in Euro NCAP, these cars prioritize a sporting appearance and excel in handling and straight-line acceleration. Common body styles include coupé and convertible, often featuring limited rear passenger space. While most S-segment cars employ a front-engine design, a notable part with mid-engine or rear-engine configurations belongs to this category.

3.1.2 Market[1] Share and forecast.

Following the 2019 disruption due to Covid, the global car market is slowly recovering with a 4% increase, while the European market remains nearly stable (-1.5%) (Table 1). Forecasts show a growth trajectory detached from the GDP trend. Despite reduced registrations post-pandemic, market share distribution among segments has mostly remained unchanged, favoring SUVs at the expense of lower mediums and MPVs (Figure 3).

Table 1. Global new car registrations (ACEA, 2023)

	2021	2020	2019	% 20/19	% 21/20	% Share 2021
EU	9,700	9,939	13,029	-23.7	-2.4	14.7
Europe	14,309	14,534	18,112	-20.6	-1.5	21.6
America	16,759	16,668	19,578	-19.9	+7.0	25.3
Asia	31,892	30,707	33,959	-9.7	+3.9	48.2
Middle East/Africa	3,180	2,676	3,248	-17.3	+18.8	4.8
World	66,140	63,586	74,897	-15.3	+4.0	100.0

[1] All evaluations were based on data available for the European market because it is the main one for our segment and because it is the only one with reliable and free historical data.

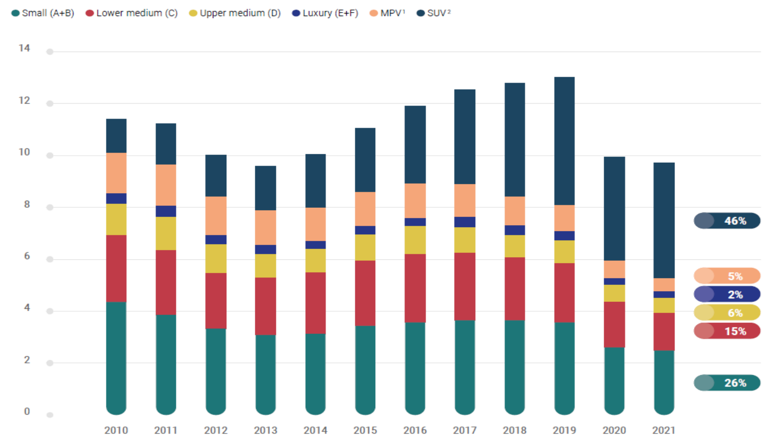


Figure 3. New cars in the EU by segment in million units, % share 2010-2021 (ACEA, 2023)

Our segment, although niche compared to mass production, aligns with the Luxury class. Despite market fluctuations, this class has kept a consistent share over time (Table 2). In summary, our analysis highlights the segment's small size compared to mass production but emphasizes its stability. Consequently, our car, regardless of the production brand, must have distinctive features to ensure success within this category.

Table 2. New car registrations in EU in k-units, % Luxury share (ACEA, 2023)

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
398,5	431,4	373,5	336,5	335,8	335,1	327,8	380,5	379,8	341,1	245,5	222,8
3,50	3,84	3,73	3,51	3,35	3,03	2,75	3,03	2,97	2,62	2,47	2,34

3.1.3 Power Unit Evaluation

To drive innovation in our segment, evaluating the engine choice is crucial, aligning with emission reduction goals set by the European Community. Regulation (EU) 2019/631, established in April 2019, mandates CO2 emission standards for new EU passenger cars and vans, with reduction targets of -15% and -37.5% for cars in 2025 and 2030, and -31% for vans by 2030. The European Commission's 'Fit for 55' climate package proposed a review, endorsing existing targets and introducing a new -100% target for 2035. Despite petrol and diesel dominating with a 60% market share in 2021 (Figure 4), alternatively powered vehicles reached a 40% market share. In Q2 2022, BEV registrations grew by 11.1%, PHEVs increased market share despite a 12.5% drop in units sold, and HEVs, while slipping by 2.2%, expanded overall market share to 22.6%. The positive trend emphasizes the auto industry's investments, with electrically chargeable cars accounting for nearly 1 in 5 new cars sold in the European Union.

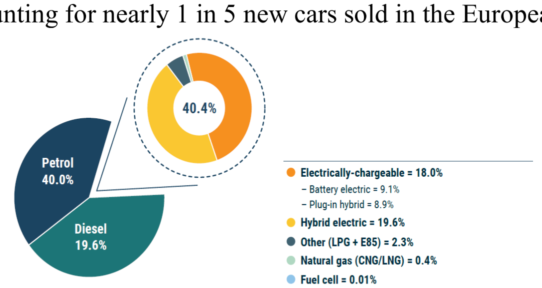


Figure 4. New cars in the EU by fuel type, market share 2021 (ACEA, 2023)

For the AER SC01 concept, the focus is on full hybrid or plug-in hybrid options, possibly with AWD through front axle electric motors. This aligns with the industry's shift toward alternative power, subject to sustained government investment in infrastructure and incentives.

4. Data Collection

Data has been gathered through a benchmarking analysis in comparison to current segment competitors using QFD, a fundamental part of the IDeS method. This analysis encompasses various tables, including importance matrix, impedance matrix, best requirements from competitors, benchmarking, top-flop analysis, and concludes with the analysis of the What-How matrix. The latter integrates QFD analysis with benchmarking to find features that require improvement compared to segment competitors, aiming to develop a competitive product.

4.1 Six Questions

The Six Questions serve as inquiries directed at prospective product purchasers to extract qualitative and technical requirements. Each answer contributes to the identification of customer requirements.

1. **Who buys it***:* Enthusiasts seeking a rich driving experience, middle-aged with a large budget.
   - *Requirements:* Design and customization.
2. **What is it for***:* Track-ready vehicle for an engaging driving experience, focusing on innovation and environmental considerations.
   - *Requirements:* Track readiness, fuel consumption.
3. **Where is it used***:* Ideal for track days, also comfortable for public roads, with the possibility for full electric mode.
   - *Requirements:* Comfort, hybridization.
4. **When is it used***:* Tailored for various enjoyable occasions, from track weekends to leisurely Sunday tours.
   - *Requirements:* Maneuverability, safety.
5. **Why is it chosen***:* Chosen for lightweight construction, maneuverability, and readiness, supplying an unforgettable yet practical driving experience.
   - *Requirements:* Weight, price.
6. **How is it used**: Track-focused design with meticulous attention to materials and reliable propulsion systems.
   - *Requirements:* Performance, materials.
   -

4.2 Importance Matrix

Derived from the first market analysis (6Q), general requirements are assessed using the Importance Matrix (
Figure 5). This matrix assigns numerical values based on the relative importance between each requirement in rows and columns: 0 if the row element is less important than the column one, 1 if the row element is as important as the column one, 2 if the row element is more important than the column one. The highest value between the total sum of each row is the most important feature that should be designed,

	Design	Price	Comfort	Manoeuvrability	Performance	Weight	Customization	Safety (ADAS)	Hybridization	Consumptions	Track Readiness	Materials	Total
Design	1	2	2	1	1	2	2	2	1	2	1	2	19
Price		1	2				2	1				1	7
Comfort			1	1	1	1	1	2	1	2	1	2	13
Manoeuvrability	1	2	1	1	1	1	1	2	1	2	1	2	16
Performance	1	2	1	1	1	1	1	2	1	2	1	2	16
Weight		2	1	1	1	1	2	2		1	1	1	13
Customization			1	1	1		1	1		1		1	7
Safety (ADAS)		1					1	1		1		1	5
Hybridization	1	2	1	1	1	2	2	2	1	2	1	2	18
Consumptions		2				1	1	1		1		1	7
Track Readiness	1	2	1	1	1	1	2	2	1	2	1	2	17
Materials		1				1	1	1		1		1	6

Figure 5. Importance Matrix

4.3 Independence Matrix

To assess the relative significance of each requirement, it is crucial to evaluate their interdependence. The Independence Matrix (Figure 6) follows a similar structure to the Importance Matrix, assigning numerical values to cells based on the relative dependency of the row's requirement on the column: 0 if the row element is entirely independent of the column one, 1 if the row element is somewhat independent from the column one, 3 if the row element is somewhat dependent on the column one, 9 if the row element is entirely dependent on the column one.

	Design	Price	Comfort	Manoeuvrability	Performance	Weight	Customization	Safety (ADAS)	Hybridization	Consumptions	Track Readiness	Materials	Total
Design		3	1				3				3	3	13
Price	3		1	3	9		9	3	9		3	9	49
Comfort		3		9	3	1	1	3	3		9	1	33
Manoeuvrability		1	9		3	9					9		31
Performance	3	9	3	3		1			3	9	9	3	43
Weight	3			9	3			3	9		3	9	39
Customization	3	1										9	13
Safety			3				3				1		7
Hybridization	1	1			9					9	3		23
Consumptions	3				9	9		1	9		3	1	35
Track Readiness	3	3	3	9	9	9	1	1	3	3		3	47
Materials	3	9					9				3		24
Total	22	30	20	33	45	29	26	11	36	21	46	38	

Figure 6. Independence Matrix

4.4 Best Requirements

Combining the results of the two previous matrices is it possible to obtain the best requirements matrix (Figure 7) that the product must meet: the highest scoring requirements will form the base on which the what-how matrix will later be built.

			Sum
Design	19	22	41
Price	7	30	37
Comfort	13	20	33
Manoeuvrability	16	33	49
Performance	16	45	61
Weight	13	29	42
Customization	7	26	33
Safety	5	11	16
Hybridization	18	36	54
Consumptions	7	21	28
Track Readiness	17	46	63
Materials	6	38	44

Figure 7. Best Requirements Matrix, the most important and independent

4.5 Competitors Benchmarking

	Jaguar F-Type	Audi TT S	Alpine A110	Alfa Romeo 4c	Supra GR 3.0	BMW Z4 M40i	Cayman s	911 Carrera 4	Nissan GT-R	Lotus Evora Sport GT	Rc 350 F Sport
Engine type	In line 4				In line 6		Boxer 4	Boxer 6	V6		V8
Charge system	Turbocharged							Bi turbocharged		Superch.	Aspirato
Traction type	RWD	RWD	RWD	RWD	RWD	RWD	RWD	RWD	AWD	RWD	RWD
Length [mm]	4470	4199	4180	3989	4379	4324	4379	4519	4710	4394	4705
Width [mm]	1885	1832	1798	1864	1854	1864	1801	1852	1895	1972	1845
Height [mm]	1311	1366	1248	1183	1292	1304	1284	1298	1370	1223	1390
Wheelbase [mm]	2622	2505	2419	2380	2470	2470	2475	2450	2780	2575	2730
Curb weight [kg]	1520	1815	1365	920	1570	1860	1385	1555	1746	1331	1765
Consumption [l/100km]	8.1	7.3	8.9	6.8	7.2	7.2	9.2	9.2	13.9	12.9	11.8
Displacement [cm^3]	1997	1984	1798	1742	2998	2998	2497	2981	3799	3456	4969
Hp/liter	148.2	158.8	160.2	136.1	113.4	113.4	138.2	127.5	147.9	118.6	68.6
Power [kW]	220.5	235	215	176.5	250	250	257.5	283	419	305.7	254
Max Torque [Nm]	400	400	320	350	500	500	420	450	637	420	530
Top Speed [km/h]	261	274	261	256	281	281	290	299	321	301	270
0-100 [km/h]	5.4	4.5	4.4	4.5	4.6	4.5	4.4	4.1	3.5	4.5	4.5
Weight/Power [kg/kW]	6.9	6	5.2	5.2	6.17	6.2	5.4	5.5	4.2	4.4	6.9
Price [k€]	68.970	63.900	60.882	65.550	66.500	73.710	75.774	126.056	105.450	135.000	97.000

Figure 8. Benchmark Matrix

This benchmark analysis (Figure 8) evaluates how competitors address customer requirements and the extent of innovation they bring to the table. Consequently, it enables the extraction of technical benchmark requirements and the required level of innovation to surpass competitors. The selected list of competitors has been presented in Figure 1. The table uses data from fairly reliable sources (Technical Specs) (Automobile Catalog) and despite potential inaccuracies, they are considered acceptable for comparison purposes. To find key technical requirements for innovation, both the best and worst-performing cars in each aspect are crucial. A column of innovations can then be created for the future sports car, where it surpasses the best car in each specific feature. While achieving superiority in all areas may be challenging, the future sports car must display substantial innovation to stand out in the market.

4.6 Top Flop Analysis

The top-flop analysis (Figure 9) gauges the innovation level needed for a new model to succeed in the market against competitors. For each car in the benchmarking analysis, the "delta" is the difference between features where it excels (Top) and underperforms (Flop). The benchmark for success is set by the best delta value, requiring the future sports car to exceed this by at least two units in terms of innovations. Two cars from the analysis serve as benchmarks:

- Alfa Romeo 4C for dimensions, weight, and aerodynamics.
- Nissan GT-R for engine performance (power, torque, and acceleration).

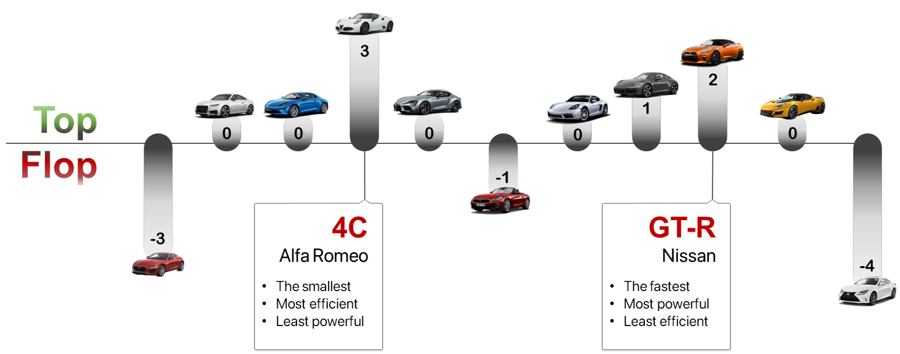


Figure 9. Top-Flop Chart

4.7 What-How Matrix

The What-How Matrix (Donnici *et al.*, 2020) (Figure 10) **Errore. L'origine riferimento non è stata trovata.**) combines QFD and Benchmarking to identify technical characteristics for improvement (higher delta value). It features the best customer requirements from the Importance and Independence Matrices on rows, and Benchmarking Analysis technical characteristics on columns. Numeric values show how well each performance aligns with customer needs: 0 if it falls short, 2 if slightly meeting, 4-6 if sufficiently meeting, and 8-10 if fully meeting requirements. The top 6 performances, closest to customer needs, constitute the innovation number contributing to the delta value. The future sports car aims for a delta of at least 5.

	Traction Type	Dimensions	Wheelbase	Weight	Fuel Consumption	Displacement	Hp/liter	Power	Max Torque	Top speed	0-100 km/h	kg/kW	Price
Manoeuvrability	10	10	10	8				2	6			2	
Performance	8	4	4		10	8	8	10	10	8	10	8	5
Hybridization	6	6	6		10	5	5	5	8	2	5		4
Track readiness	10	10	10	6	5		2	8	10	6	10	5	
Materials		2	2	10	2					4	5	5	8
Total	34	32	32	24	27	13	15	25	34	20	30	20	17

Figure 10. What-How Matrix

5. Results and Discussion

5.1 Product Architecture

Product architecture represents a more technical aspect of design planning, outlining how chosen functional components and technologies can fulfill the targets outlined by the What-How matrix, thereby enhancing desired performances. In these sections, we will explore solutions aimed at meeting the technical requirements found by the W-H matrix. The key outcomes from the What-How matrix include:

- Dimensions and Wheelbase
- Fuel Consumption
- Traction
- Torque
- Acceleration (0-100)

5.1.1 Dimensions and Wheelbase

Based on the benchmarking analysis, achieving the right size compromise is crucial for the future car to outperform competitors and satisfy customer requirements. As a sports coupe, the goal is to keep compact dimensions, ensuring sufficient width for stability and habitability, coupled with a narrow wheelbase for agility on the track. Noteworthy contenders in size include the Alfa Romeo 4C, boasting the smallest overall dimensions and the shortest wheelbase, and the Lotus Evora, recognized for its impressive width. The selected measures for the best trade-off include:

- Wheelbase: 2380 mm for enhanced agility and handling.
- Height: 1100 mm for a lower center of gravity and improved grip.
- Width: 1900 mm for greater stability, improved weight distribution, and increased habitability.
- Length: Carefully considered as a consequence of the wheelbase, with minimized overhang dimensions for best vehicle dynamics.

These size considerations aim to strike a balance, ensuring superior performance and customer satisfaction in the future sports car.

5.1.2 Fuel Consumption

Introducing a partial electric power supply stands as a significant innovation against market competitors. However, preserving the classic engine sound integral to the racing essence needs a plug-in hybrid power supply for the future sports car. Drawing inspiration from the Rally1 WRC project, this power unit solution offers a balanced compromise between enthusiasts' desires and evolving emission regulations. When coupled with E-Fuel utilization, derived from a circular emission advantage (Figure 11), it proves advantageous, boasting a higher energy density than batteries. Although E-Fuel technology is still in development, ongoing studies and experiments on world championship tracks aim to create a sustainable solution.

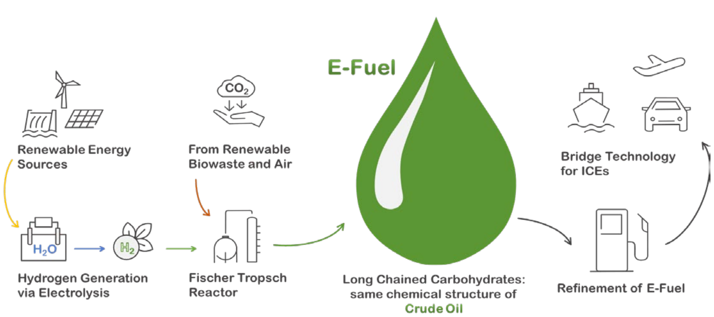


Figure 11. E-Fuel production and cycle life

5.1.3 Engine Position and Traction

The chosen power unit significantly affects the car's traction, and the chosen technical solution (Figure 12) can enhance this aspect:

Hybrid AWD: Derived from the Rally1 project, this configuration combines a rear-mounted turbocharged ICE with two front electric motors, resulting in a 572 hp all-wheel drive with nearly equal power distribution (52% ICE and

48% EMs). This setup optimizes standing starts, minimizes turbo lag, and enhances cornering. Additionally, it enables all-electric mobility in urban settings due to the plug-in solution.

Electronic Torque Vectoring (Lück, Freimann and Schneider, 2007): With front electric motors for each wheel, this system helps independent torque management without requiring an electronic mechanical differential. Torque vectoring supplies dynamic traction control, enhancing grip during cornering and acceleration. The front electric motors significantly contribute to acceleration from a standstill and exiting curves.

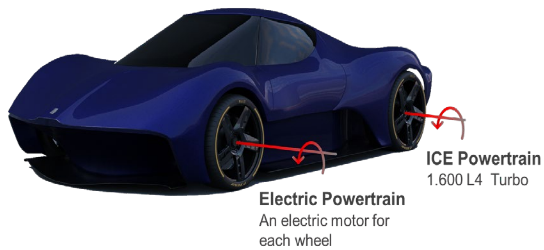


Figure 12. Hybrid AWD and torque vectoring systems

5.4 Habitability

To arrange mechanical components systematically, it's crucial to establish the occupant safety environment and driving position, adhering to predefined layouts and anthropometric data. Interior dimensions are primarily figured out by the driver's height, ensuring compliance with SAE regulations catering to a diverse range of drivers, from the 5th percentile female to the 95th percentile male. Following these guidelines and the SAE J1100 (Macey and Wardle, 2009; Pagliari, 2023) measurement index, minimum requirements for interior spaces are defined, thereby establishing the occupant environment (Figure 13).

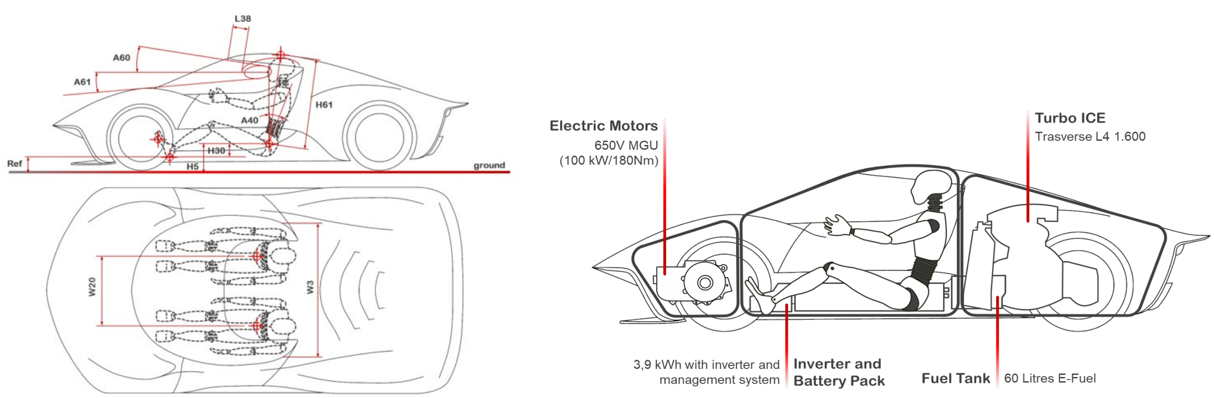


Figure 13. Habitability and Components Arrangement

5.5 Components Arrangement

With the overall dimensions and technical solutions determined, the next step involves selecting the best arrangement for fundamental components (Figure 13). Key aspects of the product layout include:

- **Chassis** Drawing inspiration from LMH endurance racing cars and the Alfa Romeo 4C, the chassis features a central monocoque and front and rear frames (Figure 14).
- **Battery Pack:** Limited plug-in hybrid battery size allows for placement in the central channel without requiring a driveshaft.
- **Electric Motors:** Positioned low on the front frame, electric motors include a separate inverter co-located with the battery.
- **Turbo ICE:** The 1600-cc turbocharged in-line four-cylinder engine adopts a transverse configuration, emphasizing a central position. Radiating masses are laterally mounted with air intake concealed by bodywork to complete the setup.

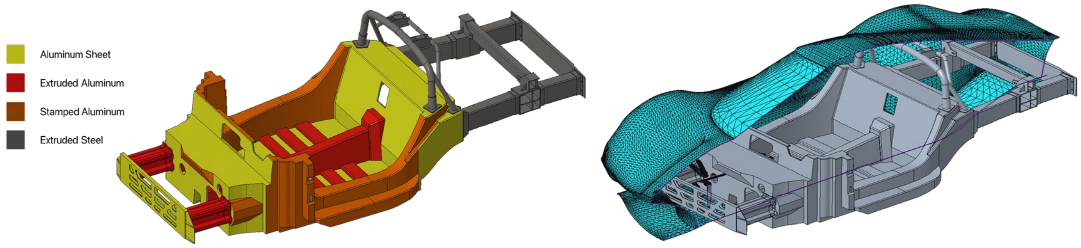


Figure 14. Chassis components and fitting

5.6 Final Design

5.6.1 Sketches and Blueprint

Utilizing the selected styling proposal, the final design sketch (Figure 15) of the vehicle was crafted. After the final sketch, a blueprint (Figure 15**Errore. L'origine riferimento non è stata trovata.**) is created to determine the actual 2D dimensions of the vehicle. This blueprint, holding the dimensions of the vehicle, will also be instrumental in crafting the 3D model for rendering.(Brevi and Gaetani, 2020).

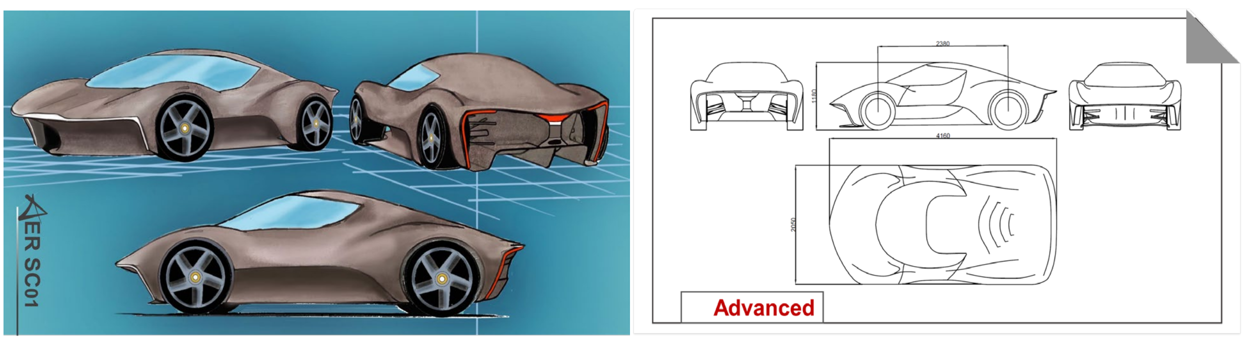
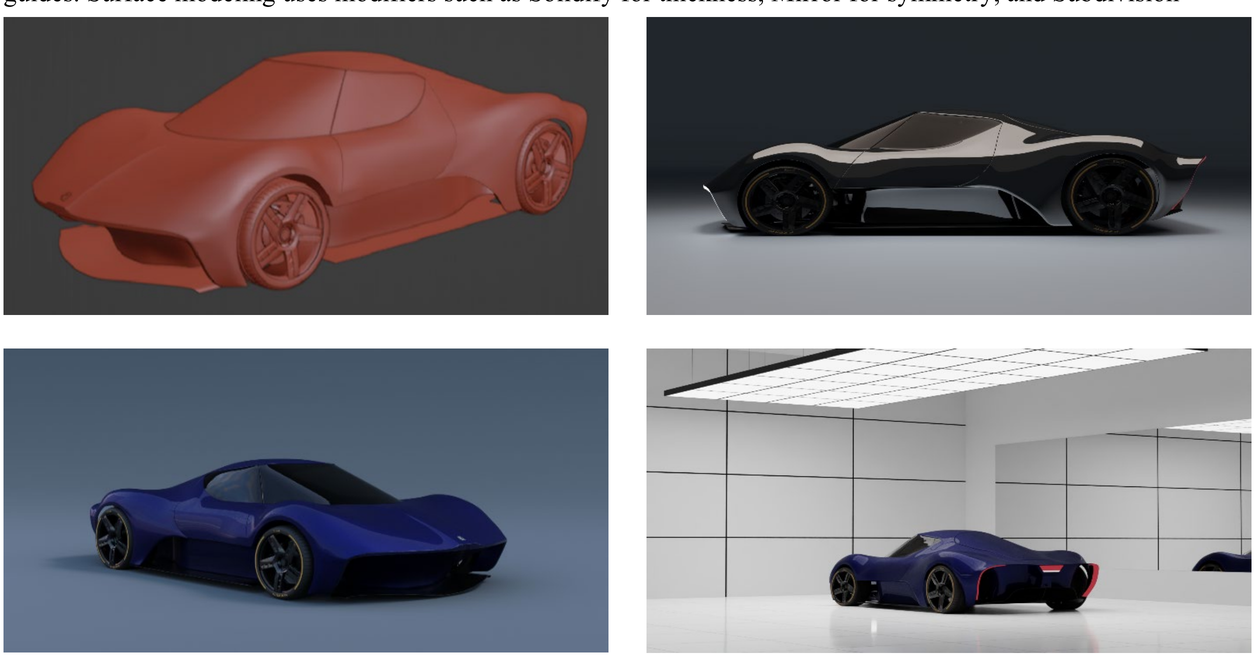


Figure 15. Final Sketch and blueprint of AER SC01

5.6.2 3D Model and Renders. To create the 3D model in Blender (Figure 16), blueprints are imported as precise guides. Surface modeling uses modifiers such as Solidify for thickness, Mirror for symmetry, and Subdivision



Surface for finer control. This meticulous process takes months to ensure a flawless model. While Blender is used for both modeling and rendering, it's illustrative rather than an industry standard. The rendering phase in Blender allows for photorealistic renders with virtual environments.

5.6.3 Prototyping

Utilizing a 3D printer, a scaled model of the car was successfully produced (Figure 17). The model is proportionally scaled at 1:20 compared to the actual vehicle and was printed in collaboration with Alma Mater Studiorum of Bologna.

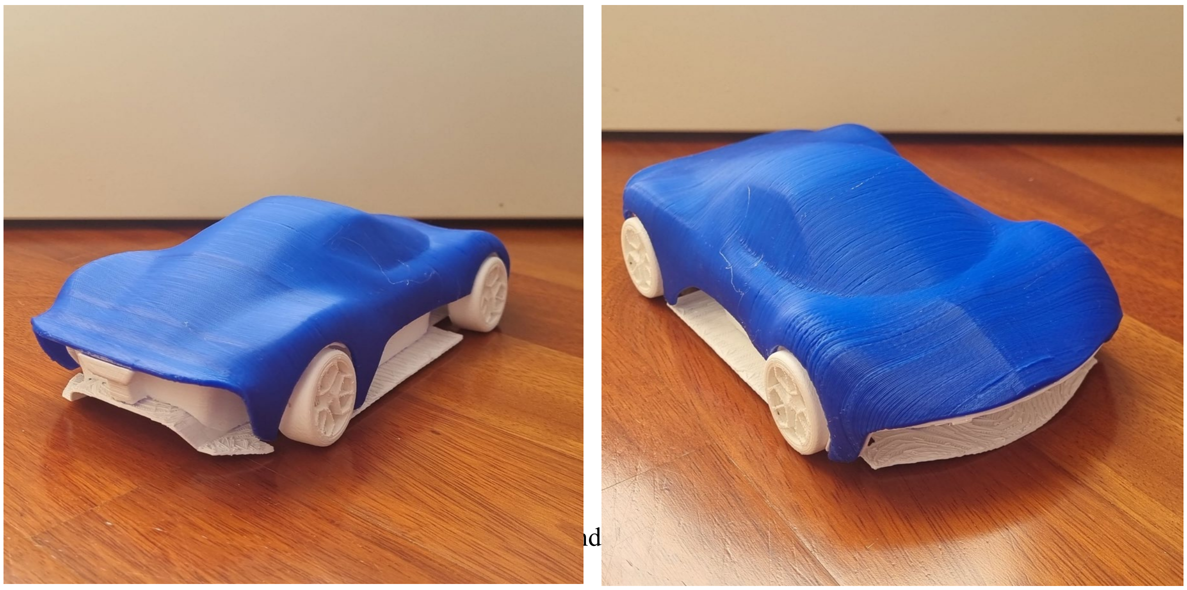


Figure 17. 3D model, scale 1:20

6. Conclusion

The entire project, focused on crafting an innovative sports car for the future, followed the comprehensive IDeS method. From first analysis and QFD to benchmarking, sketching, blueprinting, and 3D modeling, each step contributed to the final results. The success of this endeavor highlights the efficacy of the IDeS method in systematically guiding design decisions for market relevance.

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