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Master's Degree Thesis

Formula Student Race Car Technical Project Development

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Abstract

This work discusses the project development of the Formula Student electric race car developed by the Team Squadra Corse PoliTO in the academic year 2020/21 from a technical perspective. In that season I had the privilege of representing the Team both as Technical Director and Driver.

The whole vehicle project development follows the V-cycle model, vastly employed in nowadays automotive development process.

Starting from the specifications required for the product, the full-vehicle concept is defined in a preliminary phase of the V-cycle, also referred as "Target Setting". The tools needed to support the Target Setting phase, i.e. mainly the single point mass lap time simulator developed in MATLAB-Simulink and the VI-grade CarRealTime in co-simulation with MATLAB-Simulink, the context in which this was done, the different benchmarking analyses and some other aspects of the full vehicle such as its packaging and driver ergonomics are presented.

Starting from the final vehicle targets, the requirements are then deployed at assembly, subassembly and finally to component level, through different levels of layout definition, design and optimization iterations. The vehicle design is aided from the technical data management point of view by tools and documents such as Gantt charts, Bill of Materials, Failure Mode and Effect Analysis with the aim of improving the robustness of the project, following Design for Manufacturing and Assembly practices. Design books internal reports are presented as well as another tool for the technical data management inside the Team.

The manufacturing of the vehicle is presented together with the tools needed to support the production of the prototype such as Gantt charts, production BOMs, technical documentation needed to manufacture and assembly both electrical and mechanical components, inventory sheets. Manufacturing and assembly examples of relevant assemblies and components of the race car are shown. Additional information about the good practices needed in the wiring harness production are discussed.

An insight on validation branch of the V-cycle is proposed, deployed into four levels, that are component, subassembly, assembly and vehicle levels with their respective validation examples.

Final operations and maintenance of the vehicle are presented, with the tools and documents used during both service and track activities.

Acknowledgements

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Il mio pensiero finale va alle future generazioni di Squadra, mi auguro che questo breve resoconto possa tornarvi utile anche solo per l'1%, sarei infinitamente felice nel vedervi riuscire ad estarre il meglio dal passato ed a Vincere!

Marco

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1 Introduction

1.1 Formula Student Competition

Formula Student is an international student design competition which involves the departments of universities worldwide organized by SAE International (previously Society of Automotive Engineers). The competition requires the design, production and development of a small formula style race car that is evaluated by experts during each event. Each prototype built by a team can compete for one year only, therefore usually each team develops and builds a new prototype each season.

Formula Student was created in the USA in 1981 and arrived in Europe in the early 2000s. Since then, the community of Formula Student has increased throughout Europe and many new teams were founded. Formula Student Germany (FSG) is considered as the main event and generally European competitions try to follow it as a model. Aside from FSG, the main Europe events are Formula SAE Italy, Formula Student Spain, Formula Student Austria, Formula Student East, and others.

More than 400 University Teams from more than 60 countries compete together, subdivided into three main categories: Combustion, Electric and Driverless Vehicles. According to the rules, Vehicles entered into the competition must be conceived, designed and maintained by the student team members without direct involvement from professional engineers, racers, machinists or related professionals[1].

Each event on the calendar is subdivided into static and dynamic events. 325 available points out of the total 1000 are assigned to the static events:

- **Engineering Design**: Each team has to submit an Engineering Design Report (EDR) prior to the competition. It consist of an eight page document in which a technical description of the vehicle is present, among with the main reasons behind the design choices done. Starting from the EDR at the Design presentation, judges evaluate the technical design, layout, production of the vehicle both from a vehicle level and subsystem or component level when needed. Teams have to proof their knowledge to the judges both from an academic and practical standpoint. Brief clarifications on some technical designs have to be handed whenever asked. This event is not only knowledge oriented but rather it allows the judges to assess the design process, goals, thinking and reasoning behind the final product delivery.

- **Cost and Manufacturing**: The teams have to deliver a written cost report

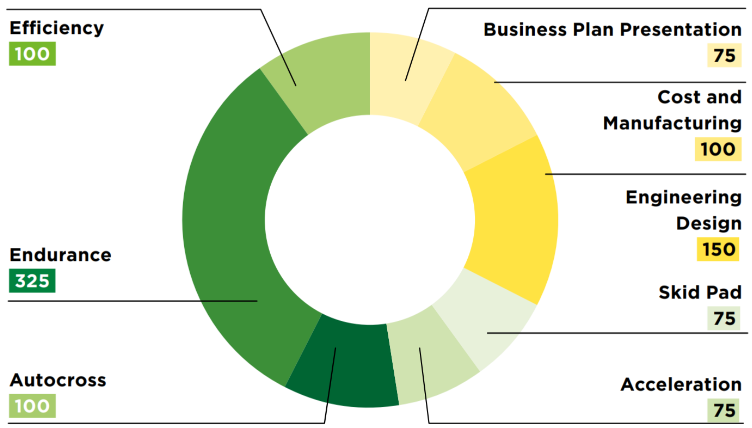


Figure 1.1: Point distribution for each event (total maximum 1000 pts) [2]

in which the vehicle components and their manufacturing process is listed in detail. In addition, the teams are asked to create a real case task, to evaluate the cost and manufacturing knowledge in a certain field of the car. During the competition Teams are asked questions from the judges about the Cost report, related to the real car.

- **Business Plan Presentation**: Each team has to develop and deliver a business model where their vehicle is presented as capable of becoming a rewarding business opportunity that creates a monetary profit. At the event the teams have to present their Business Plan in front of potential sponsors represented by judges. Different aspects are evaluated in the presentation, i.e. the content, structure and editing, as well as the team's performance in delivering it, alongside with answers to specific questions.

Before entering the dynamic events, all the teams undergo a series of technical inspection that assess the safety level of the vehicles and to verify whether they meet the rules or not. Once these inspections are cleared, the vehicle is allowed to race.

Since wheel-to-wheel racing, as it happens in many motorsports, is not allowed in Formula Student, all the dynamic events are held under the principle of racing on your own as fast as possible. The scores for each event are dependant not only on the absolute performance registered by each team but rather are related to the time registered by the best team. In this way more credit is given to successful teams to award their effort in developing a fast and reliable car.

For all the dynamic events except the Endurance, each team has up to four runs, driven by two drivers with two runs each [1]. The endurance instead is a single event driven by two drivers only. 675 available points out of the total 1000 are assigned to the dynamic events:

- **Acceleration**: The vehicle's acceleration time from a standing start is measured over a 75 m straight.

Figure 1.2: Teams at Formula Student Germany 2022

- **Skidpad**: The vehicle runs an eight-like track of 18.25 m diameter and a track width of 3 m. Each circle has to be run two times clockwise and another two times counterclockwise respectively, both second laptimes are measured and averaged.

- **Autocross**: The vehicle runs a one kilometer-long track made of straights, corners, chicanes. All round maximum performance of the vehicle is evaluated in this event since it includes low and high speed corners, high accelerations and brakings. The event is usually run by the teams with a setup of full torque and power available due to the short duration of the event. Autocross scores decide the starting order for the Endurance event.

- **Endurance**: It represents the most important event of the whole competition, nearly one third of the points are assigned to this event. The vehicle has to complete a course of 22 km similar to the one of autocross. It is divided into two stints where there is a driver change at halfway. It is very challenging since vehicle reliability, dynamics, energy management and driver ability are put under test all together. It is no surprise that usually less than half of the starting grid scores DNF. During this event energy consumption is measured too, and an efficiency score is attributed, relating vehicle efficiency and time with the best score recorded.

1.2 Squadra Corse PoliTO Team

Squadra Corse PoliTO is the Formula Student racing Team from Politecnico di Torino. The Team was established in 2004 and took part in the first Formula Student event one year later, in 2005.

So far, the Team has designed 18 prototypes, of which 17 were built and raced in competitions, divided into 7 internal combustion engine vehicles, 1 hybrid vehicle, and 9 electric vehicles.

The Team was the first Italian team to enter the electric category in 2012 and later, in 2015, the first Italian team to adopt a 4WD layout. This configuration is still adopted nowadays with latest prototype developed SC22. The object of this discussion is prototype SC21 developed during the 2020/21 season, which is the eight full-electric car designed by Squadra Corse PoliTo.

The number of Team members changes every year according to the needs but in the last few seasons it ranged around 35-65 members. An example of how the Team is subdivided internally is reported in Figure 1.3.

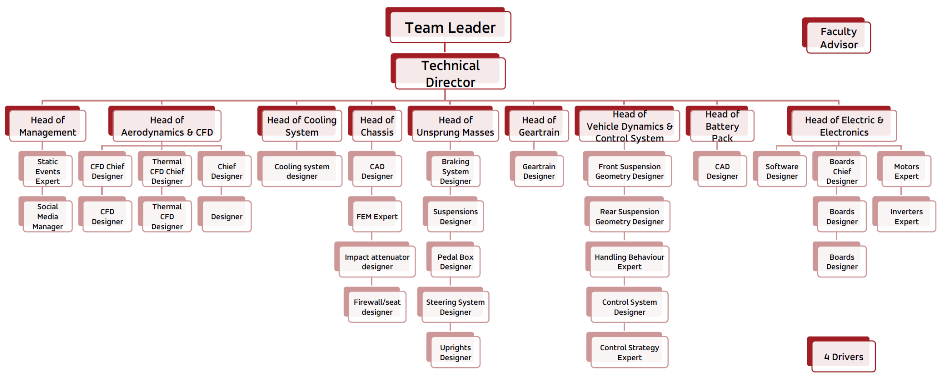


Figure 1.3: Team roles 2020/21 season

1.3 SC21 Project

The 2020 was a cornerstone year indeed in the Squadra Corse history since for the first time ever the prototype being designed in the season was not built due to Covid-19 pandemic. After some weeks of debriefing of what the future of Squadra Corse would look like under this uncertain context, a restricted group of Team members started working into new ideas and proposals to be shown to the attention of everyone remaining for the 2020/21 season. In this way an early assessment of where the Team should have put the main efforts and focus in developing the new vehicle was done.

After the aforementioned preliminary phase, target setting phase was developed in order to set main targets of the vehicle in terms of performance, reliability, manufacturability, serviceability, cost, integration of the systems. Then, the design phase went on and covered in more detail every area of the car, followed by the production phase. These two phases have been a pretty challenging exercise considering the fact that no Team member had previous experience in building a Formula Student prototype due to SC20 project production withdrawal, as already mentioned. Pre-race tests and race events are the direct consequence of the production phase, where the vehicle was put on track and validated.

Figure 1.4: SC21 Team at Formula Student Spain 2021

Figure 1.5: SC22 Team at Formula Student Alpe Adria 2022

1.4 Thesis outline

This Thesis project is structured as follows:

- **Chapter 2** illustrates the vehicle target setting phase starting from the preliminary proposals up to the final vehicle targets, as well as the tools needed to perform such operation, the context in which this was done and some other full vehicle related aspects such as its packaging.
- **Chapter 3** presents an overview of the vehicle design, with some insights the author believes worth of brief description, together with the tools needed and implemented in order to design the vehicle.
- **Chapter 4** presents the production phase, formally subdividing it into mechanical and electrical area, even though they are strictly interconnected in real life, as well as the tools needed and implemented in order to manufacture the vehicle.
- **Chapter 5** provides an insight on validation and testing phase, subdividing it into four levels, that are component, subassembly, assembly and vehicle levels with their respective examples.
- **Chapter 6** shows how the operation and maintenance of the product are carried out and how they are actually integrated into the post-seasonal tests.

All along this Thesis project the author has decided to highlight several topics that are relevant for the success of the vehicle project and to point out different crucial factors and lessons learned from this experience that could be helpful for the future Team members, both from technical and human-related sides.

2 Vehicle target setting

Designing and building a race car is a complex task, and complex tasks cannot be achieved without a clear definition of the process required to perform that task. Formula Student lifecycle belongs to automotive field, but, differently from what happens in automotive industry, it is characterized by shorter so called "time to market" (even though the vehicle is not sold to the market), and the missing of some process phases that characterize the automotive industrialization process. The Formula Student industrialization process is kind of reduced and adapted to the demands of the Formula Student world. An example of automotive industrialization process is reported in Figure 2.1. The concept and style phase is in our case reduced to concept only, and it is called "Target Setting". It is a preliminary phase of the overall project development where engineering targets, mainly technical but also organizational, are defined for the overall vehicle, for each system of the car. The design and validation process have to be constantly monitored in order we make sure that those targets are effectively reached in the final product. Product development, prototipation and testing phases are responsible for the effective engineering design phase and relative development of prototypes, that ends with final design release. Further in depth analysis is present both in Section 2.1 and 3. Industrialization phase reported in Figure 2.1 is much more complex than Formula Student world, since produced vehicles have to actually meet the real market, and not remain prototypes as they are Formula Student race cars. Furthermore, OEMs usually industrialize their process for mass-production, at the same time they have to make profit, and vehicles have to respect safety and legislative requirements, so the industrialization phase has to be carefully addressed. Pre-production and series production as well are not present in Formula Student world. I will refer to Production phase as the phase of industrialization of the race car, being one single prototype effectively produced in real life. For this reason in the following, I will focus more onto the Target Setting, Design, Production and Validation phases, as intended per the Formula Student world.

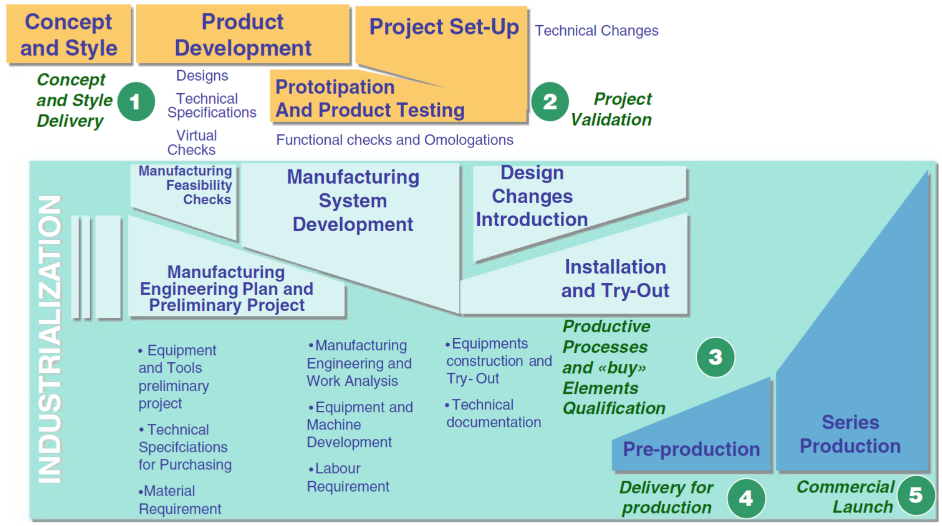


Figure 2.1: Automotive industrialization diagram[3]

2.1 V-cycle model approach

V-cycle model approach is vastly employed nowadays in the automotive development process. In the last decades, automotive industry has seen its complexity significantly grown up due to the simultaneous integration of different engineering disciplines, such as mechanical, aerospace, materials, informatics, electrical and electronics branches and due to the highly changing environment in which automotive industry is located, both from a technological and economical perspectives.

Automotive development sees different types of requirements, for instance software development follows different rules than hardware development, due to the different level of complexity management, occurring errors and failure, durability and lifecycle. Dedicated interfaces between mechanical design, simulation and software development programs are needed for the applied development platforms. At the same time, evaluation tools for testing of complete mechatronics systems need to be implemented. For this reason, parameters able to characterize the product maturity in view of the overall development processes have to be introduced. [5]

The left part of the V-cycle model is also called Verification, whereas the right part is called Validation. Starting from the specifications required for the product, the full-vehicle concept is defined in a preliminary phase of the V-cycle. This phase is what is referred as "Target Setting" in Squadra Corse environment. The requirements are then deployed at module or system level, down to subsystem and finally to component level, through different levels of layout definition, design and optimization iterations. The design of such systems is done through tools (usually softwares) such as Computer-aided design (CAD), Computer-aided engineering (CAE), Electronic Computer-aided design (ECAD), Digital mock-up (DMU) and

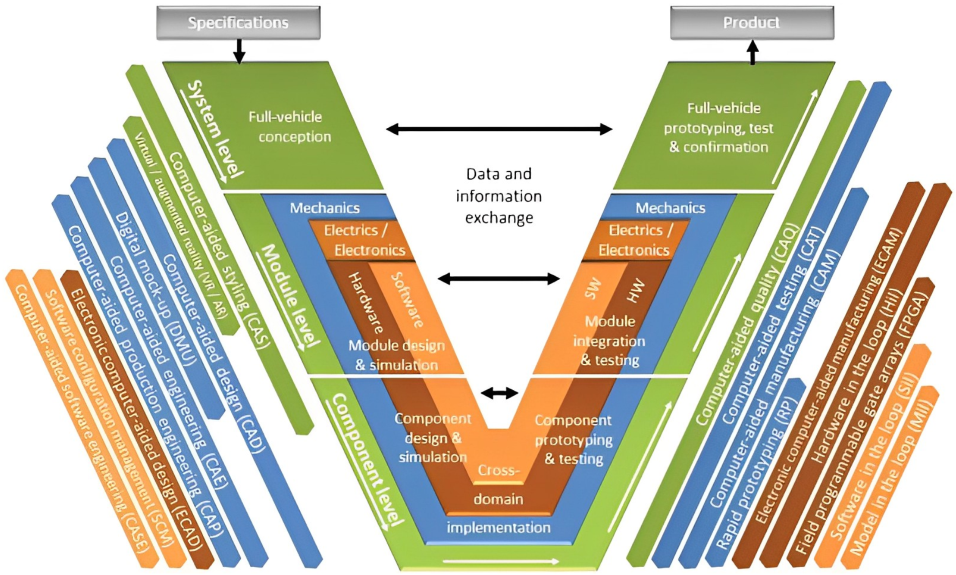


Figure 2.2: Automotive development process according to V-cycle model[4]

other.

Between the left and right part of the V-cycle model there must be cross-domain implementation, that is proper integration of the different domains coexisting in the vehicle environment, deployed at component level. At this level we must be sure that software and hardware electronics are properly integrated with the mechanical side of the component itself. The right side of the V-model results in prototyping, testing and eventual optimization (data exchange in between left and right branches of the V-model), till the final confirmation of respectively component, subsystem, system and full-vehicle level. The Validation phase is aided through tools such as Computer-aided quality (CAQ), Computer-aided manufacturing (CAM), Hardware in the loop (HIL), Software in the loop (SIL), Driver in the loop (DIL), Rapid Prototyping (RP) and other.

Typically, the development of a vehicle for what regards the subsystem and component levels, includes several iterations of the design and testing phases. This is due to the necessity of having proper optimization of the component, till it meets the desired requirements. Both the duration and complexity of these development cycles can significantly differ from domain to domain (electrical or mechanical e.g.), so it represents a big challenge for the overall development process in the sense that different maturity levels must be integrated within the same context [5].

The development process of SC21 race car has followed the proposed V-cycle approach, allowing to integrate the different modules present in the vehicle, by constantly exchanging data from and to the verification and validation phases. The tools and softwares utilized in each section of the V-model are reported and analyzed for each chapter of this Thesis project.

The entire V-model for SC21 starts with Target Setting phase, adopting a target-driven approach. Every considered solution has been analyzed using a self-developed point mass, quasi-steady-state model lap time simulator and a real-time vehicle simulation software. A sensitivity analysis has been carried out to find out different parameters sensitivity on lap time, energy consumption, and relevance in terms of points in the dynamic events. Thanks to this method, key components of the car have been identified and the Team's efforts have been focused on these. The main idea that led the Team is that an embedded system of well-designed components is more effective than a set of outstanding parts not properly integrated with each other. So, serious attention has been taken to ensure that each subsystem is organic with the whole vehicle. Different subsystems of the car were redesigned to pursue the initial targets.

2.2 Previous years events

Looking into the past is fundamental whenever a new project is being brought to life. It allows to understand where your weaknesses and strengths are, and how you can drive you new project in order to take the most out of it. As already mentioned in section 1.3, in 2021 the previous designed race car was SC20, which did not see the production due to Covid19 pandemic. SC20 car was a project developed around SC19 project, resulting in an evolution of 2019 car, rather than a revolution. Several aspects of SC19 had been collected to develop the SC20, especially for what regards the hardware part, mechanical and composites side, leaving more space for evolution in software side and reliability improvements. Furthermore, improvements in development of new tools for design phase aimed at better understanding and modeling various phenomena had been carried out during 2019/20 season.

Event	**Formula ATA**	**Formula Student Czech Republic**	**Formula Student Spain**
Endurance result	1°/26	DNF	DNF
Overall Position	1°/26	6°/15	14°/39
Competitiveness index	0.85	0.85	0.95

Table 2.1: SC19 events results

With that being said, when looking into previous years events, it is referred to competitions held in 2019 with SC19 race car. In 2019 Squadra Corse participated in three competitions, namely Formula ATA, Formula Student Czech Republic and Formula Student Spain. Formula ATA event was an historic moment for the Team since it ended with a victory, but this came with rainy conditions during autocross and endurance events. Formula Student Czech Republic event did not see a very good final position due to DNF in endurance event at the first lap due to incorrect regenerative strategy. Formula Student Spain event was marked by another DNF in endurance event after the driver change due to APPS failure. Up to that moment the Team was running a good endurance and would have ended surely higher in final rankings. Due to the availability of solid laps before DNF in FSS event and due to the nature of the previous cited events, FSS (despite the DNF) is the event that is taken into consideration for a benchmark analysis with other teams.

2.3 Competitors Benchmark

During the Target Setting phase and in Design phase as well, a benchmarking activity is done in order to understand where our vehicle performance is located compared to the world's best competitors, aiming at reducing the weaknesses and improving the overall package by means of better solutions. In the target setting phase a benchmarking activity is done looking both at static and dynamic events performance, in order to maximize the overall result in terms of points achievable at competition. For FSS event, a comparative between three teams is presented:

- Squadra Corse PoliTo
- TUFast Racing Team
- GreenTeam Uni Stuttgart e.V.

TUFast Racing Team and GreenTeam Uni Stuttgart e.V. came respectively first and third at the event, whilst TUFast was first in overall EV class world rankings at that time. FSS event showed an overall good performance in static events compared to top teams, but lacked of performance in dynamic events, especially in disciplines where overall performance of the vehicle are put under stress, such as autocross, endurance and skidpad. Those events are the ones that show mostly the car performance in lateral dynamics, as well as in braking conditions. These two are crucial for maximizing laptimes. An estimation based on pace held till 14th endurance lap and energy consumed till that time, allowed us to estimate final endurance time, as well as an energy consumed. From these values it is possible to estimate the score that the Team would have achieved if the car had finished Endurance event. It shows that 6th place would have been achieved, confirming the crucial importance of finishing endurance in perspective of scoring high amount of points at competition.

Place	Car Num	Team	Business Plan Score	Cost Score	Design Score	Skid Pad Score	Acceleration Score	Autocross Score	Endurance Score	Efficiency Score	Total Score
1	31	TU München	59,0	62,0	140,0	75,0	64,1	100,0	325,0	94,2	919,4
2	77	Duale Hochschule Baden- Württemberg Stuttgart	60,0	87,0	130,0	64,8	74,2	84,9	277,8	89,4	868,1
3	26	Universität Stuttgart	62,5	87,0	150,0	57,5	75,0	73,0	231,3	91,5	827,7
4	59	TU Dresden	73,5	59,0	110,0	56,7	67,7	68,1	224,3	98,6	758,0
5	124	Tallinn University of Technology / Tallinn UAS	69,0	42,0	101,0	53,6	56,8	62,0	230,2	90,8	705,4
6	96	UAS Zwickau	39,0	83,0	99,0	70,4	58,9	59,1	162,2	97,0	668,6
7	119	Karlsruhe Insititute of Technology	56,5	80,0	140,0	65,4	66,3	19,9	74,2	95,0	597,5
8	54	UPC Barcelona - ETSEIB	73,0	80,0	99,0	50,6	3,5	24,1	114,3	96,6	541,0
9	14	TU BUDAPEST	44,5	46,0	85,0	44,9	51,4	37,4	122,6	89,9	521,7
10	48	University of the Basque Country (UPV/EHU)	61,0	84,0	97,0	28,4	26,4	4,5	104,8	96,0	502,1
11	64	TU Kaiserslautern	54,5	98,0	55,0	49,7	25,0	17,9	88,8	100,0	488,9
12	33	ETH Zürich	58,0	100,0	120,0	56,0	57,3	43,6			435,0
13	111	ESEIAAT - UPC	72,0	96,0	95,0	45,8	50,9	39,5	25,0		424,2
14	146	Politecnico di Torino	68,9	91,0	86,0	42,3	59,7	51,5			399,4

Figure 2.3: FSS19 overall results

Event	SC	Greenteam Stuttgart	TuFast Munich
Skidpad	42.3	57.5	75
Acceleration	52.7	75	64.1
Autocross	51.5	73	100
Endurance	**DNF**	231.3	325
Efficiency	**DNF**	91.5	94.2
Business plan	68.9	62.5	59
Cost	91	87	62
Design	86	150	140
TOTAL	**392.4**	**827.8**	**919.3**
Δ	-	**+435.4**	**+526.9**

Table 2.2: FSS19 overall results table

Event	SC	GreenTeam Stuttgart	TuFast Munich
Skidpad	42.3	57.5	75
Acceleration	52.7	75	64.1
Autocross	51.5	73	100
Endurance	170	231.3	325
Efficiency	100	91.5	94.2
Business plan	68.9	62.5	59
Cost	91	87	62
Design	86	150	140
TOTAL	**662.4**	**827.8**	**919.3**
Δ	-	**+165.4**	**+256.9**

Table 2.3: FSS19 overall results table estimation

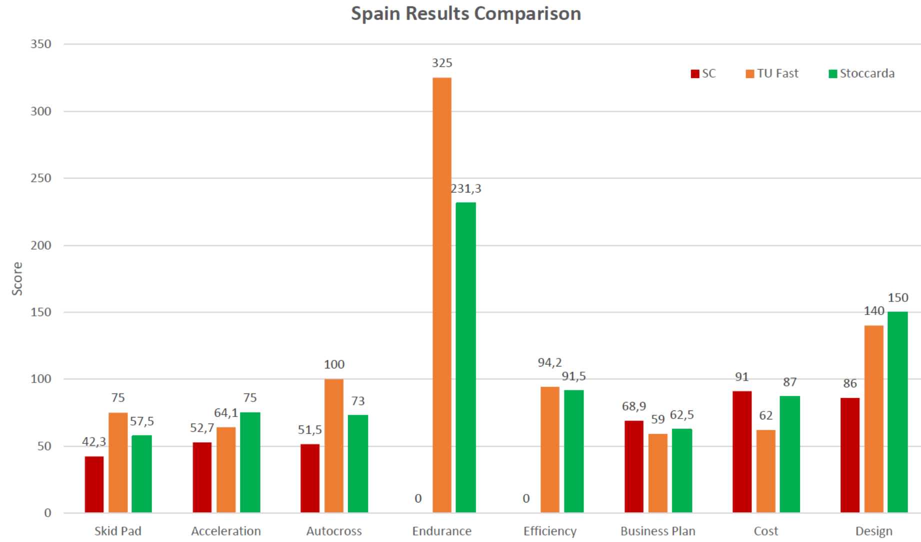


Figure 2.4: FSS19 overall results histogram

2.3.1 Static events

Business Plan and Cost events went very good compared to top teams. In fact, in both events the Team scored higher points than competitors. Team proved to present well documented and well studied reports, superior to top teams.

Design event on the other hand did not went that good with respect to top teams, and led to major difference in overall static results with top teams. Whilst business plan score is very much susceptible on the way the plan is presented as well as the judges that make up the jury in that specific event, cost and design event are less prone to have big discrepancy along different juries in different events, due to their more technical related nature. For this reason, design event and design of the new car had to be taken seriously into consideration if wanted to reduce the gap with top teams. In particular, low points in design event were attributed due to the choice of some technical solutions not sufficiently motivated and supported by technical data, able to confirm and validate the solution proposed, as well as due to the choice of some technical solutions that, from an engineering perspective, could have been better proposed or modified, in order to be better designed.

2.3.2 Dynamic events

Dynamic events showed bigger gap compared to top teams. Both skidpad and autocross showed big performance gaps from the leaders, whilst acceleration did not went that bad, ending up mid-higher end of rankings. This suggested at a first glance that the SC19 car had good performance in longitudinal dynamics (positive accelerations) and poor performance in cornering as well as in braking conditions.

Looking at the FSS19 Endurance pace comparison, there is a clear performance

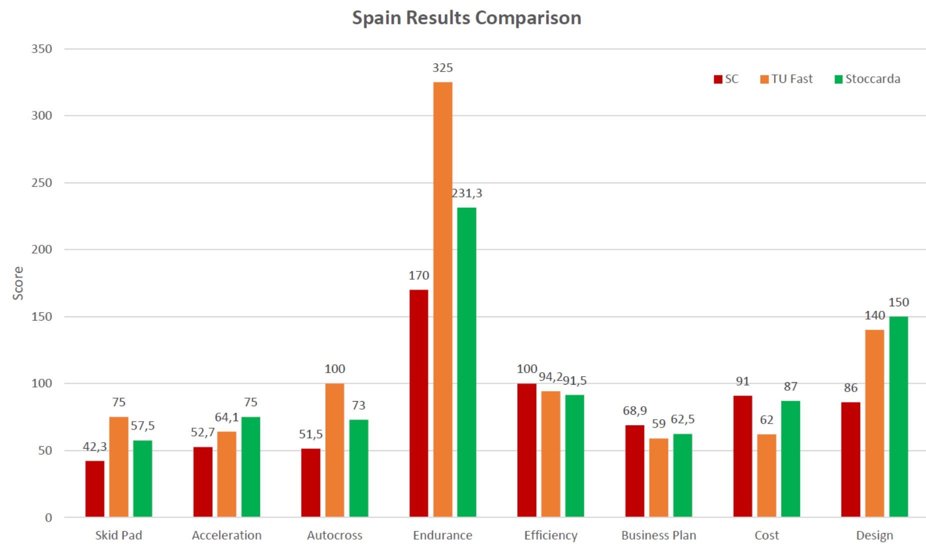


Figure 2.5: FSS19 overall results histogram estimation

gap between SC and the top teams, with an average gap of $-8.6s/lap$ with TUFast and $-4.9s/lap$ with GreenTeam. This delay can be analyzed in the following estimation:

- Vehicle concept and design ($-3.9s/lap$)
- Drivers training ($-2.2s/lap$)
- Vehicle tuning in pre-seasonal tests compared to FSS19 tuning condition ($-2.5s/lap$)

This gap can be partially recovered by drivers training and vehicle tuning but from vehicle concept and design contribution only $-2.3s/lap$ can be realistically gained from SC19 and SC21 looking at lap time simulations in the following chapters.

We decided to compare different KPIs that severely determine the dynamic performance of a FSAE race car. These KPIs are reported as follows:

- Vehicle mass
- Weight distribution
- Aerodynamic coefficients
- Energy stored in HV accumulator

Mass of the other teams are available to every team, they are published for each event. A first comparison amongst different competitors allows us to understand two key factors: winning teams have significantly lighter cars, but if we consider

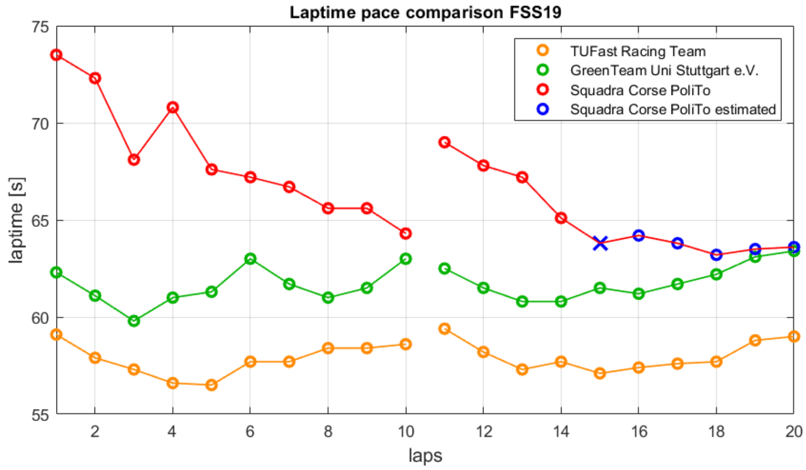


Figure 2.6: Laptime pace comparison FSS19

2nd to 5th classified race cars, the average car mass is 175 kg, 13 kg far from SC19 weight in FSS event. In order to understand where this big difference comes from, a comparison analysis on detailed subsytem of the car has been done. This comparison has been done between SC and TUFast teams, with some values clearly available from competitors and other estimated on the basis of their technical choices. Analysis is reported in Table 2.4. Values with the (*) in TUFast column are estimated.

Main differences are from the choice of tires and powertrain package. SC adopts 185/40 R13 Pirelli slick tires on 13" OZ Racing magnesium aluminum alloy rims. TUFast adopts 16x7,5 - 10 Hoosier slick tires on 10" custom made carbon fiber rims. Both tires weigh the same amount, unexpectedly, but the main difference is in rims weight. Any weight reduction in the unsprung mass is much more beneficial compared to the same reduction of weight but in sprung mass. This is due to the fact that tires are four so any reduction of weight in a single quarter car results in four times weight saved for the overall car weight, as well as it reduces the equivalent mass significantly, as reported in Eq. 2.1. Rims only lead to a reduction of 5.8kg compared to us. The choice of 10" tires leads to completely different wheel packaging, transmission ratio, allowing to have smaller components of the unsprung mass assembly yet, lower forces and torques exchanged between these. Lower forces, more compact components lead to less compliances in the suspension members. By changing tire and brake discs diameters, there is an ability to obtain a higher braking torque. At the same time, CoG height is reduced (in our case estimated of 3% reduction with driver and 5% without driver). Pushrod inclination in yz plane is increased leading to better suspension kinematics. Aerodynamics is influenced too, with smaller wheels, even though their angular speeds are higher, lead to much more room for aerodynamic package, that can be extended compared to the 13" solution. Higher surface area where to locate aerodynamic devices allows to have higher downforce from the aero package, hence more performance from the car.

$$m_e = m + \frac{\sum_{i=1}^{4} J_{ti}}{\tau_t^2 R_e^2} + \frac{\sum_{i=1}^{4} J_{wi}}{R_e^2} \tag{2.1}$$

For what regards the powertrain package, SC uses AMK motor and inverters, whereas TUFast uses self-developed motor and inverters. Using self-developed motors and inverters has obviously the advantage of design freedom, leading to the possibility of customizing power and torque profiles according to requests, allowing to have higher power and torque output compared to most commercial-available solutions, but it is a challenging design choice since it requires deep understanding of electro-mechanical theory, as well as deep knowledge of thermal management. Proper design of heat dissipation must be carefully addressed, considering as well reliability aspects of the motors and inverters whilst cutting down unnecessary weight compared to stock solutions. Packaging aspects are also taken into consideration, especially for the inverters, since they are located inside the chassis, if custom-made, they could be shaped as needed (with some limitations of course). Motors and inverters are one of the primary source of weight gap between us and TUFast racing team.

Further preliminary studies into the 10" tires compound from Hoosier showed that their performance is competitive with the currently used 13" Pirelli ones. The adoption of 10" tires has not been contemplated this season for technical, time and sponsorship reasons aswell, but still remains the go-to switch to be made in future seasons.

From the mechanical side, the chassis in one of the area where some improvement has to be done, among with cooling and unsprung mass components such as the uprights. Different fasteners choice from TUFast such as titanium alloy screws leads to some difference in weight as well. Aeropack instead, is very much lighter in our case, but mainly due to lower downforce package compared to TUFast, as it is reported in Figure 2.9.

From the electrical side, apart from what already mentioned for motors and inverters, gap exists in the HV and LV wiring harnesses, with probably better optimized routings and wiser connectors used. Another aspect noted in the previous events is that TUFast user far less braids in their harnesses, leading to lighter yet less reliable and organized system. For the HV accumulator there is not that much difference if we are looking in pure weight gap, but there actually is for composites side, since SC adopted in 2019 season Li-ion cells, whereas TUFast adopted Li-po cells. Being that TuFast has higher HV accumulator capacity (1.0 kWh more) compared with us, and that usually Li-ion cells are lighter than Li-po cells, there is certainly a gap for what concerns the packaging of the HV accumulator, as well as with its HV wiring harness.

In the end the gap of unsprung mass is equal to 14 kg, whereas the gap of sprung mass is equal to 8 kg.

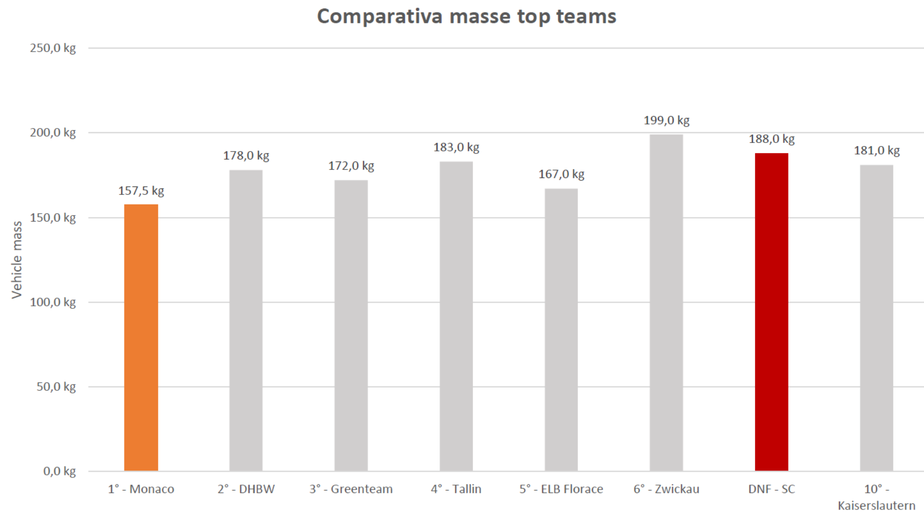
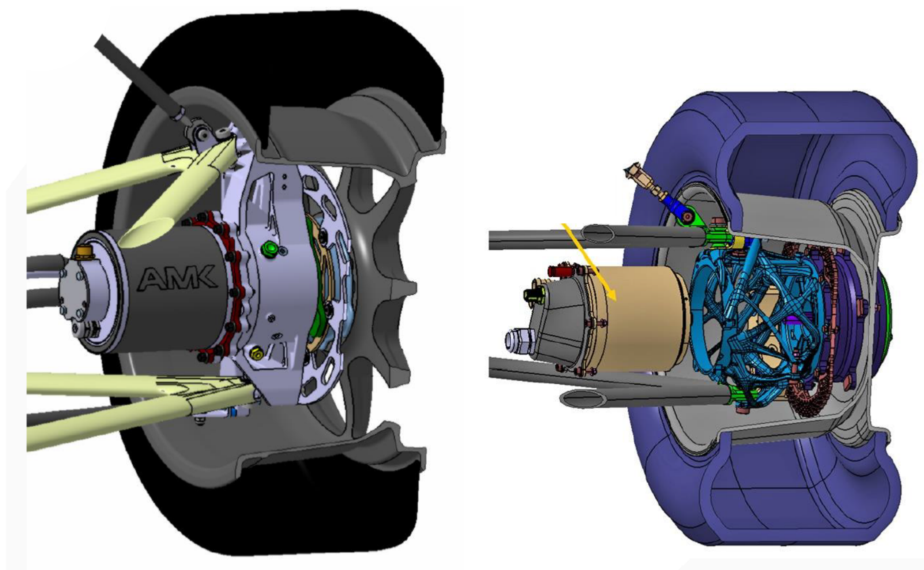


Figure 2.7: Vehicle mass benchmark FSS19

Weight repartition is another aspect that is influencing car's performance, as we will see in Section 2.4.1. There is a clear trend of top teams in shifting the weight repartition as close as possible to the middle of the two axles, with driver onboard. This is due to the fact that vehicles we are analyzing are EV, 4-wheel drive. CoG slightly shifted to the rear end improves responsiveness whilst driving, having slight oversteering behaviour, that is likeable in a racecar rather than understeer.

Aerodynamic strategy plays a big role in defining the overall vehicle performance. Aerodynamic package design choices not only affect the pure aerodynamic performance itself measurable by means of coefficients such as Cx and Cz, but influence other factors such as vehicle sprung mass, energy consumption and HV accumulator design choices, rolling resistance, suspension and brakes design, manufacturability, production costs, car's handling, vehicle dynamics controls and other. It is evident that aerodynamic strategy is strictly interconnected with several other aspects of the car, and it is crucial to evaluate the impact it has on the overall car.

A benchmark on aerodynamic strategy is done from the data available from other teams. Worth to be mentioned that some of the data presented in Figure 2.9 may not be correct 100% since other teams may have declared some false data and/or their simulations may not be validated properly. They still provide valuable information about the direction other teams are following in their design process. Amongst all the teams, it can be observed that high downforce package strategy is being pursued. In fact, all top-teams have CzA $>$ 4.0. In some extreme cases (such as TUFast), the CzA reaches values over 7.0. For what concerns the production of the aeropack, a simple KPI that is CzA/mass can be considered. Best teams are able to reach values of 0.33-0.34, whereas SC stays at 0.21. Worth to be mentioned that this value is not linear as CzA varies, since the same amount of downforce could



(a) SC20 **(b)** TUFast

Figure 2.8: Unsprung mass view comparison

Subassembly	TUFast [kg]	SC19 [kg]	Δ [kg]	Cumulative [kg]
Aeropack	23.0	13.2	-9.8	-9.8
Motors	10.0	14.8	+4.8	-5.0
Inverters	2.7	5.4	+2.7	-2.3
Rims	4.0	9.8	+5.8	+3.5
Tires	14.5	14.5	0.0	+3.5
Monocoque	17.0 *	19.9	+2.9	+6.4
Uprights	2.2 *	3.2	+1.0	+7.4
HV accumulator	37.3 *	37.8	+0.5	+7.9
Antiroll bars	2.4 *	3.2	+0.8	+8.7
Transmissions	4.0 *	6.0	+2.0	+10.7
Pedalbox	1.5 *	2.3	+0.8	+11.5
Electrical	7.0 *	8.9	+1.9	+13.4
Cooling	7.4 *	9.4	+2.0	+15.4
Fasteners	2.9 *	3.9	+1.0	+16.4
Brakes	3.6 *	4.6	+1.0	+17.4
Residual	18.0	31.1	+13.1	+30.5

Table 2.4: Detailed vehicle mass benchmark with TUFast FSS19. (*) Estimated mass.

Team	Front mass repartition
TUFast Munich	50%
KIT Karlsruhe	50%
NTNU Trondheim	49%
Greenteam Stuttgart	49%
ELB Florace Dresden	48%
AMZ Zurich	47%
SC	45%

Table 2.5: Front mass repartition with driver onboard benchmark 2019 season

be reached by different efficiencies of the aeropack, and for low downforce packs there is still the presence of wings supports that usually generate a null amount of downforce. Significant improvement must be done in order to save some weight.

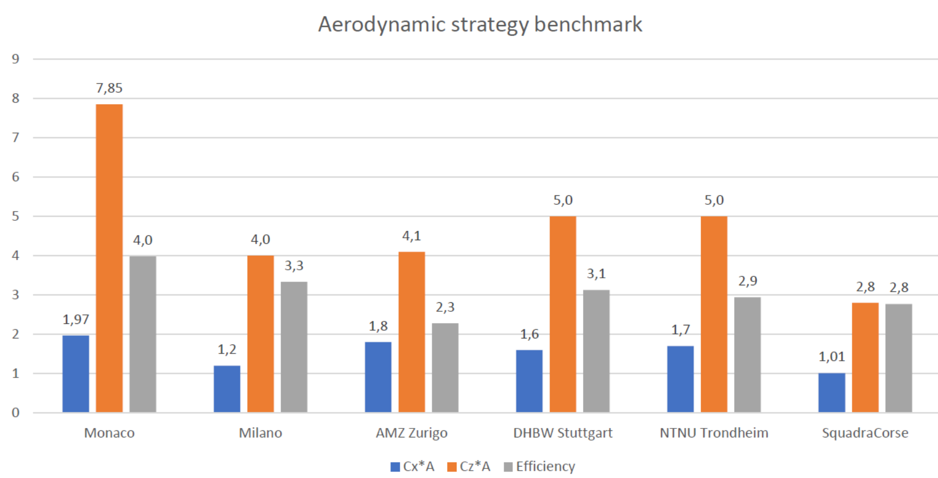


Figure 2.9: Aero benchmark 2019 season

Energy strategy is another crucial aspect of target setting, if not the most important factor when defining targets for a new FSAE vehicle. This affects mainly the performance of Endurance event, that usually is the one that mostly affects final event's ranking. Strictly related to HV accumulator capacity is the cell choice, but that will be covered in Section 2.5. Similar for what concerned aerodynamic strategy, also here the goal is to have as high as possible energy content in the accumulator in order to complete the Endurance event with high laptime pace, but at the same time cutting down weight as much as possible. For SC19 race car the trend was to have low downforce package and energy onboard towards the lower-end of the comparison. all top teams resulted in higher energy content, but with limited mass of the vehicle, resulting into higher accumulator capacity/vehicle mass factor, that is another KPI. There is a clear increasing trend that links this

Team	Aeropack weight [kg]	CzA/mass
TUFast Munich	23.0	0.34
Greenteam Stuttgart	15.3	0.33
AMZ Zurich	12.5	0.33
NTNU Trondheim	15.5	0.32
Dynamis PRC Milano	16.0	0.25
SC20	13.2	0.21

Table 2.6: Aero weight comparison 2019 season

Team	Mass [kg]	Capacity [kWh]	Capacity/mass [kWh/kg]
1st - TUFast	157.5	7.0	0.044
2nd - DHBW	178.0	8.2	0.046
3rd - Greenteam	172.0	7.6	0.044
4th - Tallinn	183.0	7.7	0.042
5th - ELB Florace	167.0	6.8	0.041
6th - Zwickau	199.0	6.4	0.032
DNF - SC	188.0	6.0	0.032
10th - Kaiserslautern	181.0	5.6	0.031

Table 2.7: Energy and mass benchmark 2019 season

KPI with final ranking: the higher this KPI is, the higher final ranking is likeably to be achieved. SC19 resulted in 0.032 kWh/kg whereas DHBW Stuttgart had the highest value of 0.046 kWh/kg.

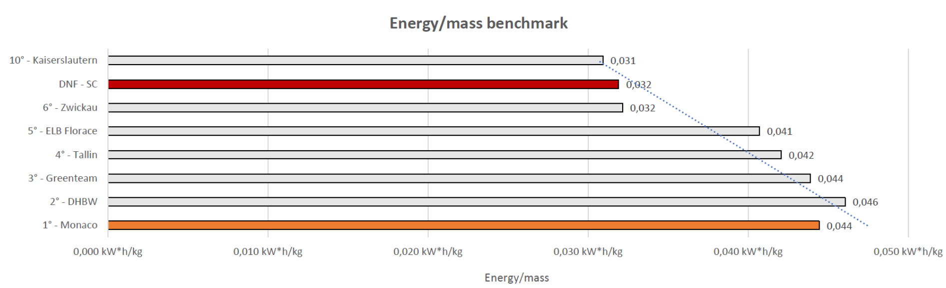


Figure 2.10: Energy over mass benchmark 2019 season

2.4 Lap time simulation

After having done all the considerations above, it is time to switch to simulative environment. The fast and continuous evolution of digital technology has impacted also the automotive industry. Nowadays modern cars and race cars as well, are featured with many ECUs and sensors, that need to be properly integrated and work together. The time for development and design of a new car has been seriously affected by the complex scenario in which automotive industry is located, leading to shorter and shorter time to market.

In this context, laptime simulative environment has been proven effective in significantly reducing the time to market and shorten the development phase of a new vehicle, allowing to make choices without the need of using conventional testing methods such as the implementation of prototypes like mule cars. This applies in race car scenario too, where the objectives of new vehicle development are different compared to road cars, but the degree of complexity of simulations remains an important topic to deal with, considering also that usually a shorter development time is needed compared to road cars.

Nowadays, in a race car, all the sensors and ECUs communicate through digitalized signals by means of controlled area networks (CAN). These signals are collected and retrieved with a data logger, in order to analyze mainly the vehicle dynamics behaviour. Vehicle signals (real data) can be compared with simulation signals (simulation environment data) in order to properly validate laptime simulators.

Lap time simulators are extensively employed during the development phase in order to cut down development time and also to allow the designers to take target setting decisions when the new prototype has not been built yet. Lap time simulators can be classified according to their solution type, especially their degree of complexity. We can identify three main solution types:

- **Steady-state simulation**: in these simulations the vehicle speed profile is computed by means of a distance-based solver working in steady-state. The trajectory the vehicle has to follow is discretized in straights and corners, where the respective longitudinal and lateral accelerations are evaluated but cannot interact with each other in the same section, leading to quite inaccurate results for racing applications. This kind of simulation is very simple in terms of computational complexity and therefore could be implemented for passenger cars in simpler driving scenarios, but in reality nowadays they have been replaced by more complex simulations.

- **Quasi-steady-state simulation**: these simulations are an evolution of the steady-state ones. The combined longitudinal and lateral accelerations are taken into account through a GGV diagram, allowing to have more realistic results, whilst including more complex effects such as the aerodynamics. The maximum cornering speed and combined cornering-braking-acceleration speed profile are obtained. These simulations are in between steady-state and transient simulations, and permits the designers to develop their own code, with relative degree of complexity, allowing them to modify the code itself whenever desired, without the constraint of a commercial available software.

- **Transient simulation**: they represent the most realistic and complex types of laptime simulations nowadays available. Differently from the previous ones, they take into account for transient phenomena happening in vehicle dynamics. They usually include at least 14 degrees of freedom vehicle models (6 DOF for the vehicle body that are longitudinal, lateral, vertical motion together with yaw, pitch and roll, plus 2 DOF for each quarter car such as vertical motion of each quarter car suspension and rotation of the wheels). In this way, each DOF will affect the vehicle dynamics at each time instant, resulting in complex differential equations to be solved at each iteration. For this reason these simulation are far more computationally expensive than the previously two described simulations. Further complexity is added by means of dedicated models of dampers, springs, anti-roll bars, tires, aeromaps in order to finely represent a digital twin of the real vehicle.

Transient simulators are further subdivided into different loop categories. We can identify three main loop types:

- **Software-in-the-loop**: the different generated C codes of the ECUs are tested in the simulation. Software integration between different control systems or software modules present in the vehicle is crucial, because it has to be tested and checked whether all the functionalities are properly working or not.
- **Hardware-in-the-loop**: this simulation is performed directly on the Hardware, meaning that the physical control unit is installed in series with the simulator, allowing to stimulate the controller with simulated vehicle signals. This allows to check the functionalities of both hardware and software without the need of having a real vehicle.
- **Driver-in-the-loop**: this simulation substitutes the previously simulated driver with a real driver in the loop. The hardware of the simulator is enriched by a real cockpit and a screen, with, in some cases, complex moving platform that replicate real driving feelings by means of motion cueing algorithms. This allows to properly simulate the vehicle with real driver inputs, substituting driver models, and at the same time to train drivers and/or to receive feedback from them whilst driving in the simulator. These kind of simulators are usually extremely expensive and are extensively adopted in racing applications, but are also employed for road vehicles, especially to evaluate driving comfort, noise, harshness and driver assistance systems.

2.4.1 Single point mass LTS

The Lap Time Simulator (LTS) developed in SC Team is a single-point mass LTS that belongs to the category of Quasi-steady-state simulators and is mainly used during Target Setting phase. MATLAB®-Simulink is considered as virtual modelling environment, in order to be easily modified for future developments. The code is developed for the endurance event in order to compute the lap as a second flying lap starting from a first one that serves as a reference.

The LTS goes through four main steps to perform the simulation:

- GGV diagram definition

- Evaluation of maximum cornering speed: track map is subdivided into several segments, for each segment, from the curvature radius, pure lateral acceleration, speed and vertical forces are calculated by an iterative process, if lateral calculated acceleration for that segment complies with maximum reachable by the vehicle, the iteration is stopped, and next segment is analyzed.

- Evaluation of combined cornering/braking speed profile: by another iterative process taking into account GGV diagram, the longitudinal deceleration in braking is calculated. Velocity profile now is combined between cornering and braking.

- Evaluation of combined cornering/braking/acceleration speed profile: the speed profile is modified taking into account acceleration constraints, such as combined grip of the tires, electric powertrain phenomena such as electric motors maximum torque available, power allowed, motors efficiency map, electric motors torque repartition, HV accumulator voltage and internal resistance, state of charge (SOC). Other data are calculated as well, such as total laptime, total distance covered.

The LTS allows to perform simulations in order to calculate the following targets (direct and indirect):

- Main vehicle parameters sensitivity

- Laptime and energy consumed

- FSAE event points sensitivity for different vehicle configurations

- Targets for the new vehicle SC21

Starting from the vehicle data of the SC19 car in FSS event, we decided to perform a sensitivity analysis on the following parameters:

- Vehicle mass

- Weight distribution

- Max limited power in endurance event

- Aerodynamic coefficients

- Energy stored in HV accumulator

Vehicle	**SC19**
Vehicle mass	188 kg
Front mass repartition (with 68kg driver)	45%
Wheelbase	1525 mm
Track	1200 mm
CoG height (from ground)	275 mm
Aerodynamic CzA	2.36 *
Aerodynamic CxA	1.08 *
Total power	80 kW (140 kW without restrictions)
HV accumulator configuration	140s4p Li-Ion cells active air cooled
Nominal HV accumulator capacity	6.05 kWh
Maximum HV accumulator voltage	588 V
Maximum EM Torque (peak)	21 Nm x 5 s
Maximum EM speed	20000 rpm
Maximum vehicle speed	120 km/h
0-100 km/h acceleration	2.5 s
Tires	185/40 R13 Pirelli slick tires on 13” OZ Racing Mg/Al alloy rims

Table 2.8: SC19 main technical features, (*) data validated in wind tunnel

The sensitivity analysis is performed starting from the SC19 baseline data according to the following sweeps:

- Front mass repartition: 40% - 60%
- CzA: 1.0 - 5.0 (with constant aerodynamic efficiency 2.2)
- Vehicle mass: 175 kg - 190 kg
- CoG height (from ground): 245 mm - 280 mm
- Max endurance power: 50 kW - 80 kW

From Figure 2.11 it is possible to understand the impact of each single parameter onto laptime and energy consumed per lap, as a first approximation analysis. Reducing the mass has a positive impact both on laptime and energy consumed per lap. Reducing CoG height from ground has a positive impact in terms of laptime but detrimental for the energy consumed per lap. This could be deceiving but the reason behind is that the vehicle is capable of achieving higher cornering accelerations, thus driving faster and consuming more energy compared to higher CoG, having kept unchanged all the other parameters. Increasing the maximum power available improves laptime but worsens the energy consumption due to the higher power demanded. Front mass repartition shows a local minimum for the laptime at around 50% because the vehicle is 4WD. Aerodynamic downforce increase shows a decreasing trend in the laptime. This is due to the fact that downforce allows to increase tire load, thus increasing forces at contact patch that the tires can guarantee to keep vehicle under control, without a significant increase in mass and relative moments of inertia.

Starting from Baseline configuration, several strategies are capable of achieving faster laptimes, but some are more viable than others. We do have to take into account that not all these factors can be changed in a indefinite range, and in particular, their parameter variation in percentage is different factor by factor.

Weight repartition for example, is one viable option in the sense that rearranging the packaging during a completely new project is possible, as well as playing with suspension inner hardpoints in the x direction in order to shift the weight repartition to the desired way. Their percentage variation though is limited to few percentage points. Mass as well is one variable that is always perceived as a target to be minimized whenever designing new vehicle and has high impact on laptime, but it is susceptible to other targets definition, such as increase in aerodynamic package size, or choice of energy available in the HV accumulator. Max power available is impacting as well the performance of the vehicle but it is strictly correlated again with the energy available in the HV accumulator. CoG height is wanted to be minimized and has high impact on laptime but is strictly related to packaging and to main design choice configuration, such as 10" vs 13" wheels. Only big design changes allow to have significant CoG height changes.

Apart from these facts, there is an important consideration to be said: not every factor can be changed easily far from the baseline percentage-wise. For example, a reduction of 5% in mass (-10 kg reduction) results in -0.3 s laptime gained, whereas an increase of 5% in CzA (+0.12 increase) results in -0.15 s laptime gained. By looking at this only, one could think that reducing the mass is much more effective in reducing laptime but we are missing the overall picture, in fact reducing the mass by 10kg requires an extreme effort during the design phase and could also affect reliability of the vehicle, especially if that weight is cut through critical mechanical components too. Increasing the CzA of +0.12 instead looks a much more viable option. Furthermore if we are looking at the derivative of various curves in Figure 2.11, we can understand that an increase in aerodynamic downforce is much more effective if we are starting from a baseline of low downforce, and then the curve tends to saturate in laptime for higher values. Instead, other solutions such as increase in maximum power available are yes a solution into reduction of laptime but come at lower derivative and therefore less effect moving towards high values of the relative sweep.

Starting from these considerations, the increase of CzA of several percentage points comes as the most reasonable solution to achieve faster laptimes, and it shows to be consistent with the benchmark of top-teams. How much aerodynamic downforce and drag to be selected as a target comes from different constraints:

- Energy available in the HV accumulator and relative increase of mass
- Increase in mass and CoG of the aerodynamic package
- Time available to develop a new aerodynamic package

- Realistic aerodynamic efficiency achievable by the new aerodynamic package
- Manufacturing time, complexity and costs

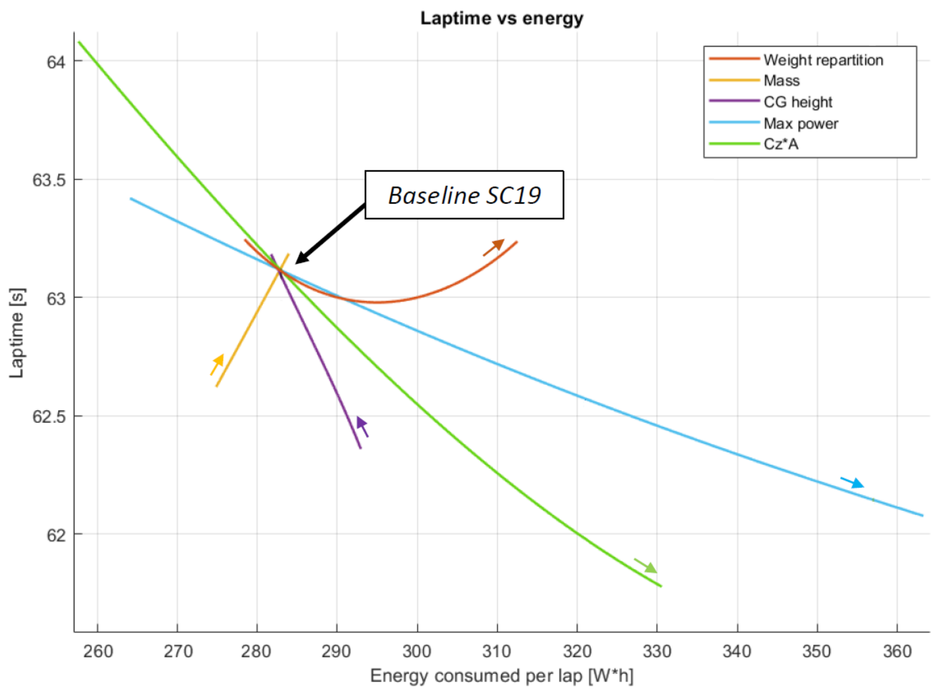


Figure 2.11: LTS Sensitivity laptime vs energy

2.4.2 VI-CarRealTime

VI-CarRealTime is a solution developed by VI-Grade company that represents a "real-time vehicle simulation environment utilizing a single simplified vehicle model"[6]. It falls amongst the category of transient simulators and it is used in co-simulation with Matlab-Simulink environment in particular for the Control system part of the vehicle and to better analyze the great amount of vehicle states signals output from VI-CarRealTime. In our scenario it is used to reproduce a high-fidelity digital twin of the real car, by modeling the most important subsystems present in it. The developed digital twin has the following peculiarities:

- Real vehicle wheelbase, track widths, CoG and other dimensions
- Real sprung, unsprung and driver masses with relative mass distribution values
- Full vehicle estimated inertias (data from CAD)

- Suspension and steering elasto-kinematic (models from Adams Car environment)
- Real mechanical braking system data
- Aerodynamic maps (data from the validated CFD model)
- Powertrain model: EM motors traction, coasting and braking torque vs speed maps and their positioning, powertrain efficiency maps, transmission ratio and transmission efficiency
- HV accumulator model: cell internal resistance, series, parallels, max power
- Tire Pacejka Magic Formula 6.1 model (data from the Pirelli TIR file)

Three main simulation types are available in VI-CarRealTime environment: the standardized maneuvers, the file driven events and the max performance events. The standardized maneuvers reproduce globally known standardized automotive maneuvers in open or closed loop, they are useful as a benchmark. The file driven events are customizable events where the user can define different variables of the simulation such as path, sequence of actions and speed profile. The max performance events are characterized by a reference path subdivided in sectors and by a maximum distance from the reference path. The driver model has to follow such path and reduce the maximum deviation from the reference path.

VI-CarRealTime is a tool that SC has been used both during the Target Setting phase, as well as during Design and Validation phases.

2.5 Final vehicle targets definition

The definition of final vehicle targets focuses on the event which has the most impact in terms of points: the Endurance. All the main parameters affecting vehicle performance seen in 2.4.1 are important, but the most crucial one is the energy stored in HV accumulator. This because it shows a cascading effect upon all the other parameters. For this reason, the selection of the HV accumulator is extremely important for the whole vehicle. The choice of HV accumulator capacity is actually done in parallel with the cells technology and configuration in series and parallel. This because the cells layout determines the capacity, the voltage, the power and other variables.

Looking at Table 2.7 we understand that if we want to increase the KPI accumulator capacity/vehicle mass we face two possible roads from SC19 baseline: one is to reduce the mass keeping the capacity constant, the second one is to increase the capacity with consequent mass increase. The first case leads to a small increase of the KPI, whereas the second one leads to a significant increase of the aforementioned 2.13. We decided to follow the second one because having higher capacity is more beneficial in terms of endurance pace and regenerated energy compared to smaller accumulator with less vehicle mass. In order to obtain a KPI = 0.040 kWh/kg (not the best compared to top teams but considered reachable looking at the Teams' knowledge at the time the SC21 target setting was underway),

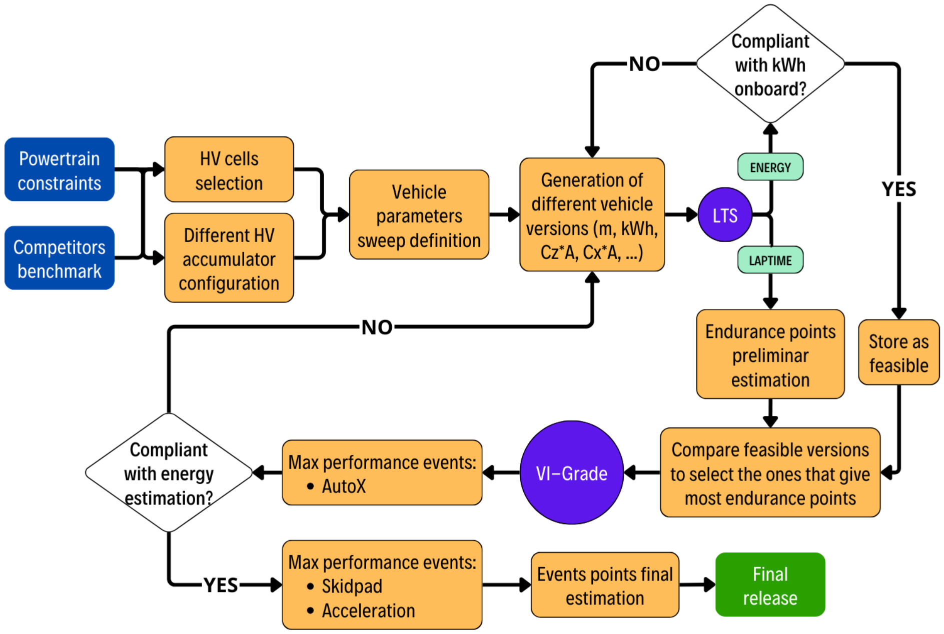


Figure 2.12: Target setting workflow

the increase of capacity is of +1.8 kWh, that brings an increase of vehicle mass of estimated +7 kg, mainly due to higher cells mass.

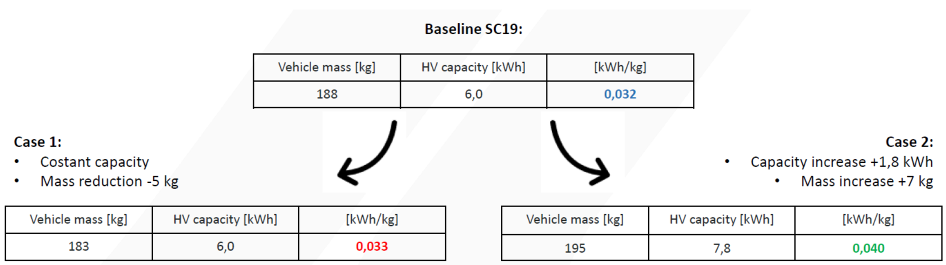


Figure 2.13: Energy over mass KPI strategies

The choice of the HV accumulator capacity has to be done considering also the regenerated energy during endurance. Taking into account the accumulator energy, the regenerated energy over the total one, the powertrain mean efficiency, the energy stored in the accumulator that cannot be used due to cells undervoltage and a safety factor, it is possible to obtain the mean energy consumed by the HV accumulator per lap in FSS endurance simulation. Significantly higher energy consumed per lap is present in SC21 case compared to SC19 2.9. This higher energy content available will be devoted both to higher energy consumption (higher aerodynamic drag and vehicle mass) and to higher average power output during the event.

The accumulator capacity is 7.7 kWh - being 9.7 kWh the calculated energy necessary to complete the Endurance Event at the desired pace, 20 % of the total energy consumption is provided by regenerative braking. The mean powertrain efficiency considers AMK inverters and motors efficiency maps, the HV accumulator mean efficiency, the mechanical transmission efficiency. To take into account the energy that can be effectively utilized from the HV accumulator that is the real capacity of the accumulator, we look at discharge curves at different C-rates of Li-Po cells that will be mounted on the SC21 and together with the average current supplied to the motors during the endurance event, we are able to estimate the discharge efficiency. In our case about 7.3 kWh are considered out of 7.74 kWh stored in the accumulator at 3C discharge without regenerative.

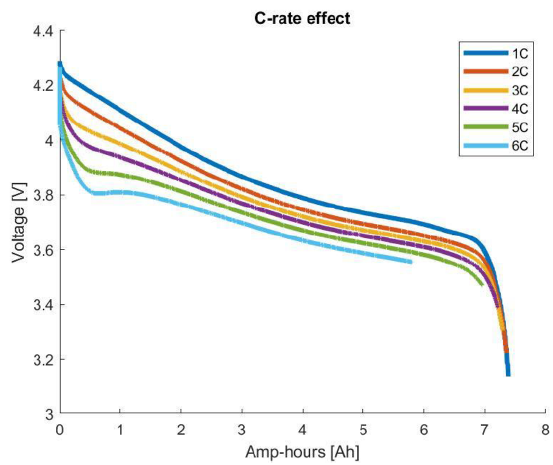


Figure 2.14: C-rate effect on discharge curves of SLPBB042126HV Li-Po cells

Vehicle	**SC19**	**SC21**
Regenerated energy percentage	17%	20%
HV accumulator capacity [kWh]	6.04	7.74
Total energy [kWh]	7.2	9.7
Regenerated energy [kWh]	1.2	1.9
Powertrain mean efficiency	0.79	0.80
Energy consumed by HV accu. [Wh/lap]	286	392

Table 2.9: Energy per lap FSS target

Considering the selected energy content, aerodynamic targets can be set. A sensitivity analysis in carried out with varying CzA and aerodynamic efficiencies, in order to see the impact over laptime and energy consumed. Results are available in Figure 2.16. Clear indication is to move towards higher values of CzA to obtain

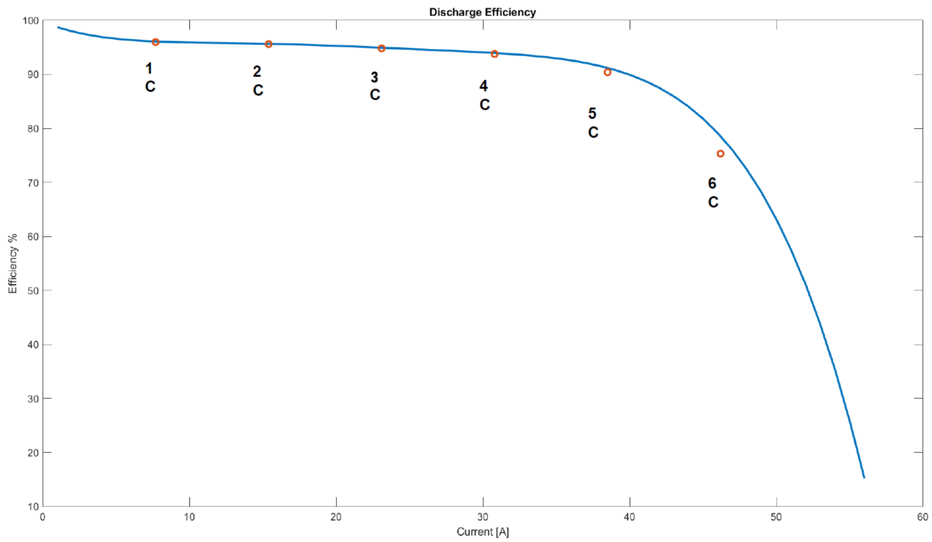
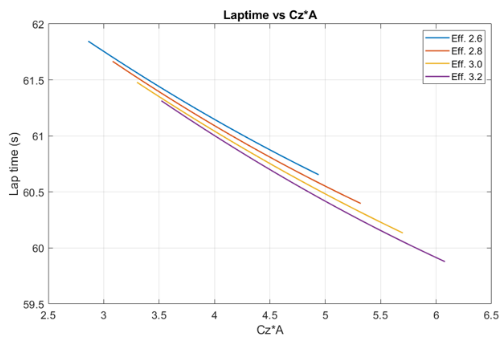
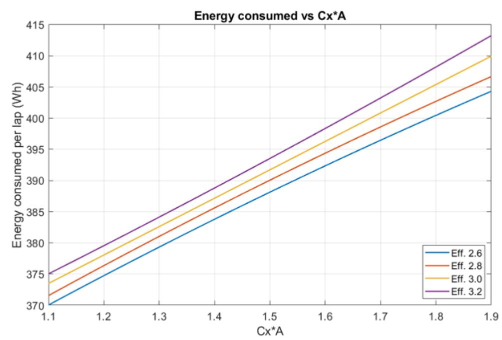


Figure 2.15: Discharge efficiency of SLPBB042126HV Li-Po cells for different C-rates

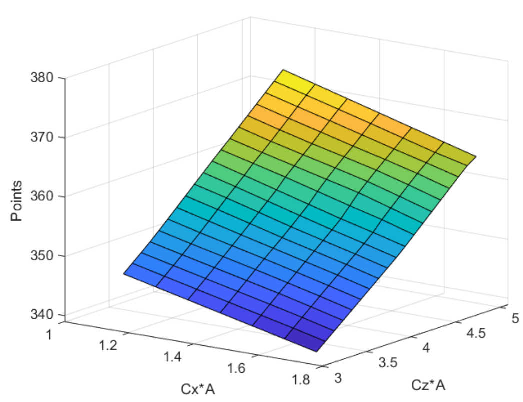
higher score in Endurance and Efficiency events. The selection of CxA comes comparing results from Table 2.9 with Figure 2.16b, the target value obtained is 1.5. The definition of the value of CzA is a consequence of CxA and is preliminarly estimated in the target setting phase thanks to the past years' aerodynamic development. In particular, the refining of our aerodynamic CFD model brings us to consider a reasonable and reachable efficiency value of about 3. It follows a maximum CzA value around 4-4.5. This value is to be maximized as much as possible during the design phase itself.



(a) Laptime



(b) Energy consumed per lap



(c) Endurance+efficiency points

Figure 2.16: LTS Aerodynamic sensitivity target analysis

2.6 Ergonomics

The following phase is devoted to define the ergonomics of the vehicle. This section is actually developed in parallel with the packaging one, since any important change in the layout of the subsystems present inside the chassis can affect the driver position, and this latter clearly constrains the packaging of the vehicle if some specific requests and targets have to be met regarding the driver ergonomics. For the sake of simplicity they are treated as separate sections but in reality they are strictly interconnected.

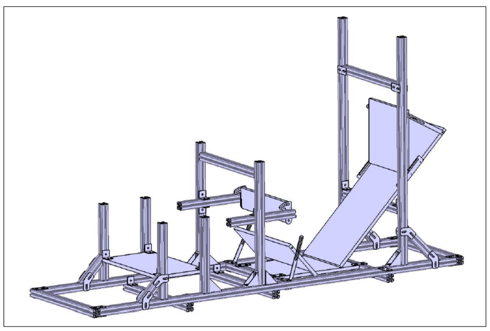
The drivers have been actively included in the target setting and design of the vehicle. The Team put a lot of time and effort to make a more organic and fluent interface between vehicle and driver. The idea to put drivers at the center of the project and try to build the vehicle according to their suggestions was born to ensure that they are driving at their fullest potential. Many FSAE cars (also previous Squadra Corse cars) show a lack of integration between driver ergonomics and engineering design of the car, resulting in uncomfortable driver positions or driver actuations. The Team believed that a driver feeling comfortable and being able to extract the full potential of the car is much more valuable in terms of laptime and safety compared to a car designed with performance as main target without paying enough attention to the driver needs.

Body posture and visibility have been studied with an ergonomic test bench. The developed bench is intended to be a solid solution for the years to come and allows to change different driving positions in a short amount of time. With this setup is also possible to check beforehand the compliance with the rules in terms of driver clearance of the helmet and steering wheel position. Further estimations are possible with the bench: CoG of the driver and brake pedal loads. The former is measured by means of load cells under the bench. In this way it is possible to properly rescale the CAD manikin representing the different driver percentiles in order to have an accurate estimation of the CoG. The latter is achieved with instrumented pedalbox and it allows to verify loads at the pedalbox assembly and to the relative monocoque panel, whilst checking the effort the driver has to make to brake with different driving positions, allowing to choose a comfortable one both for short and tall drivers.

The result of ergonomics showed a slightly more reclined driver seat compared to SC19, significantly nearer and higher steering wheel in order to improve driver responsiveness, bigger diameter steering wheel to reduce steering wheel torque, higher adjustability of pedalbox position in x direction, higher thighs support that helps in braking maneuvers. Main hoop and front hoop location is defined aswell thanks to the definition of the driver's position.

Driver interface visibility is done preliminarly in the test bench as well as with the digital mockup CAD tools available. Higher visibility is requested to see better front wing endplates for cones avoidance by designing more inclined and narrower monocoque panels in correspondence of the front hoop section.

The reachability is also considered to make every component easily accessible by

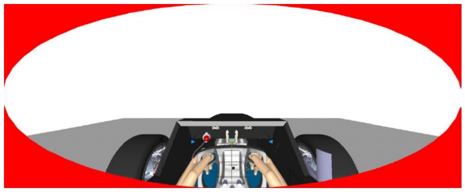


Adjustable features	
Pedalbox	X & Z
Steering wheel	X, Z & θ_y
Main hoop	X & Z
Front hoop	X & Z
Seat back	X and θ_y
Head restraint	X and Z
Thigh support	X and θ_y
Wheelbase	

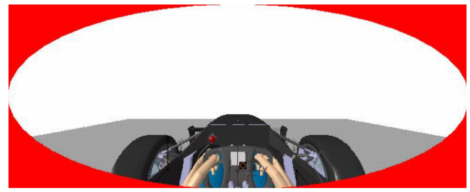
(a) CAD and adjustable features

(b) Instrumented pedalbox **(c)** Real bench with 95th percentile driver

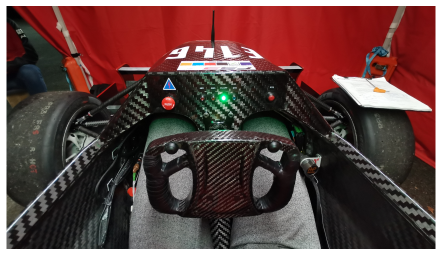
Figure 2.17: Ergonomic test bench



(a) Early release of the monocoque



(b) Final release of the monocoque



(c) Real car

Figure 2.18: Driver visibility

placing mockups in the real test bench that simulate the switches and commands present in the cockpit.

2.7 Packaging definition

The adopted workflow in the packaging is the one reported in Figure 2.19. Different solutions are considered from the previous years.

SC18 had HV and LV accumulators behind main firewall, inverters between driver and SIS, with a converging diverging undertray. This solution allows to minimize HV cable length, minimize monocoque length, and reduce inertia around z axis, whilst maintaining a single firewall.

SC19 had HV and LV accumulators behind main firewall, inverters under the driver legs, flat and diverging undertray. This solution allows to better manage mass distribution and reduce monocoque frontal area, whilst maintenance was not very accessible for the inverters and their casing was fixed to the monocoque. It required double HV firewall, increased HV cable length due to inverter positioning.

Main different solutions studied are reported in Figure 2.21. The solutions proposed report different HV accumulator configurations since this phase is held in parallel with HV accumulator selection and ends after this has been freezed. The final chosen configuration is 2.21g. This solution has the following advantages:

- Converging and diverging undertray with two inclination, 2 deg for inverter, 2 deg for HV accumulator to improve aerodynamic efficiency (result from a sensitivity analysis carried out with the lap time simulators)

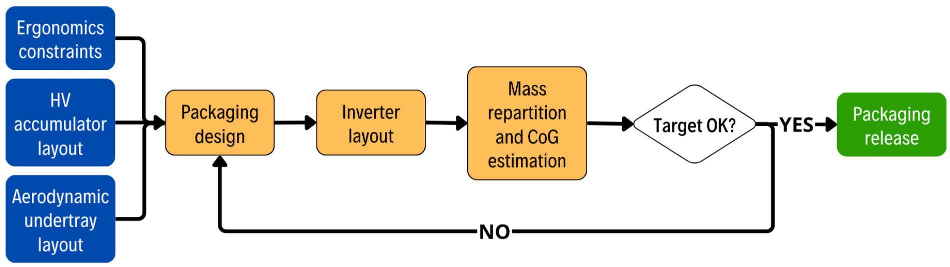
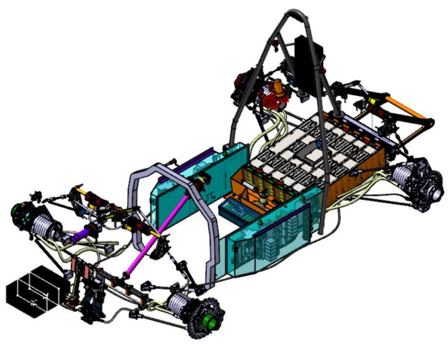
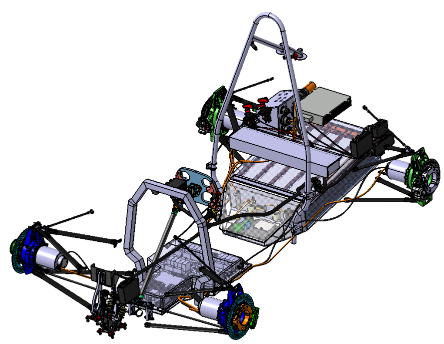


Figure 2.19: Packaging workflow



(a) SC18



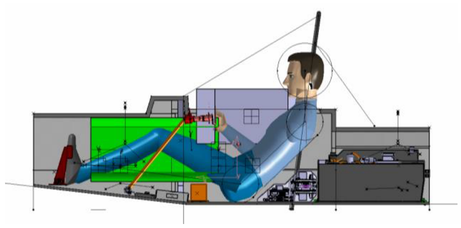
(b) SC19

Figure 2.20: Previous cars packaging

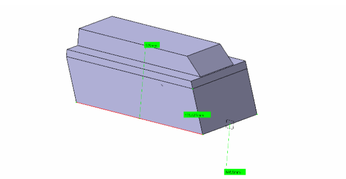
- Inverter behind the firewall that shortens HV cables length, requires one firewall only and allows to reduce CoG. Furthermore inverters in this position are very well suited to cover the triangular shape-like cross section present just behind the driver's hips, area of the car which is actually difficult to fill with other items. Easier accessibility of inverters for maintenance from the cockpit once the firewall is removed.

- LV accumulator and ECU placed below the leg with dedicated casing not requiring firewall for improved legs support, whilst maintaining low CoG. Easier accessibility of both LV accumulator and ECU from the cockpit during normal operations at the track, without having to access from the back of the vehicle inside the monocoque like in SC18 and SC19 cars

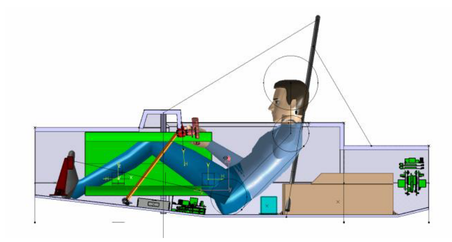
- Slim rear end of the monocoque due to 132s2p accumulator selection to improve aerodynamic efficiency



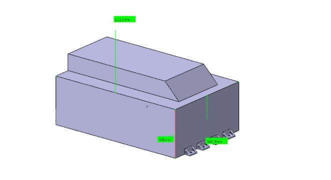
(a) 132s2p converging+no diverging



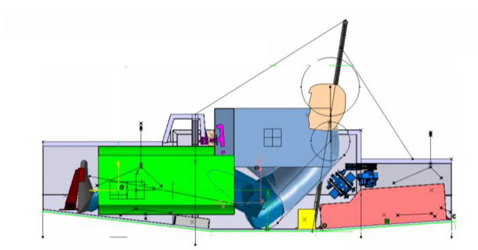
(b) 132s2p HV accumulator



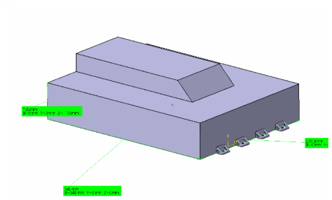
(c) 138s2p converging+diverging after HV accumulator



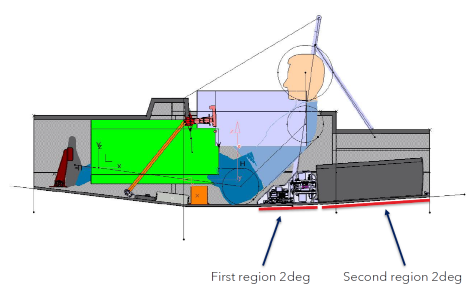
(d) 138s2p HV accumulator



(e) 136s4p converging+diverging



(f) 136s4p HV accumulator



(g) 132s2p converging+double diverging

Figure 2.21: Different packaging releases

2.8 Final organizational targets definition

During the target setting phase attention is dedicated to organization aswell, since designing and building a racecar is not only a matter of technical knowledge but also how this is managed and how people are actually working together. Starting from the previous year experience, we detected some organizational aspects to be improved and we decided to refine the processes behind these aspects, defining organizational targets whenever possible. In the following, the main issues encountered during the target setting and design phases are described. These are solved by means of countermeasures reported in the following and in Section 3.

Recruitment of the new Team members is an important phase of the new season. In the last few seasons in our Team every Team member is allowed to be part of it for a maximum of two consecutive years. This means that every year there is pretty much half of the Team that is leaving for new Team members to come in. We decided to shift recruitment earlier in the 2021 season timeline taking the advantage of the early stop of 2020 season and in order to better introduce the new Team members. From a technical point of view, the introduction of softwares tutorials by Team members allows for a faster and more efficient integration of the newcomers. The main softwares covered are Altair® HyperMesh®, Altair® Inspire®, CATIA™ V5, which are softwares usually not covered thoroughly during the curricular courses and cover mainly the mechanical design area. Let us take an example of how a tutorial is structured. Altair® tutorial has a duration of 7.5 h, split in several lessons. All the lessons are given interactively with the new Team members giving the opportunity for questions and clarifications. Lessons are recorded to improve the learning curve and to be available for future recruitments as well.

Table 2.10: Organizational issues and targets

ISSUE	TARGET	CORRECTIVE ACTION
Technical knowhow is transmitted poorly between one year and the following one, with inconsistent methodology, mainly relying onto human historical tracing rather than leaving consistent data available for the future.	Improve know how transmission from one season to another.	Improving of design books, improving the CAD quality, improving the design data shared in the drive with related updates, increase the production documentation and media.
Design books explained in Section 3.12 are written with inconsistent quality in between one Team member and another.	Design books need to be improved in detail and drawn up by all Team members designing car components.	Earlier draft of the design books, more frequent checks by technical director, provide examples of well written design books from which to take a cue.
FMEA explained in Section 3.11 written with inconsistent quality in between one division and another. Not implemented in 2020 season.	Implement again FMEA, reducing the probability of occurrence of failures and adverse events, improving the Team's responsiveness towards them, keeping track of the issues encountered during the season for the future.	Reintroduction of FMEA for all divisions, with dedicated documents to keep track of failures.

Table 2.10: Organizational issues and targets

ISSUE	TARGET	CORRECTIVE ACTION
Poor data transfer during the design phase amongst different divisions, i.e. using data not updated to the last release or design changes not correctly comunicated between divisions.	Avoid source of mistakes due to using wrong data releases.	More communication between division leaders, increasing the time spent together for a more efficient integration, better the data transfer useful for different divisions by the introduction of shared data sheets.
Nomenclature of components does not indicate the season when it was designed or introduced.	Include year of introduction in components' nomenclature.	Change the nomenclature from the current season onwards by adding a front number that reports the the two last digits of the prototype manufacturing year.
BOM structure missing of some key features to avoid potential mistakes for the production.	BOM updated with current components designed or bought and efficient to be consulted and updated.	Revision of the BOM datasheet structure and selection of a devoted responsibles.
Poor management of the inventory.	Inventory updated with current items available in store and efficient to be consulted and updated.	Revision of the inventory datasheet structure and selection of a devoted responsible.
Poor introduction to softwares used inside the Team to the newcomers due to few time available and lack of preexistent data.	Improve newcomers integration in the Team from a technical point of view, leveling up their software knowledge.	Team members already in the Team for a year create tutorials of the main softwares in order to level up the knowledge across the different new Team members.
Recruitment done too late in the calendar leads to late season start.	Anticipate recruitment by two months time.	Change recruitment and season timeline.
Too high workload focused on few human beings (core of the Team).	Lower the high workload focused on few human beings.	Spreading the workload amongst all the Team members, making them more aware of their importance and responsibility towards the project, managing better the tasks subdivision from the technical director with the division leaders.
Failed to qualify for all the events, epecially most difficult ones such as FSG.	Qualify for all the events.	Better the events' quiz preparation. Collaborate with other Teams from all the Europe, sharing methodologies and quizzes and participate together to simulations in preview of the official events.

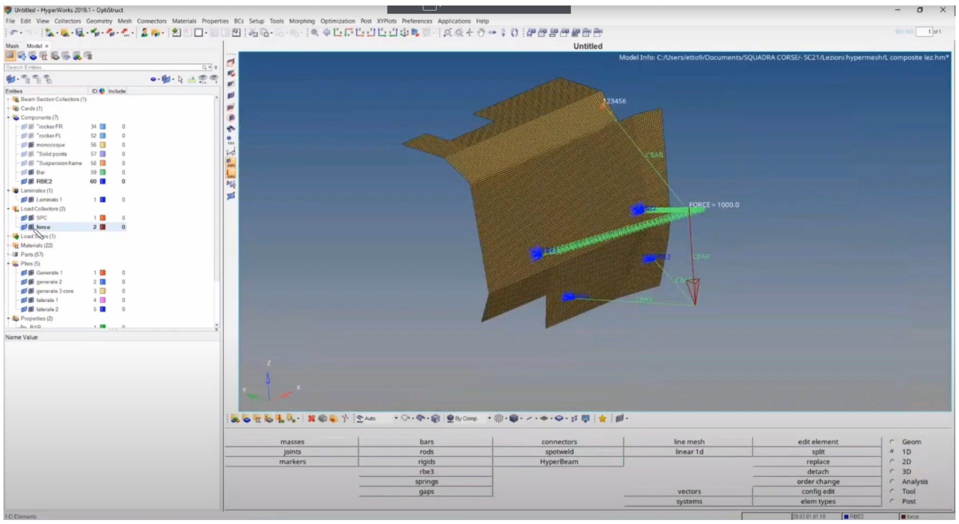


Figure 2.22: Altair® tutorial lesson

Lesson	Duration
Introduction + Geometry tab	120 min
2D + 3D + Tool tabs	90 min
1D + Analysis tabs	60 min
Topological optimization	40 min
Composites analysis and optimizations	50 min
Thermal analysis	60 min
Fatigue analysis	30 min

Table 2.11: Altair® tutorial example

3 Design

The design phase described in the following is considered as the proper design of the assemblies, sub-assemblies and components that form the vehicle. In this phase, the engineers have to design the components with in mind the both the vehicle targets set and the targets of the assembly of their respective division. It is an iterative process where several consequent releases are designed, till the results are satisfactory and meet the target set. The design phase is represented into the left portion of the V-cycle 2.2. Each division at the end of the vehicle target setting, is able to deploy those vehicle targets into sub-assemblies ones. This is done in cross-communication with the different divisions for a better integration, and it starts from the previous season experience. An example of these targets is reported in Section 3.7.

Vehicle	**SC21**
Vehicle mass	206 kg
Front mass repartition (with 68kg driver)	47.5%
Wheelbase	1525 mm
Track	1200 mm
CoG height (from ground)	272 mm
Aerodynamic CzA	3.90 *
Aerodynamic CxA	1.36 *
Total power	80 kW (140 kW without restrictions)
HV accumulator configuration	132s2p Li-Po cells active air cooled
Nominal HV accumulator capacity	7.74 kWh
Maximum HV accumulator voltage	574.2 V
Maximum EM Torque (peak)	21 Nm x 5 s
Maximum EM speed	20000 rpm
Maximum vehicle speed	119 km/h
0-100 km/h acceleration	2.8 s
Tires	185/40 R13 Pirelli slick tires on 13” OZ Racing Mg/Al alloy rims

Table 3.1: SC21 main technical features, (*) extrapolated from wind tunnel validation

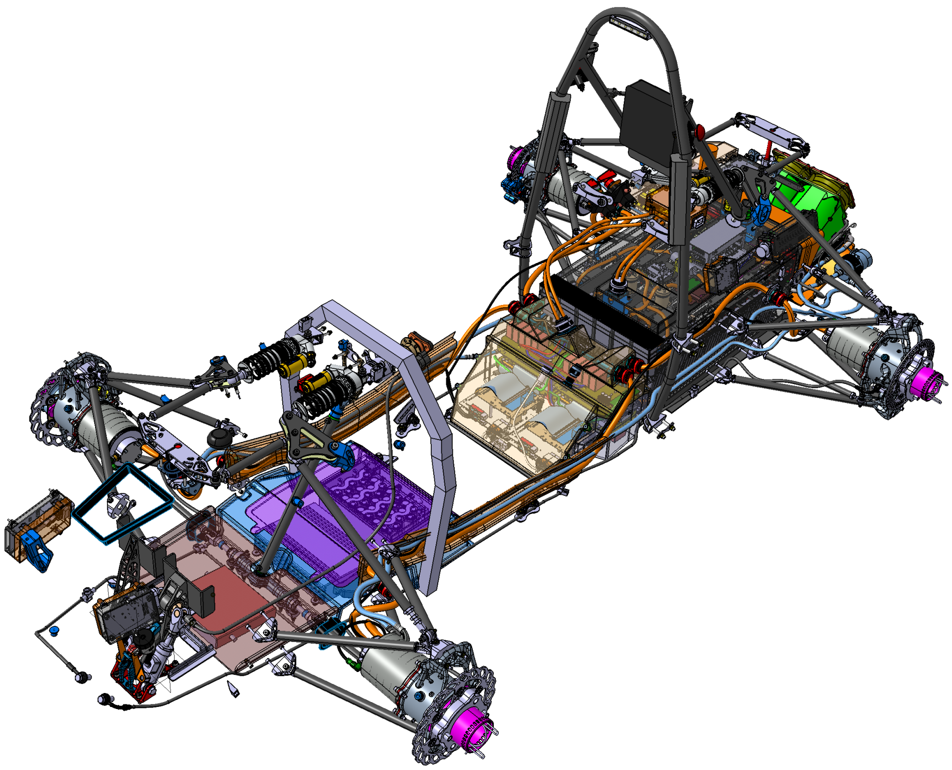


Figure 3.1: SC21 packaging

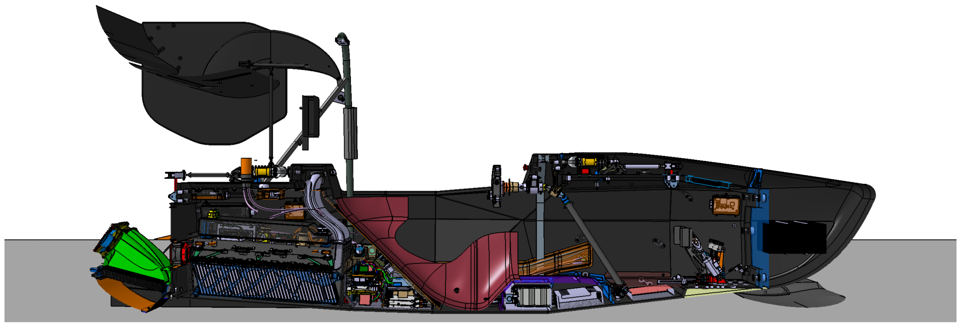


Figure 3.2: SC21 section view

3.1 GANTT

Amongst the main phases of project management there is the one called "Programming and scheduling". Programming phase consists of the assignment of due dates and time constraints to all the defined activities in order to define the project plan. The scheduling is then possible by means of two main tools that are the Gantt chart and Project Network diagrams such as CPM and PERT.

The Gantt diagram displays several activities and tasks to be done on the rows and their time collocation on columns. The activities duration is represented by bars that match the start and end date with the respective row. Gantt charts are a simple and effective way to schedule and monitor a Project, tuning the process timing involved to reach completion of the former. The main Gantt chart used in SC describes the Design phase in detail. Each division has its own dedicated section where all the design activities have their duration and order in time. The same will be repeated for the Production phase in Section 4.

Deliverables represent a tangible result that has to be completed by a specified time. Deliverables are associated to the main tasks in order to properly check after the task's completion, whether the results match the expected targets or not. Deliverables can be identified in technical documentation completion such as SES, ESF or design books, a feasibility study like the initial phase of target setting or a list of specifications such as the Design Spec Sheet (DSS).

Milestones are included aswell and represent a day in the Gantt chart where there is a verification of the Project progress by checking whether the targets are achieved and match the results or not. Several examples could be the target setting freeze, CAD freeze of the monocoque, suspension pickup points freeze, suspension stiffness freeze.

The tasks' order follows a logical sequence in a way to finish firstly tasks where the associated deliverables are necessary as inputs for other tasks. The interactions between tasks are very common and making the most out of the available time is crucial. The activities can be classified into four main categories [7, 8]:

- **Finish-to-start**: the activity B cannot start if the activity A is not yet completed.
- **Start-to-start**: the activity B cannot start if the activity A is not yet started.
- **Finish-to-finish**: the activity B cannot be completed if the activity A is not yet completed.
- **Start-to-finish**: the activity B cannot be completed if the activity A is not yet started.

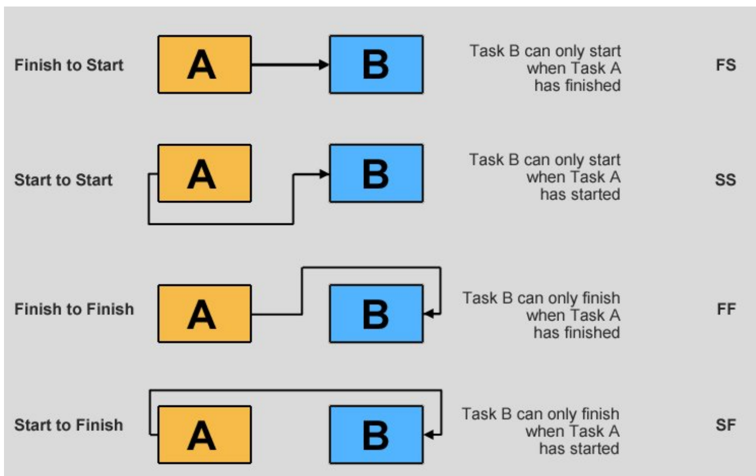


Figure 3.3: Project Management types of activities [8]

Gantt chart is very effective since it easily shows an immediate representation of the project positioning of activities along time but it has also some drawbacks. First of all, to be effective it should be consistently updated and sometimes real activities flow could not match the Gantt proposed ones. Sometimes it can be tricky to correctly predict the duration of an activity and only more than one year experience in the Team should be useful to predict the duration of never seen tasks that could happen in a new season. Moreover, the chart does not show the project logic, neither the tasks dependencies apart from their logical sequencing, and again it could be misjudged by looking at previous seasons Gantt charts. Even though the logic behind the chart is very basic, I found it very useful to look through the chart with the previous technical director and to speak with him in order to take the most out of it.

It is important to determine which are the activities that represent the bottleneck, in order to determine the so called Critical Path, that is the project path made of all the activities whose completion cannot be postponed without affecting the total project duration. In SC a method like the Critical Path Method was not adopted. Indirectly though, the selection of activities duration, the start and the due dates when redacting the Gantt chart, made automatically detect those critical activities.

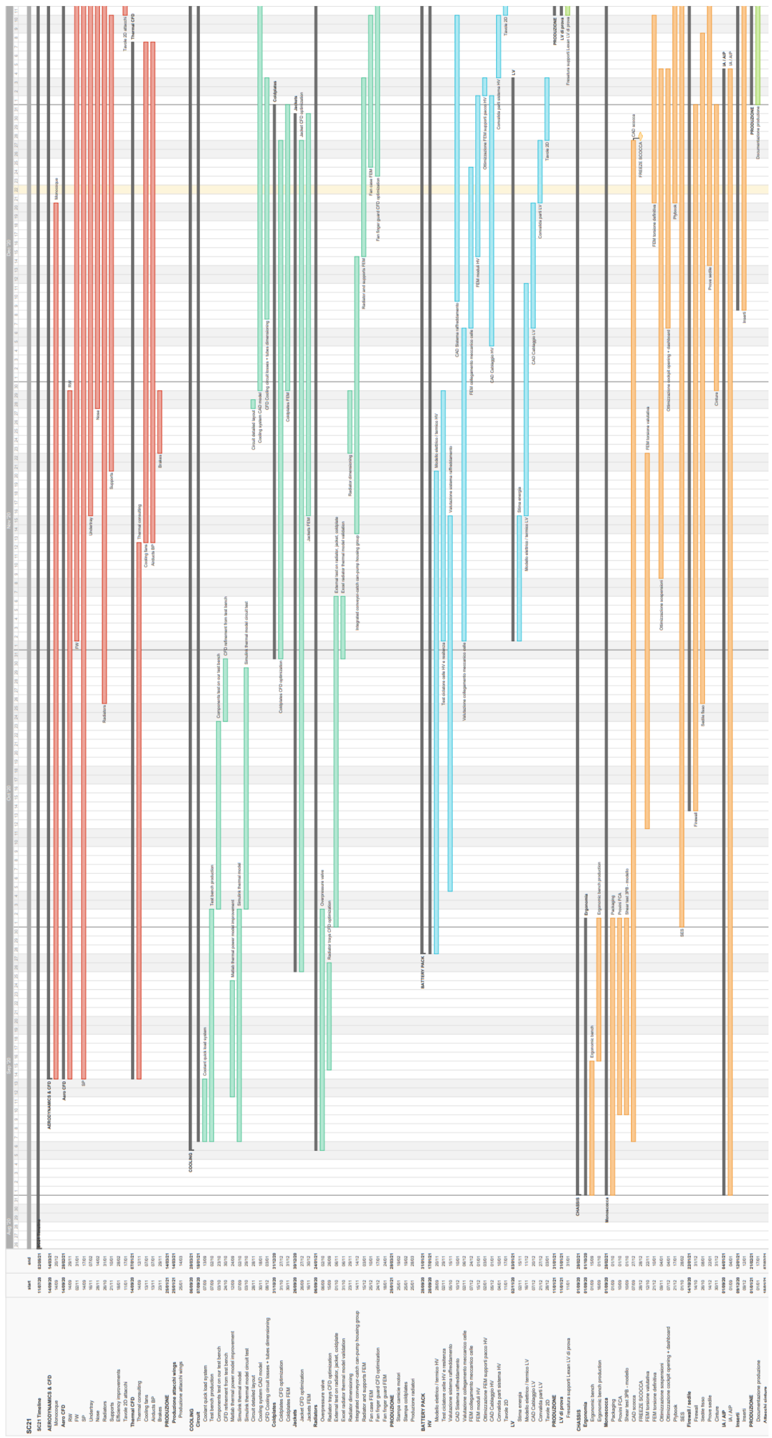


Figure 3.4: Portion of SC21 design Gantt

3.2 Tractive system

The tractive system is composed of four bought motors and inverters (AMK package), self-developed dual-stage planetary geartrains and HV accumulator. After evaluating different possible layouts, the vehicle has been equipped with four in-wheel mounted motors. A make-or-buy analysis together with season time bounded constraints, showed that the best solution was buying the motor and inverter pack from AMK due to its high power density and reliability. Moreover, such data has been used as an input for the HV accumulator, cooling system, and gearbox design.

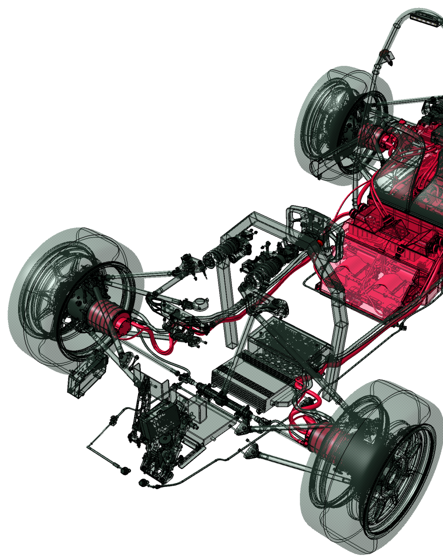


Figure 3.5: SC21 design tractive system assembly

The HV accumulator consists of 264 Li-Po Melasta SLPBB042126HV cells arranged in 132s2p layout, air-cooled. Cooling design will be covered in section 3.5. Positive locking has been ensured for cell connections. The accumulator voltage (502 V nominal, 574 V maximum) has been decided considering the characteristic speed of the motor and the field weakening. The obtained accumulator capacity is 7.74 kWh. The choice of selecting Li-Po cells over Li-Ion ones comes also from the thermal point of view. In fact, from FSS19 endurance event the temperatures the HV accumulator reached were 56.6°C with expected values that overcome the 60°C maximum limit imposed by regulations.

Another reason for the switch to the Li-Po cells is represented by the fact that these have higher C-rates both in charge and discharge, allowing to draw more current during accelerations and allowing to regenerate more in braking. Li-Po cells have much lower internal resistance so this translates also in much lower voltage drop, resulting in higher voltage of the accumulator during endurance, allowing the motors and inverters to work in areas of higher efficiency. The packaging of the HV accumulator is being redesigned by utilizing custom made 3D printed Ultem

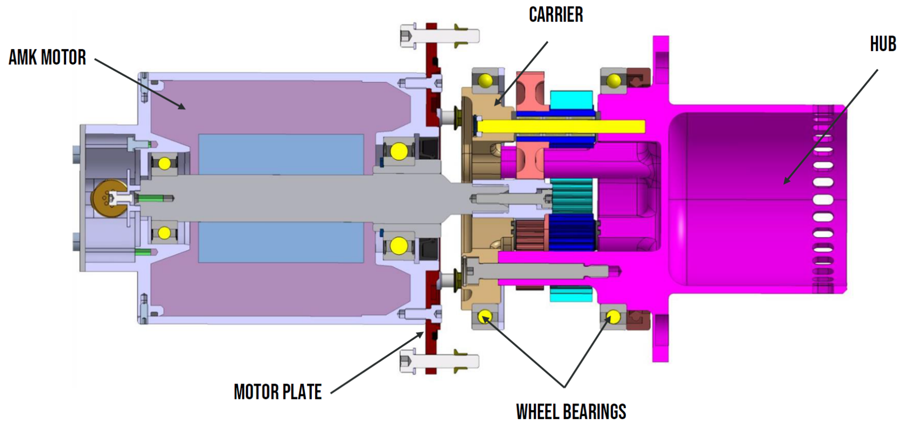
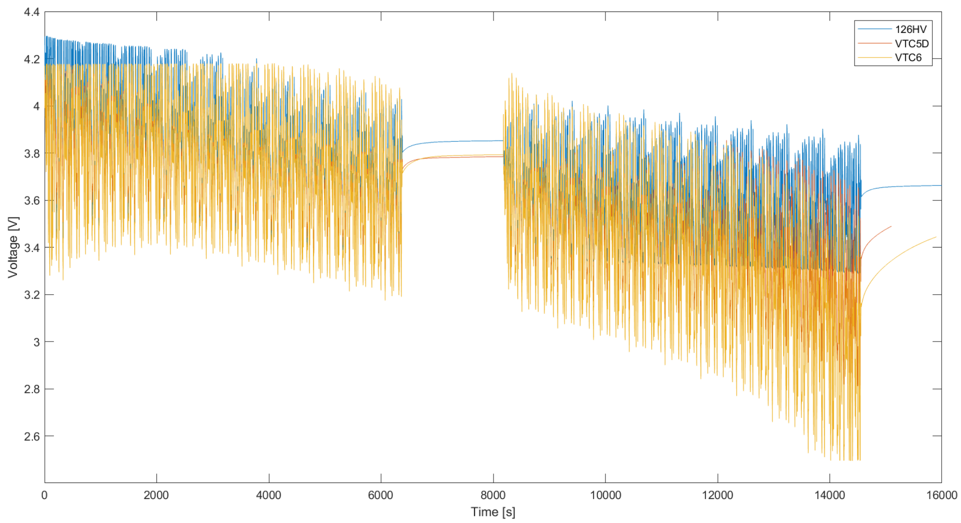


Figure 3.6: SC21 motor and geartrain section view

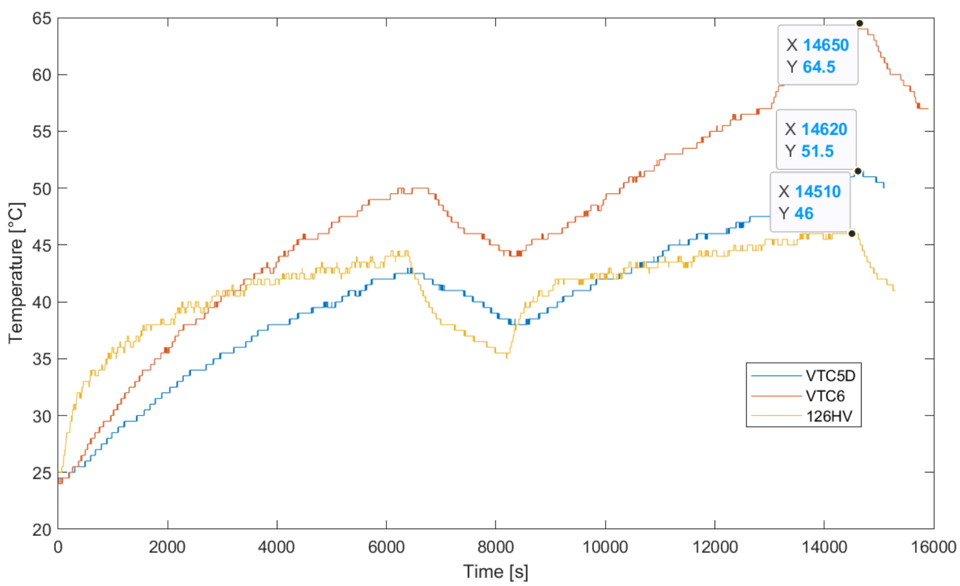
cells housing, topologically optimized, to be fit inside a custom CFRP fire retardant accumulator housing. Li-Po cells tabs are then mechanically connected to the busbars. HV BMS is supplied and customized by a partner company.

The transmission ratio has been selected as a compromise between the maximum torque exploitable by the tires, both at the front and rear axle, and motor parameters, mostly the efficiency and magnetic characteristics. The transmission itself is a dual stage epicyclic gearbox, as it is mounted inside the wheel uprights, its design must be as compact and lightweight as possible. This design choice allows to reach high transmission ratios while keeping its dimensions low. In such a speed reducer there are four different gears: the sun gear which is mounted directly on the motor spline, two planetary gears, respectively first and second stage, and a ring gear fixed to the upright.

AMK package is specifically designed for Formula SAE teams and includes a kit of four motors and inverters. The DD5-14-10-POW are PMSM motors with an extremely high density of power, providing up to 35 kW of power and 21 Nm of torque, weighting only 3.55 kg. AMK inverters kit based on IGBT power modules is disassembled and rearranged according to a more compact packaging that fits our racecar, allowing to cut down weight and volume.



(a) Voltage



(b) Temperature

Figure 3.7: Comparison between Li-Po and Li-Ion in Endurance FSS19 simulation on bidirectional current source

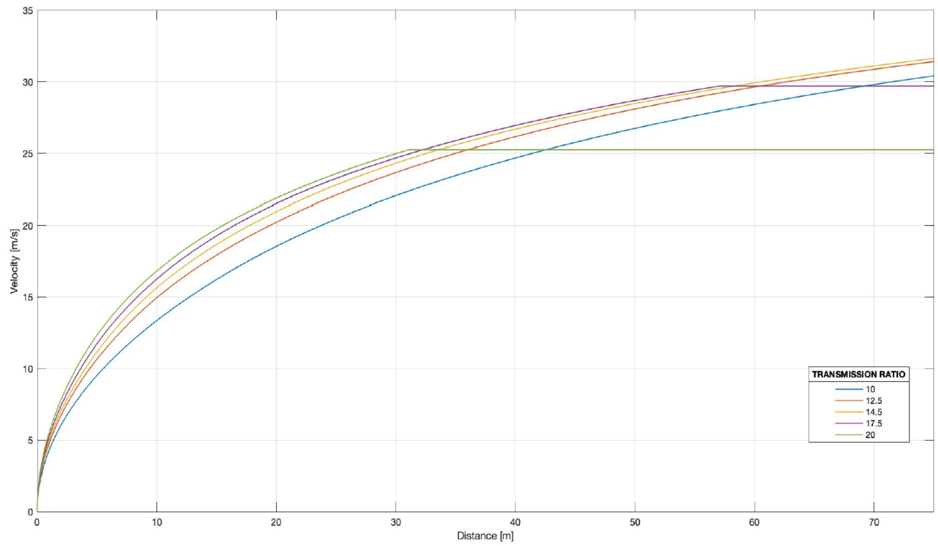


Figure 3.8: Acceleration velocity plot for transmission ratio selection

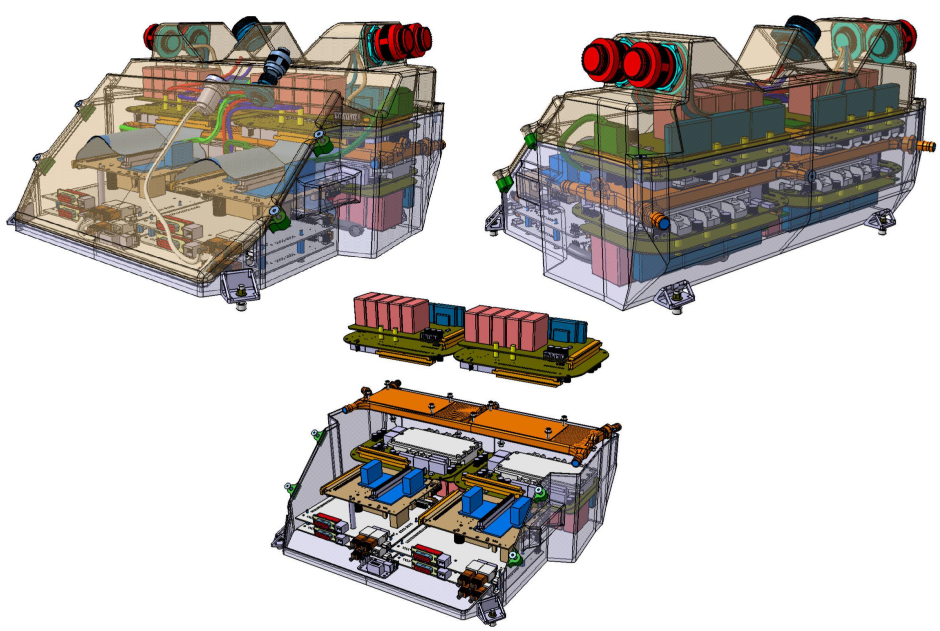


Figure 3.9: SC21 inverters assembly

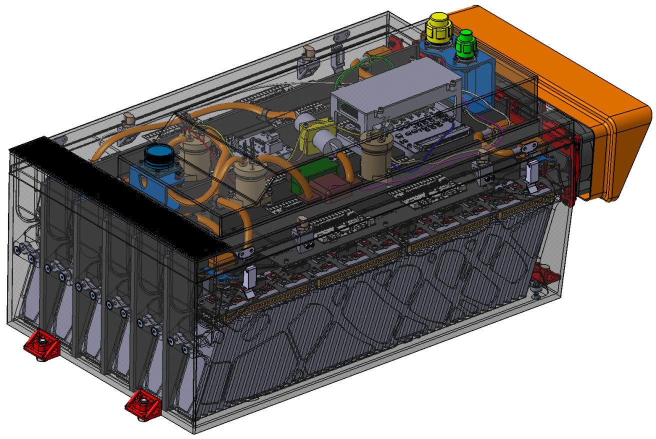


Figure 3.10: SC21 HV accumulator assembly

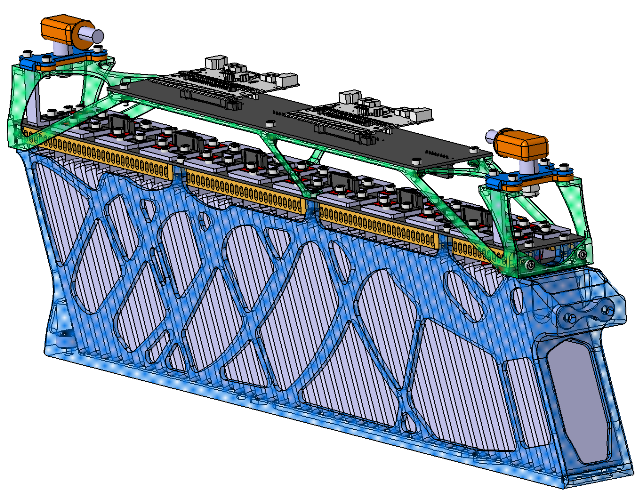


Figure 3.11: SC21 HV accumulator module

3.3 Low voltage electronics

The design of LV electronics focused on new design of custom boards, the addition of sensors present onboard devoted to further validation and control, and the revision of the wiring harness.

Custom boards redesigned are:

- **Battery Management System (BMS) LV** for low voltage battery
- **Micro controller based boards** for: CAN communication, sensors acquisition, steering wheel for driver interface, cooling automation PWM fans control
- **Hardwired only circuits** for HV detection circuitry and safety operations such as implausibility events, stuck relays

Other than custom boards, semi-custom boards are employed for:

- **BMS HV**
- **VI board** for HV bus sensing of the voltage and current

Commercial boards mounted on the car are:

- **DSpace MicroAutoBox II**: vehicle control unit , in which the control system of the vehicle, implemented in Matlab®, is executed
- **IMD**, Bender IR55, for monitoring the insulation between TS+ and LV-
- **IMU**, SBG systems, for GPS navigation
- **Modem** for wireless telemetry

Communication between boards is made through CAN-bus 2.0A. Four buses are presents in the vehicle

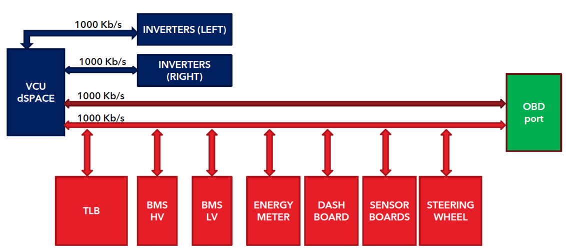


Figure 3.12: CAN-bus

The design of the PCBs is mainly done with software KiCad.

The design of both LV and HV wiring harness is done priminarly in CAD environment with a full size 3D CAD mock-up to trace the harnesses around the vehicle and define the wires length. This mockup includes also boxes positions and connectors.

Wiring harness design is done sequentially to the first versions of PCBs design in order to have well clear the connectors pinout. A functional drawing is employed to better figure the schematic of all the wires. Wiring harness codes management is done in Excel sheets, where for each connector are listed the signals for each pin both from input and ouputs, as well as for wiring braids management.

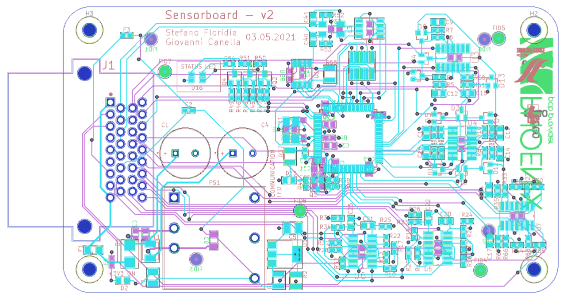


Figure 3.13: SC21 sensorboard design

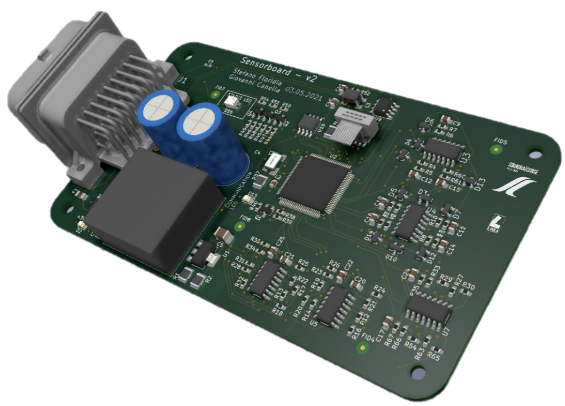


Figure 3.14: SC21 sensorboard rendering

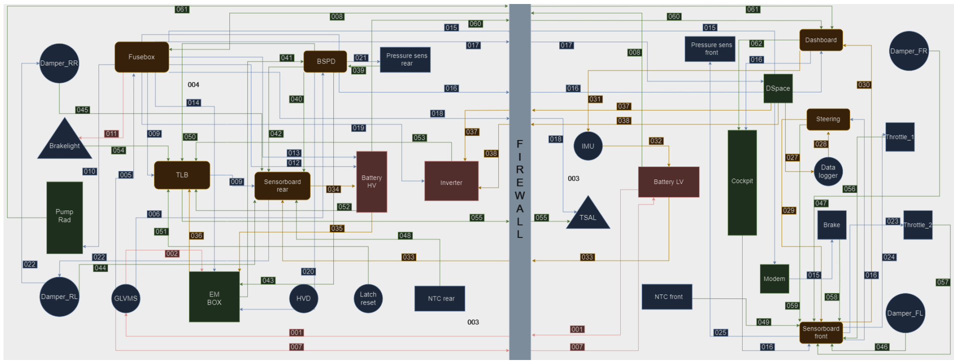


Figure 3.15: LV wiring harness functional drawing

CODE	DESCRIPTION	FROM	TO
001	24V battery	Battery LV	GLVMS
002	24V meas point	GLVMS	EM BOX
003	GND	Battery LV	EM BOX
004	GND	EM BOX	Fusebox
005	24 V+ GND - DIRECT	GLVMS	Fusebox
006	24 V+ GND - DIRECT	GLVMS	BSPD
007	24 V bms lv	GLVMS	Battery LV
008	Relay CMD	Battery LV	Fusebox
009	24 V + GND - REAR BOARDS	Fusebox	SENSORB REAR
010	24 V + GND - PUMPS & FANS	Fusebox	REAR LEFT - MONOCOQUE
011	24V - BREAKLIGHT + GND	Fusebox	BREAKLIGHT
012	24V + GND BP FAN	Fusebox	BP FANs
013	24V + GND - BMS HV	Fusebox	ACCUMULATOR CONTAINER
014	12V + GND - EM	Fusebox	VI BOARD
015	12V + GND - MODEM - ESTEN	Fusebox	MODEM + BRAKE PEDAL
016	24V + GND - FRONT BOARDS	Fusebox	DASH - COCKPIT - SENSORB FRONT
017	24V + GND - DSPACE	Fusebox	DSPACE
018	24V TSAL	Fusebox	TSAL
019	24V + GND INVERTER SX/DX	Fusebox	INVERTER PACK
020	5V+GND - CURRENT SENSOR	BSPD	EM BOX
021	5V+GND - BRAKE SENSOR REA	BSPD	BRAKE PRESSURE REAR
022	3V3+GND - DAMPERS REAR	SENSORB REAR	DAMPERS REAR
023	5V+ GND - THROTTLE 1	SENSORB FRONT	THROTTLE 1
024	5V + GND - THROTTLE 2	DASH	THROTTLE 2
025	5V+GND - BRAKE SENSOR FRO	SENSORB FRONT	BRAKE PRESSURE FRONT

Legend functional drawing harness
24V
gnd
Cavi "accorpati"
Segnali
CAN
SHUTDOWN

Figure 3.16: LV wiring harness codes

3.4 Vehicle dynamics and Control systems

Vehicle dynamics division is responsible for the suspension kinematics design, target setting and laptime simulation, tires analysis, the control systems design present on the car and dynamic performance analysis. Laptime simulation was already covered in Section 2.4.

The kinematics of the suspension system has been developed with the aim to exploit the entire tire's potential. A major focus was put on maximizing camber recovery to have a good balance between cornering and traction outside turns since this is the most important point for lap time reduction. Moreover, the caster and king-pin angles have been designed considering the vehicle stability and driver feelings. Other targets were minimization of roll center movement and minimization of the jacking force that can affect the whole elasto-kinematic performance of the suspension. The tire choice has been made considering different commercial solutions. Pirelli was selected as a manufacturer because of the possibility to cooperate with them to develop the compound and structure of the tires to suit our needs as well as for the previous years knowledge.

Every information (motor and inverter status, temperatures, accumulator parameters, errors) is accessible in real-time to the box via a telemetry system, which also provides voice communication between driver and box. The control system of the vehicle is split into three key parts: vehicle state estimation, vehicle dynamics controls, and power management. State estimation consists of the evaluation of the instantaneous velocity of the vehicle made with a fuzzy logic controller. Vehicle dynamics feature a Yaw rate controller made with a feedback controller embedded with an optimization of torque distribution among the four wheels to generate the desired yaw moment taking into account the limits of the tires and without affecting the natural driveability of the car. The traction control is based on the speed difference between the CoG of the vehicle and each tire. To avoid excessive heating of the motors, a tool was designed to recognize the most critical axle and redistribute the torque when possible. The power management system has different settings designed to fit properly for each dynamic event, in particular, the maximum motor performance (i.e. torque) is the desired target for acceleration and autocross, otherwise, for the Endurance event, an energy-saving map has been developed.

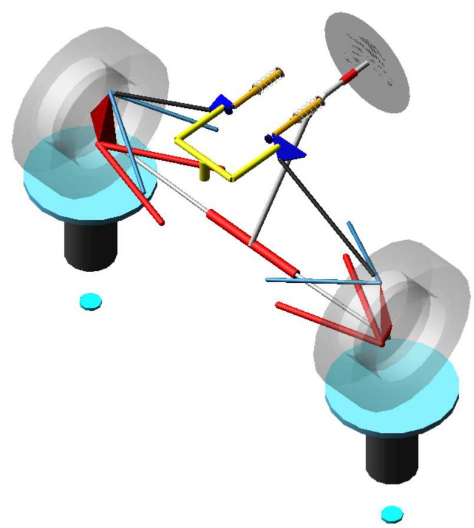


Figure 3.17: Adams Car front suspension model

3.5 Aerodynamics and Cooling

The aeropack has been completely redesigned and also the modus operandi has been revised. In the first part of the season, a new airfoil database was made that helped in the definition of the new custom multi-wings used in the car. This was possible by 2D parameters optimization software that gives us the most performance set of multi-wings, then tested with the whole car, both in longitudinal and cornering CFD simulation.

Once defined rear wing, sidepod, and front wing airfoils, the development focused on the achievement of the final targets employing several parametric analyses and employment of aerodynamic devices designed to improve the aerodynamic efficiency of the whole aeropack. A completely different strategy was adopted for the undertray, given the predominant 3D phenomena that occur on this part of the vehicle, all the analysis was made with the whole vehicle.

The development started with the SC19's monocoque, in cooperation with the chassis department, taking into consideration the target position of the CoG, obtaining the final packaging of the new vehicle. Later on, in collaboration with the cooling department, the radiator was placed on the final divergent part of the undertray, in order to improve the performance of the latter, tested in CFD with different speeds of the car and different fans' angular velocities. Front and rear flaps have different regulations to setup the vehicle in the test phase and tear down the Cx during the acceleration event. While the designers worked on these themes, the CFD analysts were constantly improving the CFD model thanks to the wind tunnel experience with the 2019's vehicle, considering our current computing resources. As well as standardizing the CFD's post-processing, in order to better compare the different aerodynamics solutions and their influences on the whole car. Because of the complexity of the aeropack, the design was manufacturing process oriented and this latter was simplified using 3D printed with MJF technology PA12 flaps with lattice structure cores, with a slight increase in weight, but increasing repeatability and tolerance management and a reduction of costs and manufacturing time. Final design aerodynamic parameters: Cz = 4.37, Cx = 1.45, E = 3.01, Ref. Area = 1.028 m^2, aerodynamic balance = 50.6% front.

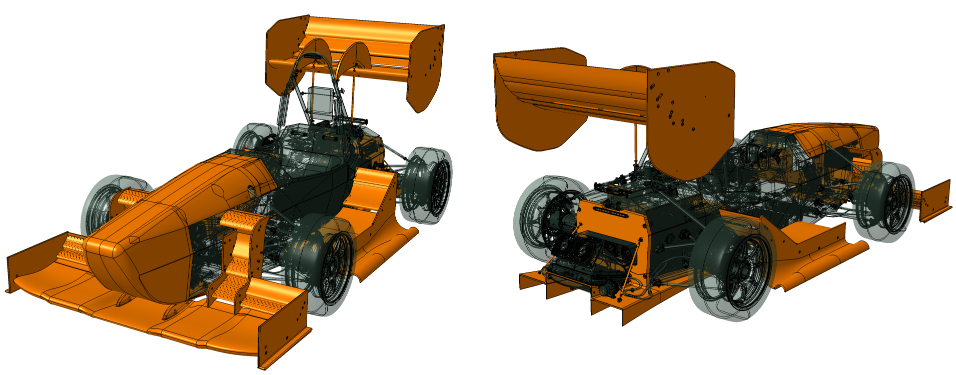


Figure 3.18: SC21 design aerodynamic assembly

The cooling system features custom additive manufactured AlSi10Mg heat exchangers for inverters and motors, both optimized in their internal flows to maximize heat exchange and to reduce pressure drops. A single heat exchanger is designed for the four IGBT power modules called coldplate, resulting in a sandwich

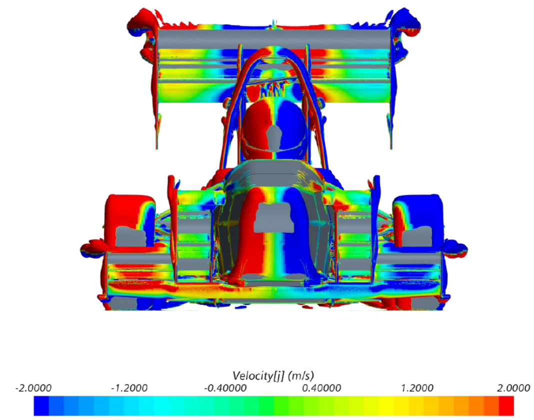


Figure 3.19: SC21 CFD result Q-criterion scene for vortex structures identification

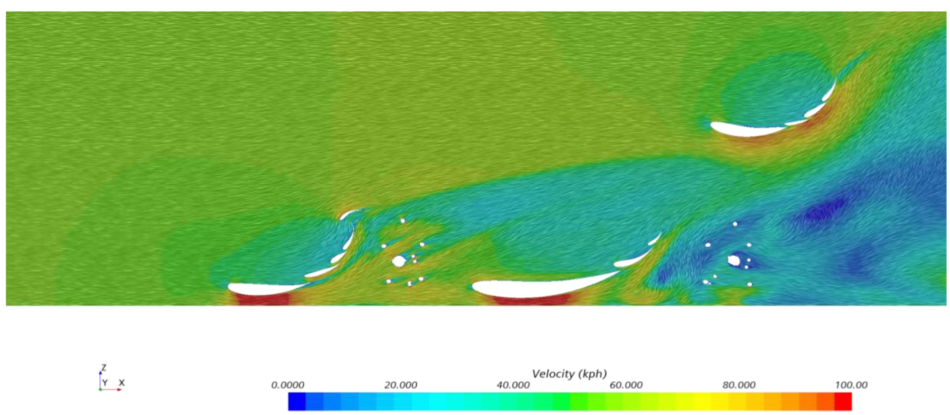


Figure 3.20: SC21 velocity scene in xz plane of the car

IGBT structure where the coldplate has four machined planes to exchange heat from the IGBTs. Very districate internal geometry of this component resulted in critical manufacturing, later described in Section 5.1. Four separate heat exchangers for each motor are designed, called cooling jackets. Extensive study has been made both for the internal geometry, a new redesign of the seals to make the assembly water tight and for the manufacturing choices. This component was critical to be optimized since in the previous prototypes they were 3D printed in PA12 MJF powder, which resulted in poor sealing and heat exchange, whilst yet having good internal flow and manufacturing repeatability.

A single radiator, internally divided for serving the two independent cooling circuits, is placed on the diffuser according to the vehicle aerodynamic concept. Such a position implies a strong dependency of the radiator airflow on the fans, which are mounted on top of the radiator by means of a 3D printed in PA12 MJF powder conveyor designed to improve the aerodynamics of the undertray and to effectively keep cool the circuit.

Both internal and external fluid dynamics are studied in CFD simulations with Simcenter STAR-CCM+ software in combination with ANSA Beta CAE as a pre-processor. Aerodynamic components design workflow is proposed in Figure 3.22.

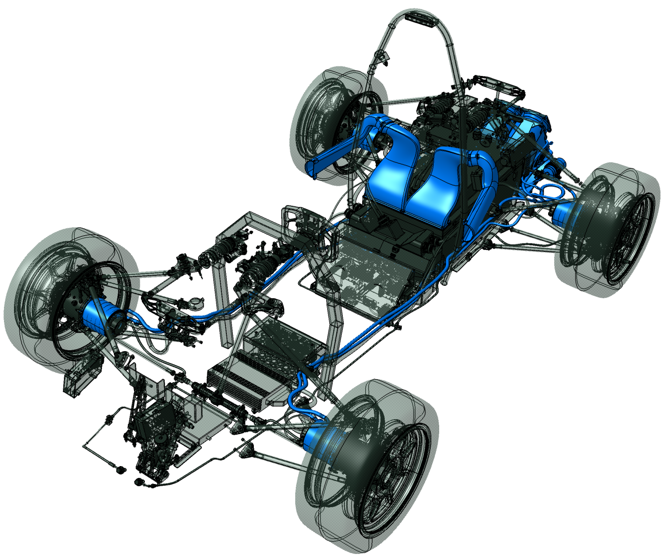


Figure 3.21: SC21 design cooling assembly

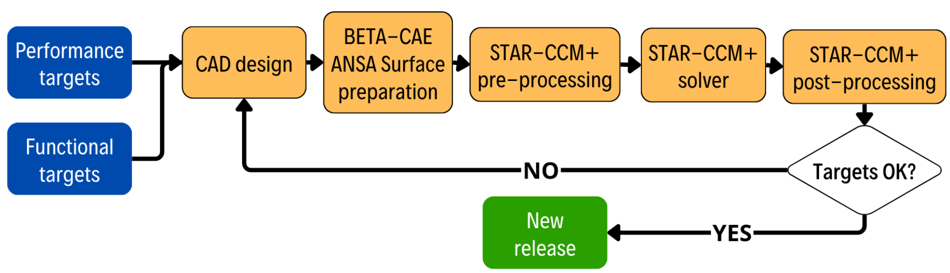


Figure 3.22: Aerodynamic component design workflow

3.6 Chassis

The monocoque is a crucial component in the automotive development since it represent the core of the vehicle where pretty much all the subsystems are mounted. The monocoque development has to follow different aspects such as structural safety, structural stiffness, driver's needs, aerodynamic constraints, manufacturability, powertrain integration constraints, unsprung masses inner hardpoints constraints.

The SC21 monocoque was completely re-designed looking at the following targets: firstly, the concept around its packaging, a deep study on different configurations has been carried out to ensure the best weight repartition (target 49% versus 45% front in SC19) and ensuring the lowest CoG height. The biggest impact is given by the tractive system positioning and the shape of the under-tray developed with the aerodynamic division. The desired CoG height has been achieved also by a custom design of the AMK inverter case positioned between the firewall and the battery pack.

The study of laminates and the monocoque characteristic dimensions has been carried out following the SES (Structural Equivalency Spreadsheet) document. Two types of pre-preg carbon fibers were adopted, one "high modulus" and one "high strength" combined with different aluminum and Nomex honeycomb densities. In correspondence of the most critical regions as suspension attachment, pedal box, cockpit opening, and steering wheel attachments, a procedure of optimization is adopted (free size and size) to minimize the compliance of the intended parts. The outcomes are CFRP plies of reinforcements to be used in the production process. Looking at weight saving, a system of CFRP and aluminum inserts has been developed. Impact Attenuator (IA), located at the front of the vehicle, is realized in aluminum honeycomb structure bonded to an Impact Attenuator Plate (IAP) realized as a carbon fiber - aluminum honeycomb sandwich panel in a similar fashion to monocoque panels.

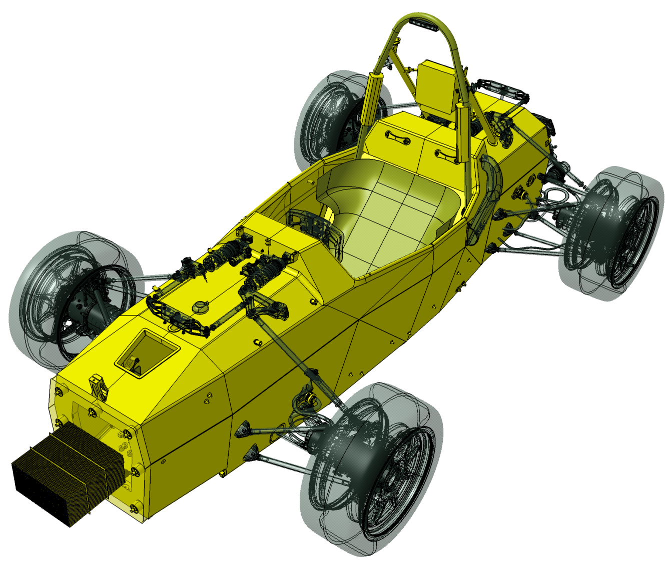


Figure 3.23: SC21 design chassis assembly

3.7 Unsprung masses

A first deployment of targets is done at assembly level, i.e. unsprung masses assembly, whereas a second one is done at sub-assembly level, e.g. uprights assembly.

Table 3.2: Unsprung masses targets

Performance targets	**Functional targets**
• Compliance minimization on suspension assembly since it affects dynamic behaviour of the vehicle • Increase reliability sufficiently high SF both on "make" and "buy" components in every load case, to ensure no break downs during events • Weight reduction where possible, without affecting reliability	• Consider other assemblies' encumbrance and clearance with their components • Make quick and easy changes to adjust vehicle setup when the car is on track • Follow directions and targets set by the dynamic division for suspension and steering assemblies • Allow adjustability of pedalbox and steering system to follow driver's ergonomics

Table 3.3: Uprights targets

Performance targets	**Functional targets**
• Lightweight components to reduce unsprung masses • High stiffness to reduce unwanted deformations that can lead to a variation of the characteristic angles • High reliability and sufficient SF to ensure working conditions in every load case	• Geometrical constraints due to surrounding components, rims, trasmission, A arms and brackets, etc. to guarantee sufficient clearance in every possible situation • Hardpoints set by the dynamic division

The suspension system is composed of a double-wishbone architecture with an anti-roll bar, hydraulic damper, and a coil spring both at the front and the rear.

The double-wishbone is made of CFRP tubes bonded to metal inserts linked to Al 7075 T6 brackets through uni-ball joints, this solution has been adopted to increase the stiffness to weight ratio of the whole lower suspension assembly and increase the reliability with respect to the previous self-made hollow CFRP A-Arms.

Rockers are topologically optimized and made of a stack of CFRP plies with Al 7075 T6 and T6Al4V bonded inserts to save weight.

Uprights have been 3D printed out of AlSi10Mg powder, to exploit the complex shape obtained from a topological optimization and increase the stiffness of this critical component. Extensive studies have been done to design these components to achieve satisfying results in terms of stiffness to strength ratio and to characterize the material according to its anisotropic properties.

Another change in the suspension assembly regards the ARB, in which a solution with a torsion bar along the z-axis and hydraulic dampers with coil springs has been adopted in order to have a simple but reliable system for both front and rear suspensions, considering that the previous cars were equipped with composite material adjustable spring knives and air dampers. With the new system to change the roll stiffness of the vehicle, it's possible to switch the torsion bar with one with a different diameter to have various torsional stiffnesses, ensuring consistent setup changes that previously were a bit tricky.

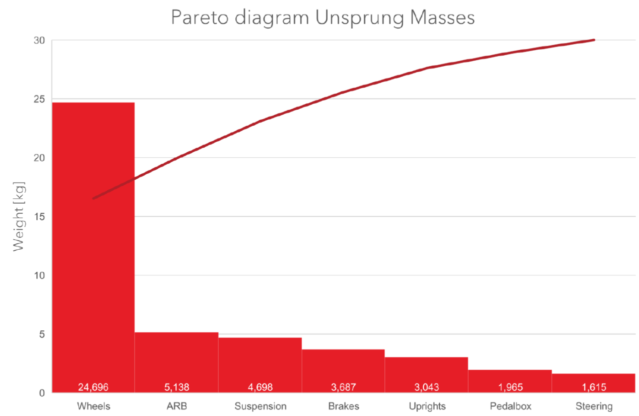
Steering assembly sees tie rods realized in CFRP as the double-wishbone CFRP tubes, linked to a very lightweight steering rack made out of Al 7075 T6. The steering column is a CFRP tube with bonded steel inserts. Double cardan joint is mounted to ensure homokinetic steering, whilst a 3D printed AlSi10Mg alloy steering support provides support to the double cardan joint.

The SC21 brakes system has two independent hydraulic circuits (front-rear) with carbon fiber braided pipes, four commercial brake calipers, and self-designed floating brake rotors. The desired brake bias is achieved through a differentiated sizing of the master cylinders and calipers, adjustable balance bar, and regenerative braking in case of further necessity. Brake rotors are 3 mm thick and have an optimized geometry in order to minimize the overheating risk, the disk geometry has been realized with waterjet-cut from sheet metal. Strenx 700 steel was chosen as the rotor's material due to its good thermo-mechanical properties and good behavior with the new Brembo brake pads compound chosen Z04, as shown by bench tests performed on the system 5.2. The Brake system is designed for the Autocross event, this is done to reduce or avoid the use of regenerative braking. On the other side during endurance, the hydraulic braking is minimized to guarantee the desired energy regeneration target.

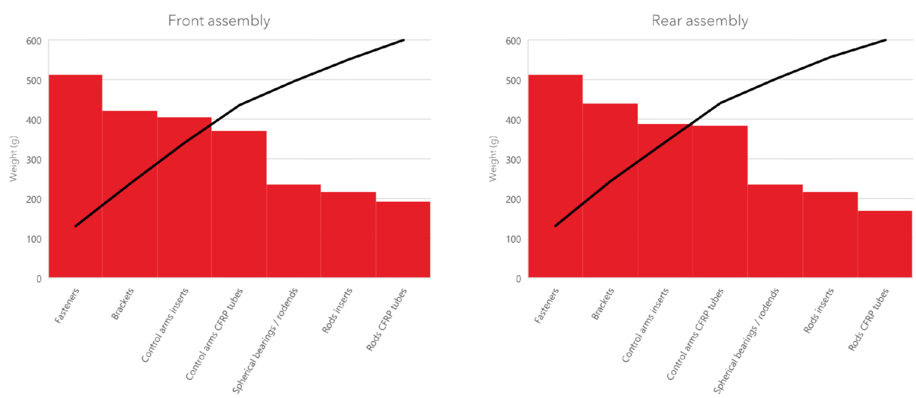
During the design of the components a workflow has to be followed. The workflow is tailored to each specific subassembly of each division. An example of workflow is proposed in Figure 3.28, where the suspension subassembly workflow is described.

Another important tool during the design is represented by the Pareto diagrams. Pareto diagrams help to effectively and rapidly see which are the main contributions to a determined outcome. Few example are proposed in Figures 3.24 and 3.34, where the mass distribution of an assembly and the whole vehicle are analysed respectively.

This tool has been largely employed in Squadra Corse history, but in my opinion it has somehow not been given its right importance during the design phase. In fact, it is easily noticeable how usually very few contributions have the largest impact



(a) Unsprung masses assembly Pareto



(b) Suspension subassembly Pareto

Figure 3.24: Unsprung masses Pareto diagrams

over an outcome. In Figure 3.24a the largest contribution over the total unsprung mass is represented by the wheels. Wheels have almost five times the contribution of ARB and suspension on their own, and the number goes up if we are considering smaller assemblies. This really makes to question again the choice of 13” wheels over the 10” ones, after what said in Section 2.3.2. From a technical point of view it is always so beneficial if the technical design focuses much more into, first of all, the most important factors of the Pareto diagrams rather than striving for weeks into saving some weight into non-crucial subassemblies of the car, with, sometimes, possible critical implications into finishing the endurance or not. At the end of the day it is more important to finish the endurance rather than having a super nice and fancy technical car that broke down. This approach has to come first of all from the technical director and the division leaders aswell, because they have a much broader view of the car compared to other Team members.

All the FEM analyses and optimizations have been carried out using Altair® HyperMesh® and Altair® Inspire® softwares. An iterative process is followed to design a component in the Verification phase of the V-cycle. FEM workflow is proposed in Figure 3.29. In Figure 3.27 the upright design workflow is proposed, the design starts from the CAD envelope that considers all the packaging constraints, moving onto the optimization results in Altair® Inspire®, the final part is first designed with polynurbs tool in Altair® Inspire® and then finished on CAD Catia V5 software.

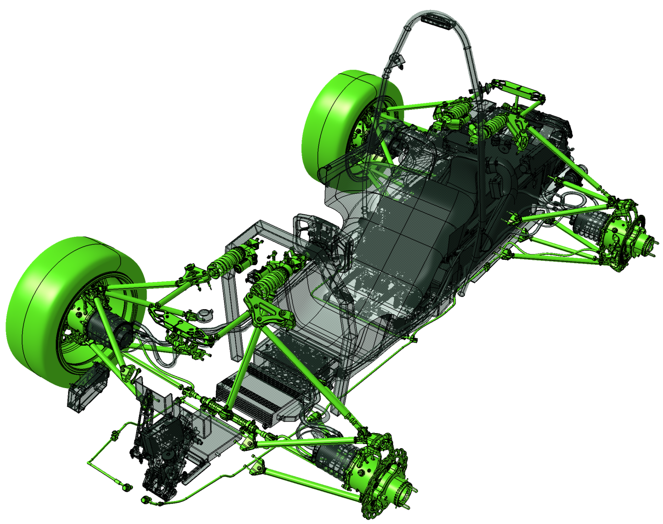
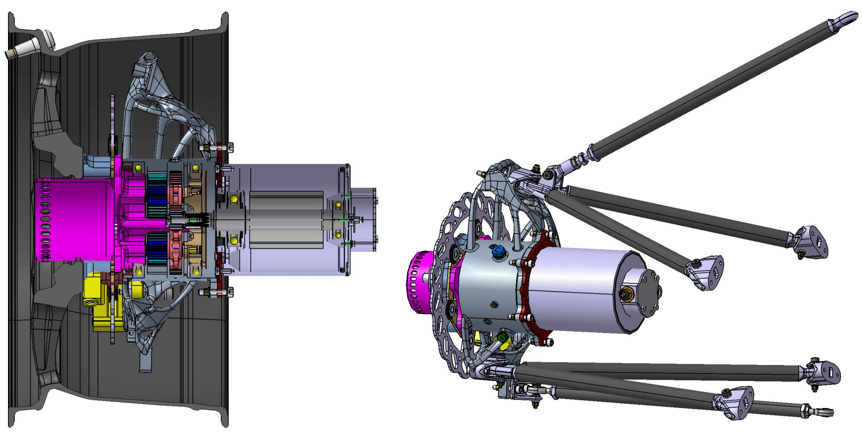
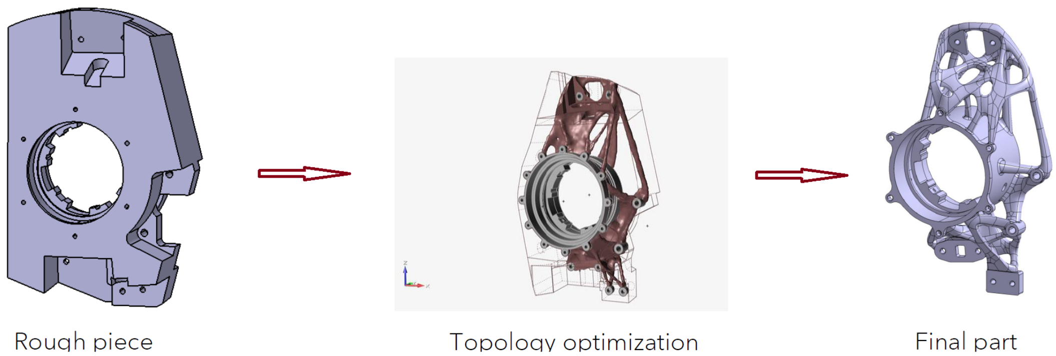


Figure 3.25: SC21 design unsprung masses assembly

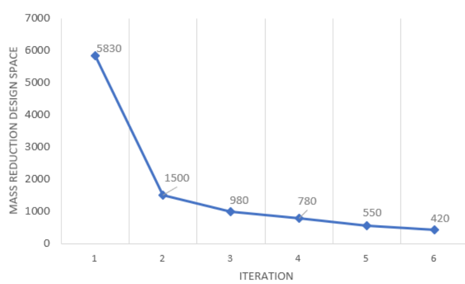


(a) **(b)**

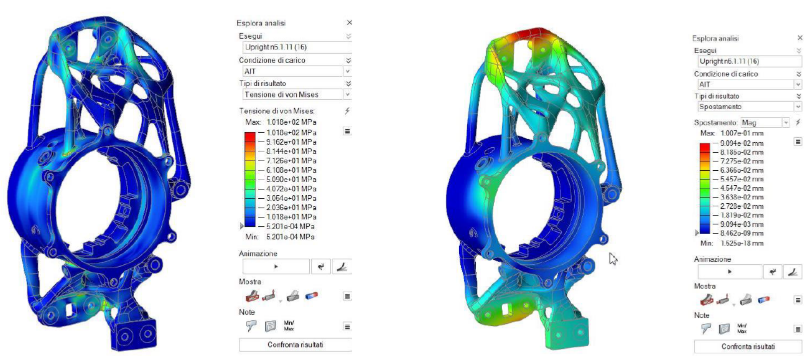
Figure 3.26: SC21 front suspension and wheel assembly



(a)



(b) Iterations necessary to achieve the final results. Mass in grams.



(c) FEM analysis results of acceleration in turn load case

Figure 3.27: Upright design

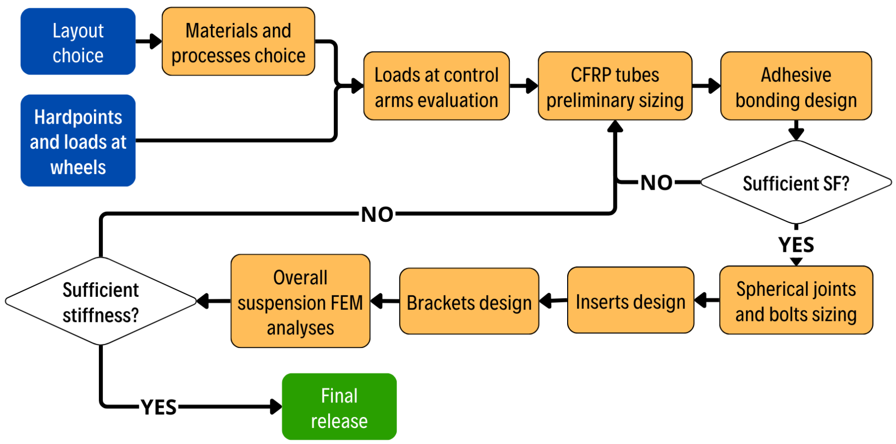


Figure 3.28: Suspension design workflow

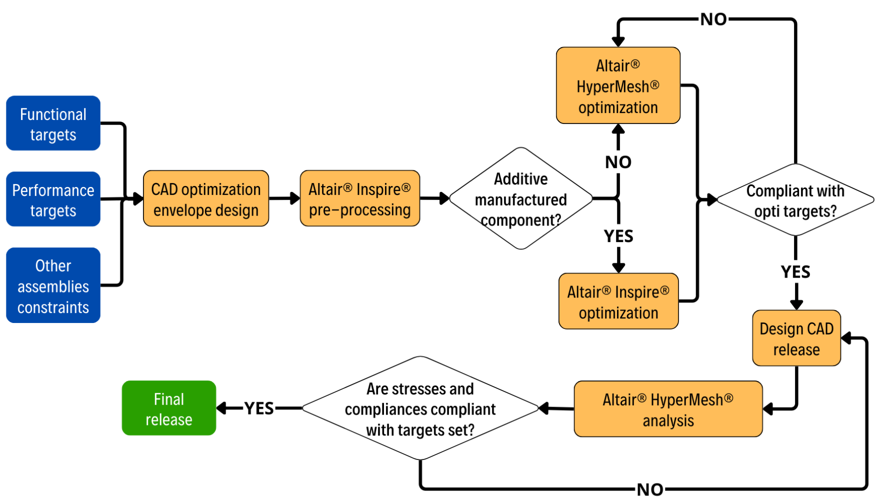


Figure 3.29: FEM component design workflow

3.8 Driver interfaces

The cockpit was redesigned starting from the results of the ergonomic test bench explained in Section 2.6 and the drivers' requests. An ergonomic CFRP seat is self-developed, along with adjustable pedals and steering wheel. The seat has been designed starting from a real driver mold. The seat is realized of CFRP plies with a variable thickness Rohacell core and dedicated inserts.

Pedalbox is adjustable in x-direction of +/- 40 mm from the 75th percentile position. Pedal themselves are realized by a combination of Al 7075 T6 topologically optimized and machined bodies with CFRP plates mounted on top to obtain an optimal yet light foot contact. Throttle pedal allows for different spring stiffness configuration and drives by-wire the throttle command. Brake pedal has two Brembo master cyclinders for front and rear circuits, with dedicated balance bar to adjust brake bias by means of a cable that reaches the cockpit. Brake pedal assembly includes a gas spring that integrates the regenerative braking with the hydraulic one, crucial task in electric vehicles.

The steering wheel is made out of CFRP and integrates a display along with different switches, allowing the driver to monitor all the crucial parameters of the car during the race and manage the vehicle in case of communication problems on the telemetry system side. Every information (motor and inverter status, temperatures, accumulator parameters, errors) is accessible in real-time to the box via a telemetry system, which also provides voice communication between driver and box. Steering wheel can be adjusted in x direction by means of dedicated CFRP spacers.

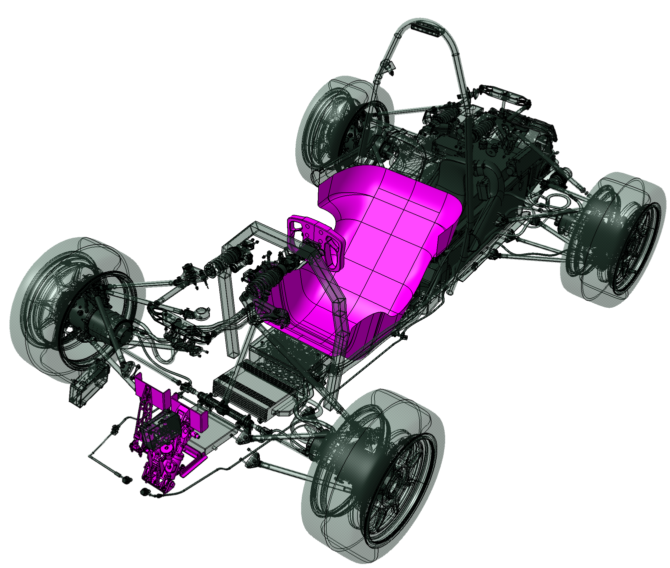


Figure 3.30: SC21 design driver interfaces assembly

3.9 Manufacturability and Serviceability

To make the most out of the available budget and to be able to quickly build the vehicle without affecting the quality level, the prototype design has been carried on considering manufacturability and ease of assembly as priorities. Guidelines on DFMA (Design For Manufacturing and Assembly) have been developed within the Team using experience and manufacturer suggestions and adopted since the beginning of the project.

3.9.1 Design for Assembly

Considering the nature and complexity of each component or system of the vehicle, proper design precautions shall be adopted.

- Reduce to minimum the number of required tools to assemble the system/device;
- Avoid requiring special tools for assembly.
- Avoid interference coupling for parts wich may require maintenance.
- If possible, design symmetrical parts.
- Avoid slight asymmetries in parts. If necessary, insert features to allow correct orientation of the part.
- If necessary, split assembly in sub-assembly each of which may be removed and disassembled independently from the others.
- Reduce to minimum small parts difficult to be handled.
- Optimize shape of parts to simplify assembly.
- Avoid parts that can not be disassembled (e.g. welded parts).
- Add features explicitly intended for simplify assembly.
- Avoid coupling between disc-shaped parts and holes.
- Always consider a proper space for tools and hand operations.
- Always consider visibility as a priority.
- Place inspection holes, covers and similar parts so that access does not require removing of other parts.
- Covers and inspection doors should be either removable or fixable in open position.
- Avoid parts which function is uniquely to couple other parts.
- Increase safety factors and reliability for items difficult to be repaired (e.g. gearboxes).

- Produce maintenance and assembly instructions for complex assemblies.
- Avoid to remove healthy units to replace faulty ones. Every sub-system of the vehicle should be independently removable.
- Avoid using "select on test" components. Systems must accomodate every delivered component within the specified tolerance band (e.g. resistors +-10%).
- If possible, prefer self-locking nuts amongst the different positive locking systems available.
- Adjustment devices must be secured with positive locking systems.

3.9.2 Design for Manufacturing

Design for Manufacturing rules are intended to reduce costs and time during production. The biggest part of a product cost is influenced by design choices, only a minimal part of it is affected by the production strategy. A correct implementation of DFM principles leads to a lead time reduction, costs reduction and sponsor supplier availability increasing.

General guidelines for DFM of mechanical parts:

- Always avoid undercuts.
- Always consider the tool radius - avoid sharp concave edges.
- Reduce to minimum the required tolerances.
- Reduce to minimum the number of different threads.
- Simplify geometry if possible.
- Always assign to the part overall dimension equal or slightly lower than "round". For example, for a cylindrical part prefer maximum diameter 149 mm rather than 151 mm.
- For simple cylindrical parts consider adopting shaft basis system.
- Reduce to minimum the number of parts in the assembly.
- Maximize the use of standard parts.
- Reduce to minimum number of different machines required for producing the part.
- Avoid features not directly feasible by the direct supplier.
- Always predict possibility to fix the part to the machine during manufacturing.
- If necessary, insert features explicitly intended to simplify manufacturing.

- Reduce to minimum number of features non-directed along principle axis identifiable in the part.
- Prefer a conical 120 degrees bottom for holes over the flat ones.

It is possible to split mechanical parts between cylindrical (manufactured by mean of lathe) and prismatic (manufactured by mean of milling machines). Even if this is a rough classifications, certain rules do apply to these categories. For cylindrical parts, it is important to:

- Avoid misalignment between features
- Insert proper relief grooves and clearly indicate them on drawing
- Avoid internal turning for long parts
- Avoid parts with L/D ratio very high or very low

For prismatic parts, it is important to:

- Reduce number of non-orthogonal faces
- Increase radius in fillets for internal features
- Avoid thin features or parts
- Prefer through-all threaded holes rather than blind ones

3.9.3 Materials

Material choice is a very important part of the design process of a component. Some critical parts need an accurate study and may be produced in some non-standard material. Most components of the vehicle does not require this effort and a standard material shall be chosen form the Table 3.4 for such parts. This standard has been developed considering cost to performance ratios, availability from suppliers and manufacturability of materials. Only major reasons should lead to use a non-standard material.

3.9.4 Fasteners

Fasteners standardization must be a priority since the early stage of design. This practice may significantly reduce service time in case of issues and possible errors during production. It also help to simplify fasteners purchasing activities. Non-standard fasteners may be adopted in case of need excluding explicitly avoided items. All fasteners should be 12.9 strength class.

General rules for fasteners material selection:

- For suspension and critical safety concerning components use steel 12.9 strength class
- For bodywork and not-critical components use steel 8.8 strength class or Aluminum Al 7075 T6 if budget allows

Steel	
General purposes	39NiCrMo3
General purposes inox	304/316
Tempering	100Cr6
Welded structures	25CrMo4
Carburizing	18NiCrMo5
Nitriding	41CrAlMo7
Aluminum	
Strength-critical parts	7075 T6 (Ergal)
Fatigue-critical parts	2024 T6 (Avional)
Non-critical and/or welded parts	6082 T6 (Anticorodal)
AM SLM parts	AlSi10Mg
Titanium	
Strength-critical parts	Ti6Al4V
Plastic	
General purpose CNC parts	POM-C
Friction-critical parts	PTFE
High temperature resistant parts	Peek
General purpose AM FDM parts	ABS
Tolerances-critical parts AM MJF parts	PA12
UL94-V0 compliant AM FDM parts	Ultem

Table 3.4: Standardized materials

- For screws and nuts where electrical insulation is concerned and non structural components are considered, use plastic to cut down weight
- For high temperature critical safety concerning components use steel 12.9 strength class with suitable coating

General rules for fasteners features:

- Prefer using standardized thread dimensions, pitch and screw lengths

Vehicle components have been divided into critical and non-critical depending on requested performances and/or failure effects. A higher cost and effort allocation preference was given to the latter and a continuous dialogue with suppliers helped to adapt them to manufacturing needs.

Great importance has been attributed to serviceability, aiming at minimizing the time wasted for troubleshooting and setting-up of the car during track tests utilizing, where possible, standardized components (e.g. suspension adjustment components are the same for front and rear). Packaging has also been studied to facilitate maintenance: accessibility has been optimized for parts or systems which are more likely to need inspection and/or removal (e.g. fuse box, HV accumulator, inverters, driver seat, etc).

Additionally, service procedures have been studied and written for the most complex systems (e.g.: gearbox) to ensure that any Team member can intervene in case of need.

Periodical inspections have been scheduled throughout the whole testing phase with detailed protocols, both from the electrical and mechanical point of view. This was done to identify possible failure causes as early as possible and reduce tests downtime, and to do preventive maintenance on the components that may be more subjected to wear.

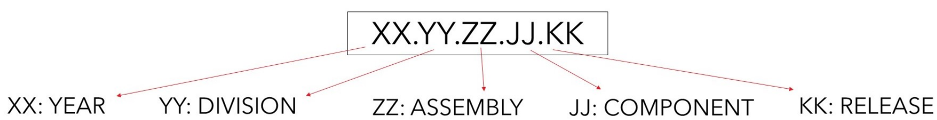
3.10 BOM

The Bill of Materials, also called BOM, is a list which contains every single component of the vehicle and every significant information about it. The BOM is one of the most powerful tools of project management. It must be daily checked and always available for every Team member. A BOM responsible should be identified for each subassembly and commissioned to keep the document updated. The BOM used in 2021 season included:

- Part Number and description
- Quantity of each part, specifying spare quantity
- Unit of measure of each part (e.g. pcs., g, ml, etc.)
- Supplier of the part
- If applicable, supplier specific Part No. or reference
- If applicable, standard with which the part complies (e.g. ISO 4762 for screws)
- If applicable, dimensions of a standard part (e.g. M4x12)
- Material and specific treatments (selectable by a list)
- The name of the part designer or responsible
- Eventual notes
- Status of the part (e.g. Design, approved, manufacturing, etc.) selectable by a predefined list which changes status color for better row visualization

It is a good practice to produce a specific BOM for each subsystem of the vehicle, in order to make each BOM easily readable. Thus, every BOM shall also include system-level information, like system name and code or competent division. The BOM must be the only document where the Part No. to Part Name correspondence is stated. The same Part No. and Part Name must be stated in the CAD data storage, so its is fundamental to update the BOM every time a change of revision or an introduction of new parts is done in the CAD system. Some additional BOMs may be produced for specific intents (e.g. fasteners BOM, individual supplier purchasing BOM, etc.).

It has to be clear by every Team member that an organized and precise attitude in redacting the BOM is of foremost importance during the Production phase, since any error present in it will cause delays and waste of resources/money when manufacturing or buying components.



CODE	DIVISION
01	Aerodynamics
02	Battery Pack
03	Chassis
04	Electric & Electronics
05	Geartrain
06	Unsprung Masses
07	Cooling
08	Vehicle Dynamics

CODE	ASSEMBLY
01	Anti Roll Bar
02	Brakes
03	CFRP Suspensions
04	Pedalbox
05	Steering
06	Steel Suspensions
07	Uprights
08	Wheels

Figure 3.31: Part No. identification code

Assembly name:	**Pedalbox**	Note:	
Assembly No:	**21.06.04**		
Division:	MNS		
Updated:	13/10/2023 18:34		
Responsible:	Bettoni		
Phone:			

Part. No.	Name	Q.ty	Spare Q.ty	Tot Q.ty	U.M.	Heat treatment	Surface treatment	Supplier	Material	Supplier Part. No.	Standard	Responsible	Note	Status
20.06.02.32.00	Banjo fitting straight	2	0	2	pcs.	-	-	Frentubo	Generic Al	-	-	Tagliavini	-	Design
20.06.04.03.04	Pedal hinge shaft	1	0	1	pcs.	-	-	Massola	Steel 39NiCrMo3	-	-	Tagliavini	-	Awaiting Approval
20.06.04.13.01	Washer pedal hinge	2	2	4	pcs.	-	-	Massola	Teflon	-	-	Tagliavini	-	Approved
20.06.04.14.00	Spring seat	2	0	2	pcs.	-	Aest. Anod.	Massola	Al 2024 T6	-	-	Tagliavini	-	stp sent to manufactur
20.06.04.16.01	Spring pin pedal	1	0	1	pcs.	-	-	Massola	Steel 39NiCrMo3	-	-	Tagliavini	-	Manufacturing
20.06.04.25.01	Heel support	2	0	2	pcs.	-	-	SC	CFRP	-	-	Tagliavini	-	Ordered
~~20.06.04.37.00~~	~~Banjo Bolt M10 x 1.0~~	~~2~~	~~0~~	~~2~~	~~pcs.~~	-	-	~~Frentubo~~	~~Generic Al~~	-	-	~~Tagliavini~~	-	~~Withdrawn~~
21.00.03.52.00	Custum washer M5x2	1	1	2	pcs.	-	Aest. Anod.	Nuova tecnomec	Al 7075 T6	-	-	Tagliavini	-	Testing
21.00.03.62.00	Custum washer M6x2	1	1	2	pcs.	-	Aest. Anod.	Nuova tecnomec	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.01.05	Throttle base	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.02.05	Throttle pedal	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.04.00	Link pedal shaft spring pin	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.09.00	Torsion spring hard right	1	1	2	pcs.	-	-	Torino spring s.a.s	Steel 10270 SH	-	-	Tagliavini	-	In Stock
21.06.04.10.00	Torsion spring hard left	1	1	2	pcs.	-	-	Torino spring s.a.s	Steel 10270 SH	-	-	Tagliavini	-	In Stock
21.06.04.12.00	Pedal hinge bushing	2	0	2	pcs.	-	-	Massola	Bronze	-	-	Tagliavini	-	In Stock
~~21.06.04.144.00~~	~~Balance bar bushing~~	~~1~~	~~0~~	~~1~~	~~pcs.~~	-	-	~~Massola~~	~~Bronze~~	-	-	~~Tagliavini~~	-	~~Withdrawn~~
21.06.04.146.02	Clevis	2	0	2	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.147.00	Balance bar	1	0	1	pcs.	-	-	Tilton Engineering	Generic steel	72-250	-	Tagliavini	-	In Stock
21.06.04.148.00	Shaft base	1	0	1	pcs.	-	-	Massola	Ti6Al4V	-	-	Tagliavini	-	In Stock
21.06.04.149.05	Gas spring lower eyelet	1	1	2	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.15.00	Locking spring washer	2	2	4	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.150.00	Gas spring	1	3	4	pcs.	-	-	Sodemann	-	GF-8-50-485 and 650	-	Tagliavini	1 spare for each lenght	In Stock
~~21.06.04.151.00~~	~~Bushing gas spring~~	~~1~~	~~1~~	~~2~~	~~pcs.~~	-	-	~~Massola~~	~~Bronze~~	-	-	~~Tagliavini~~	-	~~Withdrawn~~
21.06.04.155.07	BOTS support	1	1	2	pcs.	-	-	FCA	Nylon PA12	-	-	Tagliavini	To verify which one to use (21.06.04.155.07)	In Stock
21.06.04.157.02	Gas spring eyelet upper	1	1	2	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.158.01	BOTS prism	1	1	2	pcs.	-	-	FCA	Nylon PA12	-	-	Tagliavini	-	In Stock
21.06.04.159.00	Spacer shaft base	4	2	6	pcs.	-	Aest. Anod.	FCA	Al 6082 T6	-	-	Tagliavini	-	In Stock
21.06.04.160.00	Brake bias adjuster	1	0	1	pcs.	-	-	AP racing	Generic steel	CP2905-8	-	Tagliavini	-	In Stock
21.06.04.162.01	Screw front stop	1	1	2	pcs.	-	-	RS	Al 7075 T6	-	-	Tagliavini	7075 T6 M5 cut at 40 mm - in alternativa vite in acci	In Stock
21.06.04.167.01	Stop front	2	2	4	pcs.	-	-	Massola	Teflon	-	-	Tagliavini	-	In Stock
21.06.04.169.00	Spacer gas spring	2	2	4	pcs.	-	-	FCA	Teflon	-	-	Tagliavini	-	In Stock
21.06.04.17.00	Footing plate	1	0	1	pcs.	-		SC	CFRP	-	-	Tagliavini	-	In Stock
21.06.04.171.00	Stop rear	2	2	4	pcs.	-	-	Massola	Teflon	-	-	Tagliavini	-	In Stock
21.06.04.172.01	Remote brake bias cable screw	1	0	1	pcs.	-	-	FCA	Al 6062 T6	-	-	Tagliavini	-	In Stock
21.06.04.173.00	Gas spring mounting bar	1	3	4	pcs.	-	-	FCA	Steel AISI304	-	-	Tagliavini	-	In Stock
21.06.04.175.00	Screw rear stop	1	1	2	pcs.	-	-	RS	Al 7075 T6	-	-	Tagliavini	AL 7075 T6 M5 cut at 24 mm	In Stock
21.06.04.26.00	Link pedal shaft spring pin left	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.27.00	Spring pin spacer	2	0	2	pcs.	-	-	Massola	Teflon	-	-	Tagliavini	-	In Stock
21.06.04.50.12	Brake pedal base	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.51.16	Brake pedal	1	0	1	pcs.	-	Aest. Anod.	Massola	Al 7075 T6	-	-	Tagliavini	-	In Stock
21.06.04.52.00	Master cylinder	2	2	4	pcs.	-	-	Brembo	-	X B2.B5.11 (X B2.B5.12 and X B2.B5.13)	-	Tagliavini	-	In Stock
21.06.04.55.00	Shaft washer base hinge	2	2	4	pcs.	-	-	Massola	Teflon	-	-	Tagliavini	-	In Stock
21.06.04.62.00	Footing plate	1	0	1	pcs.	-	-	SC	CFRP	-	-	Tagliavini	-	In Stock
21.06.04.63.00	Bushing brake pedal hinge	2	0	2	pcs.	-	-	Massola	Bronze	-	-	Tagliavini	-	In Stock
21.06.04.65.00	Oil reservoir brake	2	2	4	pcs.	-	-	Brembo	Generic plastic	110A26385	-	Tagliavini	-	In Stock
21.06.04.69.00	Oil pipes brake	2	2	4	pcs.	-	-	Brembo	Generic plastic	110A26385	-	Tagliavini	-	In Stock
21.06.04.73.00	Oil reservoir support left	1	0	1	pcs.	-	-	Brembo	Generic steel	-	-	Tagliavini	-	In Stock

Figure 3.32: BOM example from pedalbox subassembly

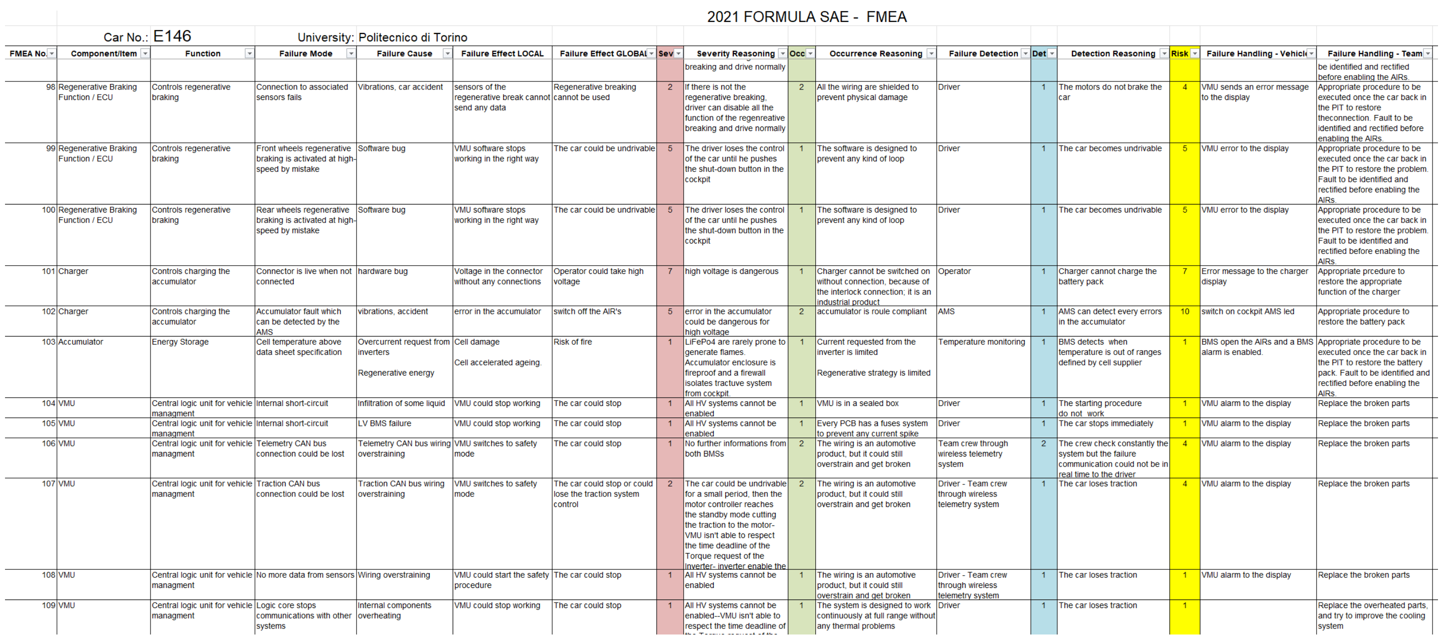
3.11 FMEA

Failure Mode and Effect Analysis, also called FMEA, is an engineering methodology tool used to identify and analyze the failure modes of a product and/or its related process and the effects these may cause both locally at component level and globally at system/vehicle level. "FMEA helps to define, identify, prioritize and eliminate known and/or potential failures of the system, design, or manufacturing process before they reach the customer with the goal of eliminating the failure modes or reduce their risks" [9].

FMEA has been performed for the whole car to manage the risk of failures and evaluate the number of spare components to be produced. For a defined item or component different potential failure modes are identified with the potential effects that may arise. A severity of the latter is chosen. Potential causes have to be identified along with their probability of occurrence. Current state-of-art design solutions to mitigate those possible failure are described along with its detection. Severity, occurrence and detection are rated on a scale of 1 to 5 and their product defines the risk associated to a potential failure mode. An explanation of the rating for severity, occurrence and detection is reported in Table 3.5.

Rating	Severity (Sev)	Occurrence (Occ)	Detection (Det)
1	No injuries may be caused, but general safety is affected by this failure	Failure occurrence is very unlikely	Certain detection of the failure
2	Light injuries may be caused by this failure	Relatively few failure occurrence	High chance of detecting this failure
3	Medium injuries may be caused by this failure	Occasional failure occurrence	Medium chance of detecting this failure
4	Heavy injuries may be caused by this failure	Frequent failure occurrence	Low chance of detecting this failure
5	Fatal injuries may be caused by this failure	Persistent failure occurrence	Failure cannot be detected

Table 3.5: FMEA ratings definition for severity, occurence and detection



2021 FORMULA SAE - FMEA

Car No.: E146 University: Politecnico di Torino

FMEA No.	Component/Item	Function	Failure Mode	Failure Cause	Failure Effect LOCAL	Failure Effect GLOBAL	Sev	Severity Reasoning	Occ	Occurrence Reasoning	Failure Detection	Det	Detection Reasoning	Risk	Failure Handling - Vehicl	Failure Handling - Team
								breaking and drive normally								be identified and rectified before enabling the AIRs.
98	Regenerative Braking Function / ECU	Controls regenerative braking	Connection to associated sensors fails	Vibrations, car accident	sensors of the regenerative break cannot send any data	Regenerative breaking cannot be used	2	If there is not the regenerative breaking, driver can disable all the function of the regenreative breaking and drive normally	2	All the wiring are shielded to prevent physical damage	Driver	1	The motors do not brake the car	4	VMU sends an error message to the display	Appropriate procedure to be executed once the car back in the PIT to restore theconnection. Fault to be identified and rectified before enabling the AIRs.
99	Regenerative Braking Function / ECU	Controls regenerative braking	Front wheels regenerative braking is activated at high-speed by mistake	Software bug	VMU software stops working in the right way	The car could be undrivable	5	The driver loses the control of the car until he pushes the shut-down button in the cockpit	1	The software is designed to prevent any kind of loop	Driver	1	The car becomes undrivable	5	VMU error to the display	Appropriate procedure to be executed once the car back in the PIT to restore the problem. Fault to be identified and rectified before enabling the AIRs.
100	Regenerative Braking Function / ECU	Controls regenerative braking	Rear wheels regenerative braking is activated at high-speed by mistake	Software bug	VMU software stops working in the right way	The car could be undrivable	5	The driver loses the control of the car until he pushes the shut-down button in the cockpit	1	The software is designed to prevent any kind of loop	Driver	1	The car becomes undrivable	5	VMU error to the display	Appropriate procedure to be executed once the car back in the PIT to restore the problem. Fault to be identified and rectified before enabling the AIRs.
101	Charger	Controls charging the accumulator	Connector is live when not connected	hardware bug	Voltage in the connector without any connections	Operator could take high voltage	7	high voltage is dangerous	1	Charger cannot be switched on without connection, because of the interlock connection; it is an industrial product	Operator	1	Charger cannot charge the battery pack	7	Error message to the charger display	Appropriate prcedure to restore the appropriate function of the charger
102	Charger	Controls charging the accumulator	Accumulator fault which can be detected by the AMS	vibrations, accident	error in the accumulator	switch off the AIR's	5	error in the accumulator could be dangerous for high voltage	2	accumulator is roule compliant	AMS	1	AMS can detect every errors in the accumulator	10	switch on cockpit AMS led	Appropriate procedure to restore the battery pack
103	Accumulator	Energy Storage	Cell temperature above data sheet specification	Overcurrent request from inverters Regenerative energy	Cell damage Cell accelerated ageing.	Risk of fire	1	LiFePo4 are rarely prone to generate flames. Accumulator enclosure is fireproof and a firewall isolates tractuve system from cockpit.	1	Current requested from the inverter is limited Regenerative strategy is limited	Temperature monitoring	1	BMS detects when temperature is out of ranges defined by cell supplier	1	BMS open the AIRs and a BMS alarm is enabled.	Appropriate procedure to be executed once the car back in the PIT to restore the battery pack. Fault to be identified and rectified before enabling the AIRs.
104	VMU	Central logic unit for vehicle managment	Internal short-circuit	Infiltration of some liquid	VMU could stop working	The car could stop	1	All HV systems cannot be enabled	1	VMU is in a sealed box	Driver	1	The starting procedure do not work	1	VMU alarm to the display	Replace the broken parts
105	VMU	Central logic unit for vehicle managment	Internal short-circuit	LV BMS failure	VMU could stop working	The car could stop	1	All HV systems cannot be enabled	1	Every PCB has a fuses system to prevent any current spike	Driver	1	The car stops immediately	1	VMU alarm to the display	Replace the broken parts
106	VMU	Central logic unit for vehicle managment	Telemetry CAN bus connection could be lost	Telemetry CAN bus wiring overstraining	VMU switches to safety mode	The car could stop	1	No further informations from both BMSs	2	The wiring is an automotive product, but it could still overstrain and get broken	Team crew through wireless telemetry system	2	The crew check constantly the system but the failure communication could not be in real time to the driver	4	VMU alarm to the display	Replace the broken parts
107	VMU	Central logic unit for vehicle managment	Traction CAN bus connection could be lost	Traction CAN bus wiring overstraining	VMU switches to safety mode	The car could stop or could lose the traction system control	2	The car could be undrivable for a small period, then the motor controller reaches the standby mode cutting the traction to the motor-VMU isn't able to respect the time deadline of the Torque request of the Inverter- inverter enable the	2	The wiring is an automotive product, but it could still overstrain and get broken	Driver - Team crew through wireless telemetry system	1	The car loses traction	4	VMU alarm to the display	Replace the broken parts
108	VMU	Central logic unit for vehicle managment	No more data from sensors	Wiring overstraining	VMU could start the safety procedure	The car could stop	1	All HV systems cannot be enabled	1	The wiring is an automotive product, but it could still overstrain and get broken	Driver - Team crew through wireless telemetry system	1	The car loses traction	1	VMU alarm to the display	Replace the broken parts
109	VMU	Central logic unit for vehicle managment	Logic core stops communications with other systems	Internal components overheating	VMU could stop working	The car could stop	1	All HV systems cannot be enabled--VMU isn't able to respect the time deadline of	1	The system is designed to work continuously at full range without any thermal problems	Driver	1	The car loses traction	1		Replace the overheated parts, and try to improve the cooling system

Figure 3.33: FMEA portion example

3.12 Design books

In Squadra Corse data management there is the implementation of the so called Design Books which are internal reports that describe thoroughly the design process, design choices, constraints, results, errors and future suggestions for improvement. They represent a standardized way to trace historically the design data of each season for each subassembly of the car. In this way, both the present and the future generations of SC can access the data with easiness and repeatability. In these reports it is fundamental to highlight all mistakes done and all design fail in order to achieve a faster growth of the project as a Team.

The structure of the Designbook is the following:

- **Heading:**
  It recalls personal information of the author.
- **Summary:**
  List of the contents of the book through a summary at the beginning of the document.
- **Overview:**
  Attach one or two CAD images to show the described subsystem and illustrate its functionality in detail.
- **Previous year layout analysis:**
  Analysis of previous year component: pictures and description of solution adopted. Briefly describe how component worked during previous year and which were its key feature (performance, reliability, ease in production, cost, ease in assembling, judges verdict, drivers feedback). In case of failure or bad behaviour, deeply describe the causes of bad performances, the causes of failure. Not only bad stuffs must be highlighted, but also positive ones.
- **Solutions benchmark:**
  Through online research, solutions seen in races and social media comparison, all design layout possibility are observed, listed and analysed. During this evaluation, cost, manufacturability, reliability (not only performances) are taken into account.
- **Target and constraints setting:**
  After the analysis of all possible layout, constraints must be fixed. Starting from FS-Rules to be respected and constraint relative to other divisions restrictions, handling, safety, assembling, manufacturer specific requests, etc. First functional targets, then performance ones are indicated and need to be reached.
- **New components design:**
  It is necessary to write a list of design steps (design workflow) adopted during design phase, then deeply analyse all of them. Personal comments, mistakes to avoid, future improvements enrich the document itself. Personal acknowledgements are most important feature to be highlighted: analytical

results, validation test, estimation of parameters, logic followed. In case of use of software (FEM or CFD analysis, kinematic simulation, thermal analysis) some model features useful for the realization of good models need to be added. Ex. (optimization procedure followed, FEM mesh details, software setting adopted). All data found on internet sites must be referenced by adding link to the site in exam. In case of CAD, all components inside an assembly must be differentiated by the use of different colours.

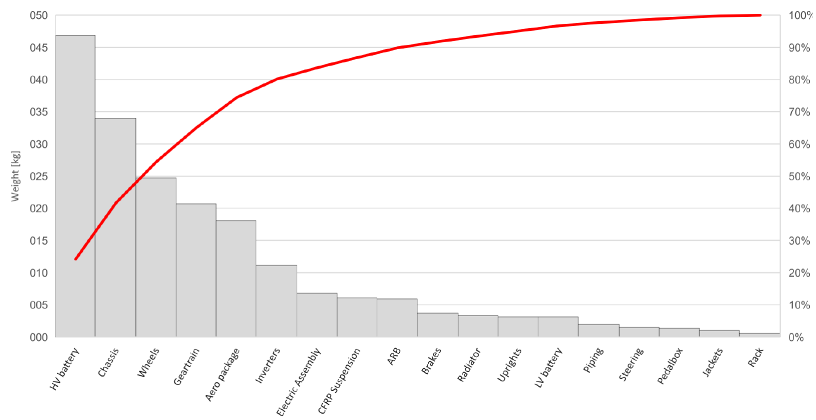


Figure 3.34: SC21 Pareto diagram

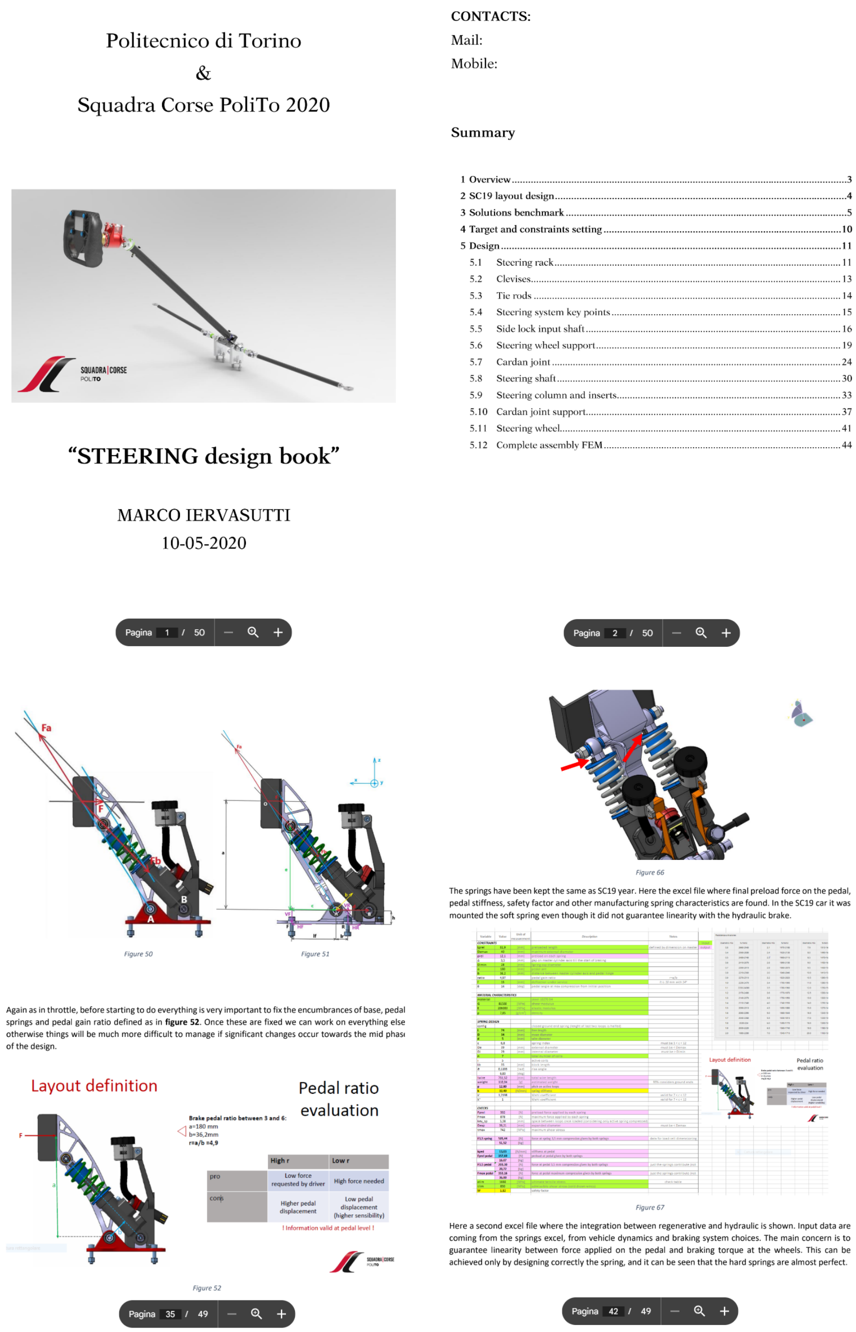


Figure 3.35: An example of pages coming from designbooks

4 Production

Production phase is referred as the phase of industrialization of the race car, being one single prototype effectively produced in real life. Looking at the V-cycle, this phase is located in the right hand side of the cycle, starting from component level that can be either validated by itself or mounted in its sub-assembly and validated with the other components. Even though design phase seems to be the most difficult one, production phase proves to be very challenging and must not be underestimated from project management point of view. Also for the Production phase, the Gantt chart has to be drawn up. The same principles apply as per the design phase with the main difference that there are external factors that can drastically change the duration of each bar, e.g. sponsors that may have considerably longer lead times than the ones expected, regional or global shortage of some components/material or some machinery failure used in manufacturing. For this reason, higher "safety factor" has to be taken into account in duration of each activity and reduce as much as possible the "finish to start" activity sequencing.

Not all the divisions end the design phase and start the production one at the same time. Critical components such as the monocoque shape design, are freezed way early in the design phase compared to other components, and thus start the production phase earlier as well. In the next sections I will divide the production in mechanical and electrical areas, analyzing their aspects, production timing and criticalities, but it is just a formal subdivision, they are both actually deeply interconnected.

4.1 Mechanical area

Mechanical area encloses all the components that are designed to be manufactured by means of traditional manufacturing technologies, such as machining processes, welding, painting, sheet metal forming, adhesive bonding, self-piercing riveting, laser cutting, water-jet cutting, metal 3D printing, plastic 3D printing.

The main workshop for SC21 season is located inside Stellantis plant in Mirafiori, less than five minutes by car distance from university campus where Squadra Corse office is located.

Services inside the plant:

- Machining operations
- Additive manufacturing

- Laser cutting
- Welding
- Metrology room
- Painting shop
- Possibility to perform tests

Advantages:

- Rapid prototyping
- Reduction of time losses related to trips toward other suppliers
- Interaction between designers and workers

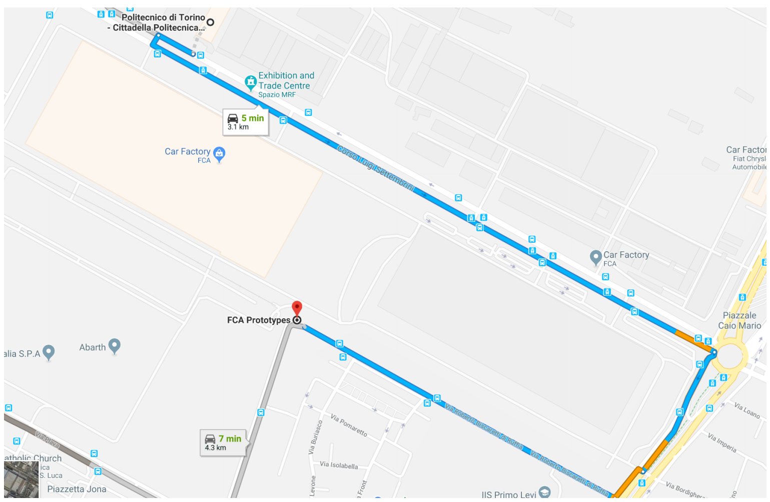


Figure 4.1: Workshop location in Torino

All the components of the car can be classified according to their policies: make, buy or co-makership. In FSAE, the most part of the components is made in-house or in co-makership due to budget and time reasons due to the fact that the Team wants to learn by doing. Bought components instead are either the ones that require huge technical knowledge to be designed (such as electric powertrain components), or the ones that from a ratio economical effort over development effort is not favorable (such as Inertial Measurement Unit), or simply standardized components (such as screws and nuts) or safety related components prescribed by rules (such as Insulation Monitoring Device).

Our components can be subdivided into more detailed categories:

1. Bought components that come ready to be assembled (BUY policy)

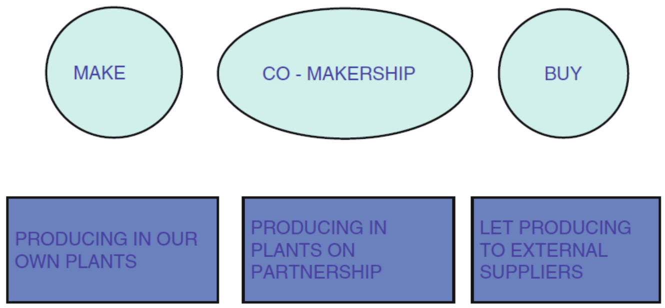


Figure 4.2: Make or buy policies [3]

2. Designed in-house but fully outsourced components that come ready to be assembled (BUY policy)

3. Designed in-house but outsourced components that require in-house finishing prior to assembly (BUY policy)

4. Designed in-house but outsourced components that require in-house preparation (BUY policy)

5. Designed in cooperation with technical partners but outsourced components where partners have complementary interest in developing new solutions (CO-MAKERSHIP policy)

6. Designed in-house and fully insourced components (MAKE policy)

Let us make an example for each category.

Product 1: A mechanical component that is typically bought are the brake master cylinders.
Product 2: The vast majority of mechanical components of unsprung masses division are of this category, such as any suspension bracket or insert.
Product 3: Typical components are 3D printed either SLM, MJF or FDM. Post processing required could be sand blasting, MJF powder removal, or supports removal. Other examples are moulds for carbon fiber parts, that require post-processing after being CNC machined, before being ready to initiate the carbon fiber lay-down.
Product 4: Typical components are carbon fiber components that need to cure in autoclave.
Product 5: An example are the suspension uprights, 3D printed in SLM in cooperation with the partner supplier. Design of these components was carried along with them, adapting our technical needs with their manufacturing constraints as well as carrying validation studies on printing process with various test specimens prior to the final print.
Product 6: Examples could be moulds realized with sheet metal cut, folded, drilled and welded, or simple components realized from metal tubes.

Inside the Gantt charts, visual recognition by colors is adopted in order to distinguish different tasks categories. Green and pink bars indicate the phase in which a component or mould is being outsourced so its length is the actual lead time of the supplier. Green bar stands for CNC machined components or moulds, instead pink ones are 3D printed. Light blue bars are the production phases where direct labor from the Team members is required either to pre or post-process a component or mould or to in-source produce a part. Grey bars indicate testing phase that is dealt with in Section 5.

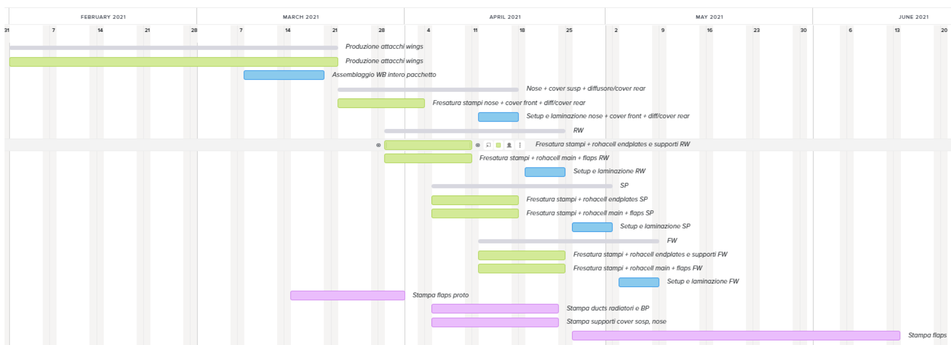


Figure 4.3: Production Gantt chart for aerodynamics

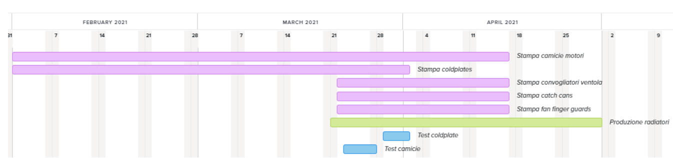


Figure 4.4: Production Gantt chart for cooling

The manufacturing of the car starts with the monocoque, first the moulds, then the monocoque itself. All the other subassemblies manufacturing go in parallel but giving priority to structural components of TS powertrain and LV battery that require prior testing before mounting them onboard. Along with these they go cooling system components and specifically inverter coldplate that needs to be mounted inside the inverter pack, and is not intended to be disassembled when the inverter pack is completed for testing. Then, continuing with the mechanical part, components that require to be mounted earlier onto the car, such as suspension, ARB, uprights are manufactured first. Components such as brake discs are manufactured earlier due to bench testing. Subassemblies such as pedalbox and steering can be manufactured later. Aerodynamic components manufacturing is not critical from the functional point of view of the vehicle, being them not essential in order to run the car, but rather from the large quantity of devices to be manufactured, with respective moulds when needed. Aero devices production of our vehicle can be mainly distinguished in PA12 MJF 3D printed components, FDM 3D printed components, pre-preg carbon fiber components and resin infusion dry carbon fiber

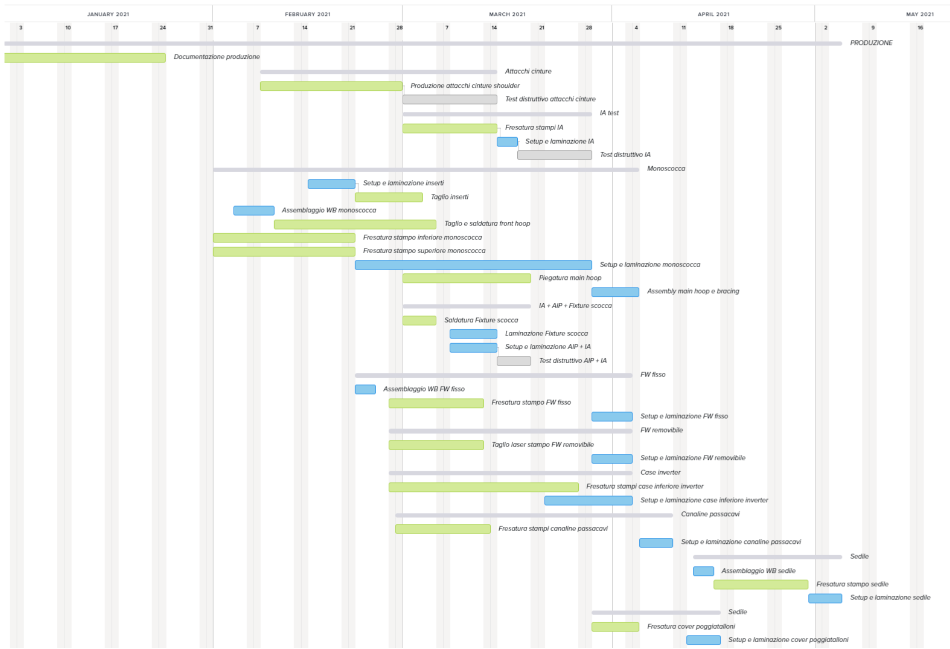


Figure 4.5: Production Gantt chart for chassis

components. The order of production follows the importance of the components, in fact front and rear wings supports, together with dedicated CNC machined or water-jet cut inserts are produced first, followed by rear cover of the car integral with the diffuser, rear wing supports, rear wing, sidepods, front wings supports, front wing. 3D printed components flow in parallel, being produced by different processes.

An important aspect of the whole production phase is that each sponsor is different. The relationship between the Team and each sponsor has to be carefully dialed in for the proper achievement of the target set. As a Team, it is important to contact the sponsor in advance, showing to him the future plans regarding both design and production/testing. It is important to have a clear idea in mind regarding the schedule of manufacturing that you expect the manufacturer to respect, prior to the production itself. It is not well seen by the manufacturer if the Team changes idea from the initial targets, rather it is important to be consistent during time. It is very important to ask the sponsor which will be the lead time expected by them, but remember than in the vast majority of the cases there will be some delays on what scheduled together. Reasons could be several, but it is important to take them into consideration when redacting a Gantt chart. Unforeseen events may always happen, and it would be great if in Squadra Corse a risk and mitigation plan would be implemented. In our case, a great example of unforeseen event that delayed a lot the production was a failure in one of our main sponsors CNC milling machine dedicated to our carbon fiber moulds.

Coming back to sponsors relationships, it is crucial to be constantly checking

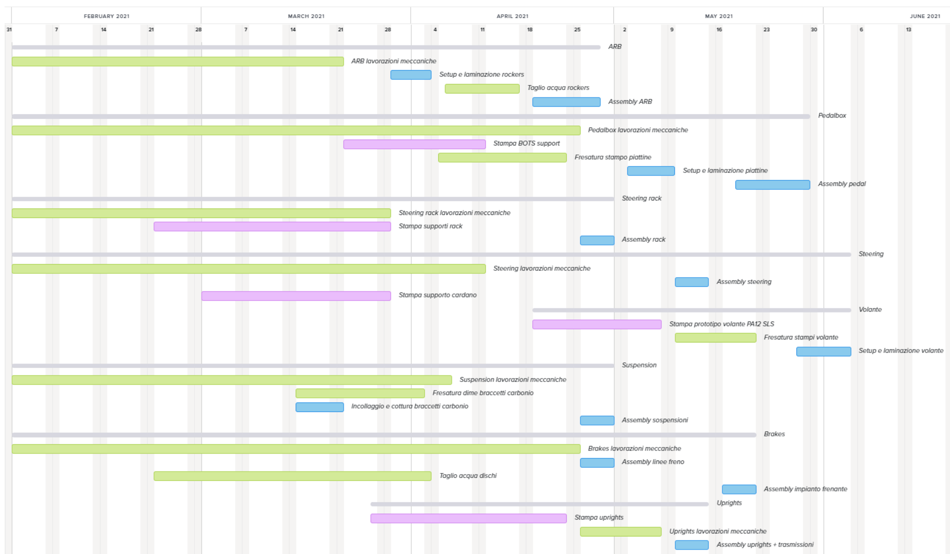


Figure 4.6: Production Gantt chart for unsprung masses

how the manufacturer process is going on in a kind but consistent way, in order to cut down some lead time. Whether it is a phone call, or an e-mail, or an online videocall, or a personal visit to the plant depending on the relationships with the sponsor: it shows interest by the Team and sometimes helps to cut down some lead time. This should be done prior to the deadline scheduled together. It is sad, understandable but true, that for several sponsors, the FSAE world comes in second place compared to real customers orders that are paying much more for the services offered in return.

Mechanical components or moulds for carbon fiber components require the following files to be manufactured:

- .stp or .igs file for 3D CAD geometry of the part
- .pdf file for 2D technical drawing
- BOM to identify quantities, part No., materials, possible treatments, notes

3D printed components require the following files to be manufactured:

- .stl file for 3D mesh geometry of the part
- .pdf file for 2D technical drawing for eventual post-processing
- BOM to identify quantities, part No., materials, possible treatments, notes

As already stated in the BOM Section 3.10, a correct redaction of the BOM is fundamental during the Production phase. Another fundamental aspect in the Production is to release correct technical drawings. In this case a double or even triple check it is worth it. Even though it may seems trivial but I want to stress on this point since in the manufacturing of our prototype I saw some errors been made just because there were errors in the drawings. It can happen when working under pressure trying to adhere to tight deadlines.

Once the components are manufactured, the subassemblies are pre-assembled as much as possible outside from the car to increase reliability and repeatibility and to be as much as possible organized, and then mounted on the car as in Figure 4.11. All the assembling operations are performed exclusively by the Team members, independently of the policy concerning the components.

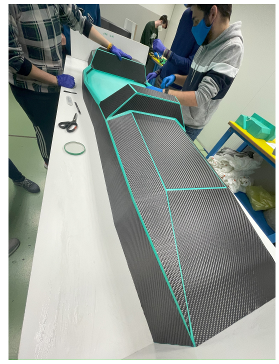
Squadra Corse PoliTo - Formula Student Electric 2021		Fornitore:	Massola	Note:	Scadenza 21.06.04.149.05 : 22/03/2021
Assembly name:	Pedalbox				
Assembly No.:	21.06.04				
Division:	Unsprung masses	Scadenza:	12/04/2021		
Updated:	08/04/2021				
Responsible:	Bettoni	Totale Codici	21		
Phone:		Totale Pezzi	43		

Part. No.	Name	Q.ty	Spare Q.ty	Tot Q.ty	Heat treatment	Surface treatment	Material	Sub Supplier	Supplier Part. No.	Standard	Notes	Status
20.06.04.03.04	Pedal hinge shaft	1	0	**1**	-	-	39NiCrMo3	-				Matematica consegnata
20.06.04.13.01	Washer pedal hinge	2	2	**4**	-	-	Teflon	-				Matematica consegnata
20.06.04.14.00	Spring seat	2	0	**2**	-	Aest. Anod.	Al 2024 T6	Lattes				Matematica consegnata
20.06.04.16.01	Spring pin pedal	1	0	**1**	-	-	39NiCrMo3	-				Matematica consegnata
21.06.04.01.05	Throttle base	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.02.05	Throttle pedal	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.04.00	Link pedal shaft spring pin RIGHT	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.12.00	Pedal hinge bushing	2	0	**2**	-	-	Bronze	-				Matematica consegnata
21.06.04.146.02	Clevis	2	0	**2**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.148.00	Shaft base	1	0	**1**	-	-	Ti6Al4V	-				Matematica consegnata
21.06.04.149.05	gas spring eyelet lower	1	1	**2**	-	Aest. Anod.	Al 7075 T6	Lattes			Scadenza: 22/03/2021	Prodotto
21.06.04.15.00	Locking spring washer	2	2	**4**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.157.02	Gas spring eyelet upper	1	1	**2**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.167.00	Stop front	2	2	**4**	-	-	Teflon	-			si valuta anche altro materiale plastico	Matematica consegnata
21.06.04.171.00	Stop rear	2	2	**4**	-	-	Teflon	-			si valuta anche altro materiale plastico	Matematica consegnata
21.06.04.26.00	Link pedal shaft spring pin LEFT	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.27.00	Spring pin spacer	2	0	**2**	-	-	Teflon	-				Matematica consegnata
21.06.04.50.12	Brake pedal base	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.51.16	Brake pedal	1	0	**1**	-	Aest. Anod.	Al 7075 T6	Lattes				Matematica consegnata
21.06.04.55.00	Shaft washer base hinge	2	2	**4**	-	-	Teflon	-				Matematica consegnata
21.06.04.63.00	Bushing brake pedal hinge	2	0	**2**	-	-	Bronze	-				Matematica consegnata

Figure 4.7: Pedalbox production BOM

(a) WB700 moulds preparation

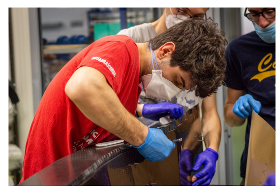
(b) WB700 moulds sanding



(c) Outershell mould lamination

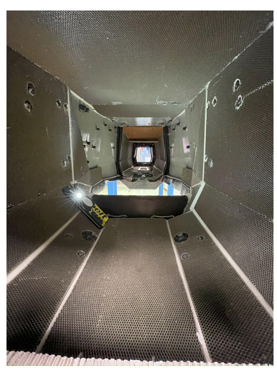
(d) Outershell mould vacuum bag

(e) CF moulds post processing

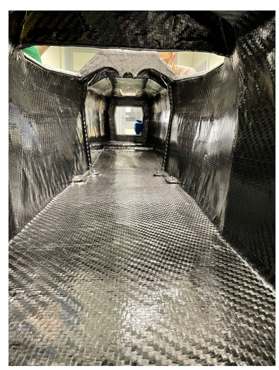


(f) Outershell lamination

(g) Outershell with inserts

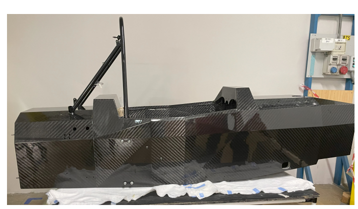


(h) Innershell core



(i) Innershell lamination

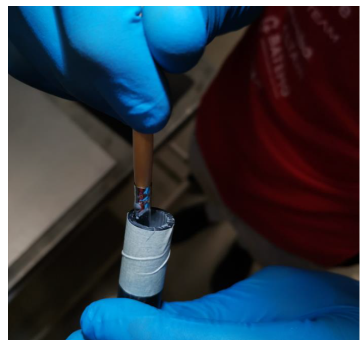
(j) Monocoque after moulds extraction



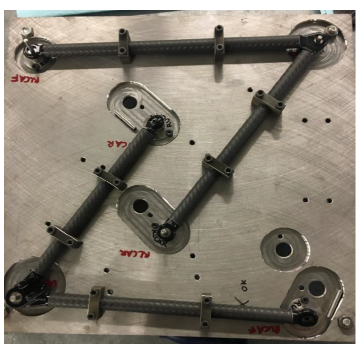
(k) Final monocoque after painting

Figure 4.8: Monocoque production

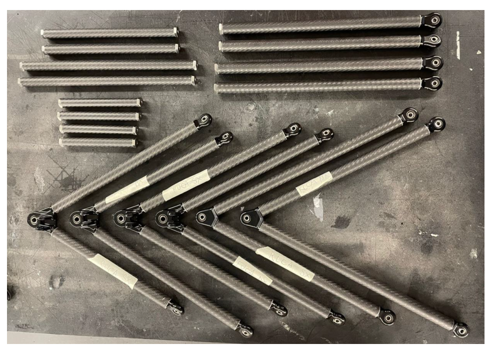
(a) Application of the epoxy resin on inserts



(b) Application of the epoxy resin on tubes

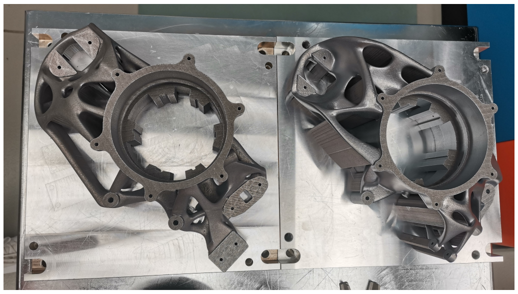


(c) Arms ready to be cured on a specifically designed mould



(d) Final arms and rods after cure

Figure 4.9: Suspension control arms production



(a) SLM front and rear printed uprights

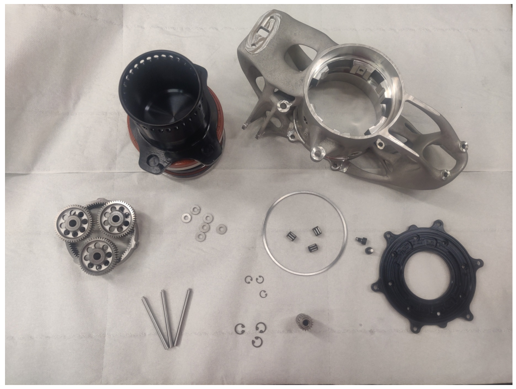
(b) Printed upright after wire EDM cut

(c) Supports removal

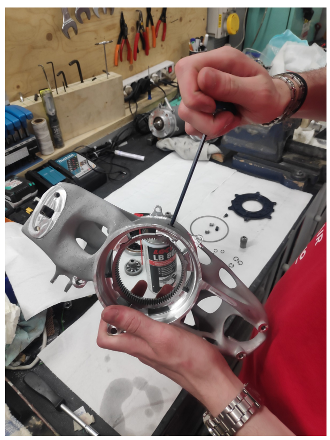
(d) Prior and after sand blasting

(e) Final upright after machining mounted on the car

Figure 4.10: Upright production



(a) Gearbox components, wheel hub and upright



(b) Ring gear mounting

(c) Carrier mounting

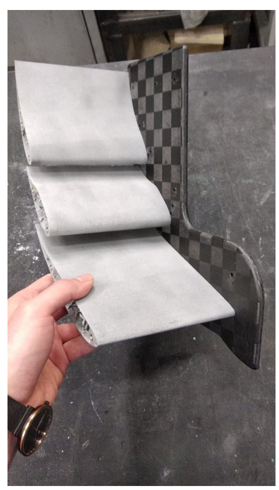
(d) Final unsprung mass assembled on the car

Figure 4.11: Gearbox assemblying

(a) Sidepod mould CNC machining

(b) Rear wing endplate lamination

(c) Post-processing of rear wing supports



(d) Assembled PA12 flaps

Figure 4.12: Aerodynamic components production

4.2 Electrical area

The production in electrical area is concerning the following aspects:

- Custom boards 2
- Semi-custom boards 5
- Commercial boards mounting 1
- HV accumulator assembling
- LV accumulator assembling
- Stock inverter pack disassembling and assembling in new configuration
- Motors mounting 1
- HV wiring harness
- LV wiring harness

First of all, electronic printed circuit boards are sent to the manufacturer in different batches, and tested as soon as they arrive to the workshop. LV wiring harness is manufactured in parallel with the boards manufacturing and testing. Once the LV wiring harness and LV accumulator are assembled and ready to be mounted on the car, LV circuits testing can start.

After the LV wiring harness manufacturing, the HV wiring harness is realized.

Inverter pack, HV accumulator and motors are assembled on their own on bench. HV accumulator manufacturing goes in parallel with the LV boards manufacturing since it takes long lead time.

LV testing continues with the remaining LV circuits, once the HV components are mounted on the car.

In the following subsections a brief description of the manufacturing in electrical area is proposed.

4.2.1 Printed Circuit Boards

Both custom and semi-custom PCBs require the following files to be manufactured in outsourcing:

- .gbr files used in CAM softwares to describe the printed circuit board images such as copper layers, solder mask, legend, drill data
- BOM of the components related to the PCB to trace the components to buy, with quantities, component codes, component types, notes
- .pdf files for 2D drawing for eventual post-inspection by the operator to check whether all the components are mounted on the PCB and the silkscreens are compliant with the specs.

Riferimento	Valore	Impronta	Specifiche	Datasheet	Footprint	PN	Technology	Qty
C1	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C2	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C3	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C4	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C7	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C8	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C9	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C13	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C16	100 n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	etail/Kyocera-AVX/08055C104KAT4A?qs=2u	user.it/datasheet/2/40/X7RDiele	zero805	08055C104KAT4A	SMD	1
C11, C12, C18, C19	10p	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	00F5GACTU?qs=%2Fha2pyFadugbiD%2F0nh	/datasheet/2/212/KEM_C1003_	zero805	C0805C100F5GACTU	SMD	4
C14	3.3n	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	il/KEMET/C0805X332K5RAC7800?qs=t6es7	sheet/2/212/1/KEM_C1062_C0G	zero805	C0805X332K5RAC780	SMD	1
C15	6.8p	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	5C689K5GACTU?qs=%2Fha2pyFaduiar9eUpc	/datasheet/2/212/KEM_C1003_	zero805	C0805C689K5GACTU	SMD	1
C17	470p	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	1K5RACAUTO?qs=%2Fha2pyFaduh4ZdT7bw	sheet/2/212/1/KEM_C1014_X7R	zero805	C0805S471K5RACAUT	SMD	1
C20, C23	330u	Capacitor_Electrolytic:UKL1V331KHD	Detail/Nichicon/UKL1V331KHD?qs=jY7%252	mouser.it/datasheet/2/293/e-uk	zero805	UKL1V331KHD	THT	2
C10, C21, C22	4.7u	Capacitor_SMD:C_0805_2012Metric	Detail/TDK/C2012X7R1H475K125AE?qs=P1J	uct/capacitor/ceramic/mlcc/cata	zero805	2012X7R1H475K125A	SMD	3
C25	1n	Capacitor_SMD:C_1206_3216Metric	1206C102KGRACAUTO/5762232?s=N4IgTCB	heet/2/212/1/KEM_C1076_X7R_	1206	1206C102KGRACAUT	SMD	1
C5, C6, C26	1u	tprints:C_0805_2012Metric_Pad1.15x1.40mm_HandSo	l/KEMET/C0805X105K5RACAUTO?qs=HBWA	sheet/2/212/1/KEM_C1062_C0G	zero805	C0805X105K5RACAUT	SMD	3
C24	100u	itor_SMD:C_1210_3225Metric_Pad1.42x2.65mm_Hand	CL32A107MPVNNNE?qs=%2Fha2pyFaduhgy	mouser.it/datasheet/2/585/MLC	1210	CL32A107MPVNNNE	SMD	1
C27	100u	Capacitor_SMD:C_1210_3225Metric	CL32A107MPVNNNE?qs=%2Fha2pyFaduhgy	mouser.it/datasheet/2/585/MLC	1210	CL32A107MPVNNNE	SMD	1
C277	100n	Capacitor_SMD:C_0402_1005Metric	ics/CL05A104KA5NNNC?qs=%2Fha2pyFaduh	mouser.it/datasheet/2/585/MLC	zero402	CL05A104KA5NNNC	SMD	1
D1	LED_RAGB	R+E22:W22GB_Led:AAA3528	GKQBKS?qs=%2Fha2pyFaduj9RYOG0SVas6%	t/datasheet/2/216/AAA3528LSE	otprint:Kingbright PLC	AAA3528LSEEZGKQBK	SMD	1
D2	0,7V	footprints:D_SMB	l/diodes-incorporated/B240-13-F/717690?s	datasheet/2/115/DIOD_S_A0001	SMB	B240-13-F	SMD	1
D3	1N4448WS	DiodoCAN:DiodoCAN	emi/1N4448WS?qs=sGAEpiMZZMvxX9Q80w	ser.it/datasheet/2/308/1N914BV	DO-41_SOD81_P10.16	1N4448WS	SMD	1
D4	APT2012LVBC/D	prints:LED_0805_2012Metric_Pad1.15x1.40mm_HandS	12LVBC-D?qs=%2Fha2pyFaduiHa94wCqtxl%	er.it/datasheet/2/216/APT2012L	zero805	APT2012LVBC/D	SMD	1
D5	APT2012LSYCK/J3-PRV	prints:LED_0805_2012Metric_Pad1.15x1.40mm_HandS	LSYCK-J3-PRV?qs=%2Fha2pyFaduiHa94wCq	t/datasheet/2/216/APT2012LSY	zero805	APT2012LSYCK/J3-PRV	SMD	1
D6	APT2012LSECK/J4-PRV	prints:LED_0805_2012Metric_Pad1.15x1.40mm_HandS	K-J4-PRV?qs=%2Fha2pyFaduiHa94wCqtxlxIE	t/datasheet/2/216/APT2012LSY	zero805	APT2012LSECK/J4-PRV	SMD	1
DCAN1	24V	PESD2CAN_215:SOT95P230X110-3N	w.mouser.it/datasheet/2/916/PESD2CAN-1	user.it/datasheet/2/916/PESD2	SOT23	PESD2CAN,215	SMD	1
DZ3	30,4V	footprints:D_SMA	electronics/SM4T30AY?qs=%2Fha2pyFaduja	user.it/datasheet/2/389/cd00283		SM4T30AY	SMD	1
F1-F10	2A	SF-1206SA200M-2:FUSC3216X105N	06SA200M-2?qs=%2Fha2pyFadui3e7VY5wdF	ns.com/docs/product-datasheet	1206	SF-1206SA200M	SMD	10
J4-J9	VSENSE	footprints:SENSE_SC19			footprints:SENSE_SC19	No mounting	No mounting	6
TH1-TH6	NTC	footprints:NTC_SC19			footprint:NTC_SC19	No mounting	No mounting	6
J2	n_02x20_Counter_Cloc	footprints:Conettore_voltaggi_SC17	-L-D-TH-DS?qs=%2Fha2pyFadugnZ2%2Fzob%	mouser.it/datasheet/2/527/mtsw	o-Fit_105310-xx06_2x	T2M-120-01-L-D-TH-D	THT	1
J1, J3, J15	EC-HMTSW-102-07-G-	footprints:SAMTEC_HMTSW-102-XX-X-S-XXX	2-07-G-S-210?qs=%2Fha2pyFadujHVfw9vlnw	mouser.it/datasheet/2/527/mtsw		MTSW-102-07-G-S-210	THT	3
J10	BAT+	ints:Molex_Mega-Fit_76825-0002_2x01_P5.70mm_Hor	064-0002?qs=%2Fha2pyFaduj7cOb8xtj%2F2	atasheet/2/276/1/1720640002_	Mega-Fit_76825-0002_	1720640002	THT	1
J11	CAR+	ints:Molex_Mega-Fit_76825-0002_2x01_P5.70mm_Hor	064-0002?qs=%2Fha2pyFaduj7cOb8xtj%2F2	atasheet/2/276/1/1720640002_	Mega-Fit_76825-0002_	1720640002	THT	1
J17	BAT	ints:Molex_Mega-Fit_76825-0002_2x01_P5.70mm_Hor	064-0002?qs=%2Fha2pyFaduj7cOb8xtj%2F2	atasheet/2/276/1/1720640002_	Mega-Fit_76825-0002_	1720640002	THT	1
J18	CAR	ints:Molex_Mega-Fit_76825-0002_2x01_P5.70mm_Hor	064-0002?qs=%2Fha2pyFaduj7cOb8xtj%2F2	atasheet/2/276/1/1720640002_	Mega-Fit_76825-0002_	1720640002	THT	1
J12	onn_02x05_Top_Botto	footprints:SAMTEC_FTSH-105-XX-X-DV	l/Samtec/FTSH-105-01-L-DV-K?qs=%252B5J	ouser.it/datasheet/2/527/ftsh_s	2.00mm:PinHeader_2	FTSH-105-01-L-DV-K	SMD	1
J13	_02x03_Counter_Cloc	rints:Molex_Nano-Fit_105310-xx06_2x03_P2.50mm_V	1306?qs=%2Fha2pyFadugmVNpkddi38Ceen	tasheet/2/276/1/1053101306_P	Nano-Fit_105310-xx0	105310-1306	THT	1
J14	CONN-2x4	Molex8pin:1053101108	310-2108?qs=%2Fha2pyFadugCKtB3Ok15vk	tasheet/2/276/2/1053102108_P		105310-2108	THT	1
J16	CONNECT_REAKTOR	Connect_Reaktor:SSM-104-XXX-DV	tDetail/Samtec/SSM-104-L-DV?qs=rU5fayqh	ouser.it/datasheet/2/527/ssm_s		SSM-104-L-DV	SMD	1
L2	100u	footprints:ACT45B	tDetail/TDK/ACT45B-101-2P-TL003?qs=SKgu	t/emc/emc/cmf_cmc/catalog/cm	footprint:ACT45B	ACT45B-101-2P-TL003	SMD	1
L3	2,2u	footprints:IND_SRP4020TA-2R2M	R2M?qs=%2Fha2pyFaduhBEh%252BdUzy7M	ouser.it/datasheet/2/54/srp4020	zero402	SRP4020TA-2R2M	SMD	1
L1, L4	L_Core_Ferrite	Core_Ferrite:BEADC1608X95N	S600-T?qs=%2Fha2pyFadujm%252BE34RrZF	ouser.it/datasheet/2/396/mlci08	zero603	BKP1608HS600-T	SMD	2
PS1	-Q24-S5-D-PDQE15-Q	footprints:CONV_PDQE15-Q24-S5-D	5-Q24-S5-D?qs=%2Fha2pyFaduhzyRbfJe98R	ouser.it/datasheet/2/670/pdqe15	ONV_PDQE15-Q24-S5-	PDQE15-Q24-S5-D	THT	1
Q1-Q8	NMOS	Mosfet:SOT65P210X110-3N	-Incorporated/BSS138W-7-F?qs=%2Fha2pyF	a.diodes.com/assets/Datasheets/	SOT-323	BSS138W-7-F	SMD	8
Q9	NMOS_GSD	footprints:SOT-323_SC-70	3K48FULF?qs=%2Fha2pyFadugx3N29WhLxk	heet/2/408/SSM3K48FU_datashe	USM-3	SSM3K48FU	SMD	1

Figure 4.13: Production BOM BMS LV

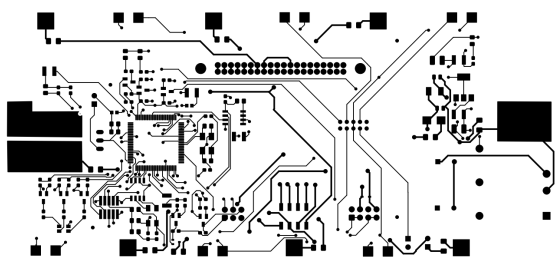


Figure 4.14: Production .pdf F-Cu BMS LV

4.2.2 HV accumulator assembling

HV accumulator starts from the HV parts and therefore all the 3D printing of casings and covers required to hold the cells in place, together with the cells selection and pre-processing (tabs punch and fold) once the casings are produced. Busbars are mounted with mechanical connection and remaining sensors/parts are added, along with LV boards to conclude the assembly of the modules.

Manufacturing of HV accumulator casing follows a similar process of other carbon fiber parts, having to realize the WB700 positive moulds, carbon fiber negative moulds and final carbon fiber casings. All the modules are ready to be mounted inside the casing in order to test the HV accumulator as a whole alone and in the car.

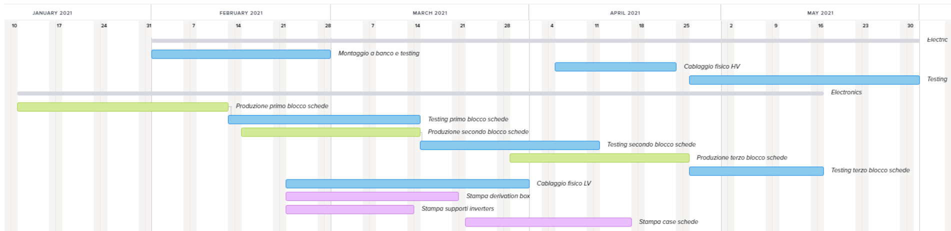


Figure 4.15: Production Gantt chart for electronics

4.2.3 LV accumulator assembling

Similar approach is adopted for the LV accumulator, with the difference of being simpler in terms of manufacturing, and of safety/operations due to the low voltage. The main difference is about the layout of the accumulator being used Li-Ion cells instead of Li-Po ones, the cells are bonded in between two CNC machined cells housings. After bonding, the cells connection are realized with wire bonding technique, that is beneficial both for the low resistance, the low weight and the safety of the accumulator. Final wiring and BMS LV are mounted to complete the pack.

4.2.4 Inverter pack

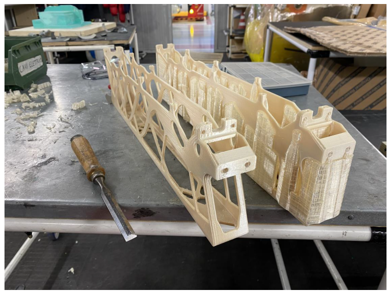
The stock inverter pack is completely disassembled in order to extract all the boards and components present inside it and reassembled in our configuration. All the wiring harness is rebuilt from scratch to accommodate the new packaging. The new coldplate is installed as well in between the power modules.

4.2.5 Wiring harness

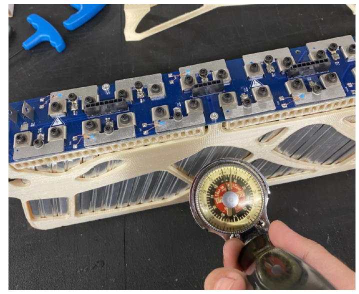
Wiring harness construction is a crucial activity, that will significantly affect the vehicle reliability. Following rules and practices must be applied while assembling vehicle wiring, with the aim of reducing errors and to simplify troubleshooting.

Wiring harness production starts from the documents reported in Section 3.3. The rules and tips that shall be adopted are the following:

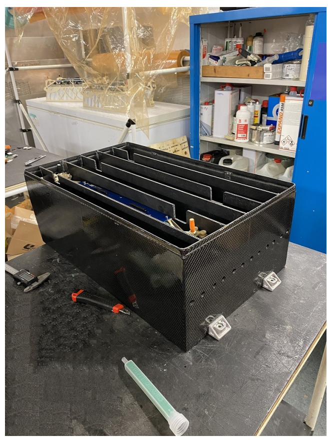
- Wiring harness working area must result in a clean and organized environment. Tools and materials that are not essential should not be present in the working area.
- Tools must be selected and tested before use on vehicle wiring
- A proper amount of spare pins must be purchased before starting wiring production
- Wiring must be constructed over a full scale 2D template generated starting from the 3D mock-up



(a) Ultem FDM printed HV cells housings



(b) Cells mounted with HV BCM board and screws tightening



(c) HV CF accumulator housing

(d) HV modules mounted inside CF accumulator housing

(e) Final HV accumulator

Figure 4.16: HV accumulator production

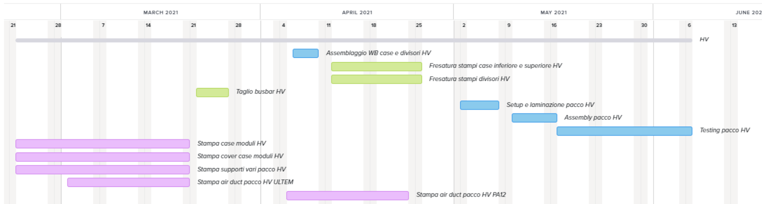


Figure 4.17: Production Gantt chart for HV accumulator

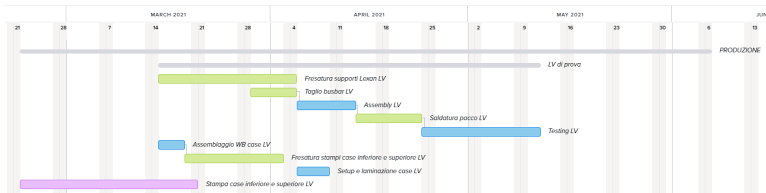
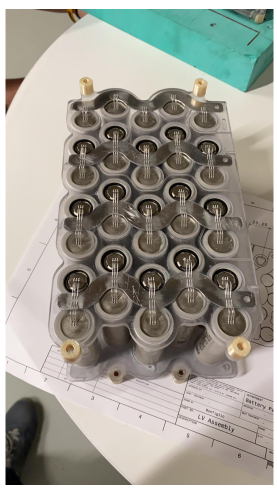


Figure 4.18: Production Gantt chart for LV accumulator

- Temporary identification labels shall be used to identify wires during harnesses construction. Connector identification code and pin number must be indicated in such labels
- Every connection must be tested before and after connectors crimping
- Insulation tape is prohibited in harnesses construction
- Avoid Ground Loops and Delta-connections for ground wiring
- Harnesses must be laced with plastic tie-zips
- T or X joints must be securely tied with plastic tie-zips in order to prevent unwanted wire strains
- Proper strain relief solution must be adopted for every connector. Service loop technique is preferred for connectors with more than 5 wires
- Connector shells shall be connected to vehicle ground using internal pins if possible - this applies for both male and female part of the connector. Metal connector shells must be grounded if placed at less than 100 mm from TS according to FS Rules anyway
- Metallic parts must be grounded using wires. Copper tape should be used only where no alternatives exist
- Avoid soldering in harnesses construction, always prefer crimped connections
- If soldering is strictly needed, always perform lashing on tinned conductors before soldering
- Always protect connections using heat-shrinkable sleeve

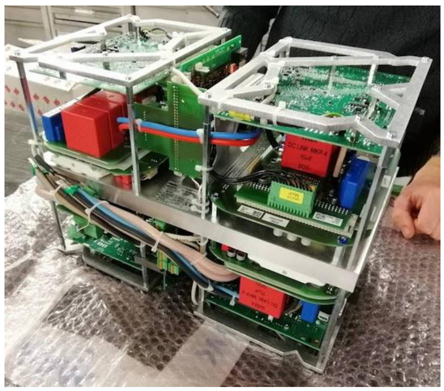
(a) LV accumulator cells bonding



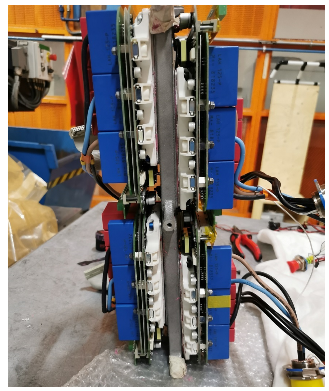
(b) Cells and tabs mounted on housings, wire-bonded cells

(c) Final LV accumulator mounted in the car

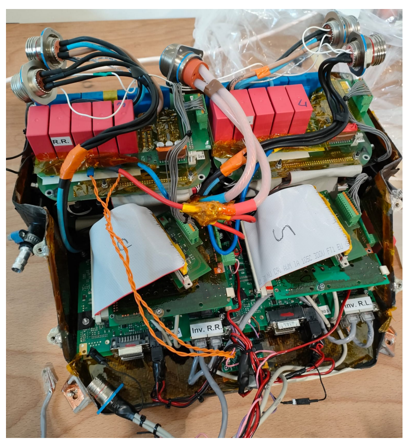
Figure 4.19: LV accumulator production



(a) Stock AMK inverter pack



(b) AMK inverter power modules assembled over coldplate



(c) AMK inverter assembled inside custom CF housing

Figure 4.20: Inverter pack assembly

- Always put crimped connections and splices in straight portions of harness and protect them from strain installing zip-ties before and after the connection
- Every harness must be protected using plastic or fabric braid
- Always connect brides at junctions using proper fabric tape
- Always reverse outside-in braid at its end and install heat shrinkable sleeves to prevent braid damage and wires exposition
- While installing heat-shrinkable sleeves at connectors, never cover the grip part of connector
- Shielded or foiled cables must be used for CAN Bus
- CAN Bus must be terminated with a 120 Ohm resistance at the starting and ending point of the chain
- CAN Bus cable shield must be connected to ground either at the starting or at the ending point of the chain
- Always install CAN Bus in parallel configuration in order to let the system tolerate load failure. If possible, split bus inside connector or in the immediately adjacent area. Avoid long T junctions in CAN Bus
- Special shielding with steel braid for crucial signals (e.g. motor encoders)
- Crimped connections must be mechanically tested while setting crimping tools and before starting cabling construction.
- Every crimped pin must be visually inspected and manually tested for mechanical strength
- Cables and connector must be designed to be as small and light as possible, adopting an appropriate wire gauge
- Harnesses must be marked so is possible to identify every part of the cabling
- Connectors must be marked so is possible to correctly match connections

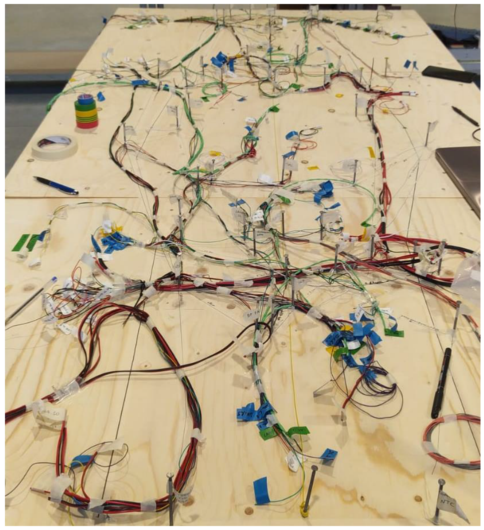
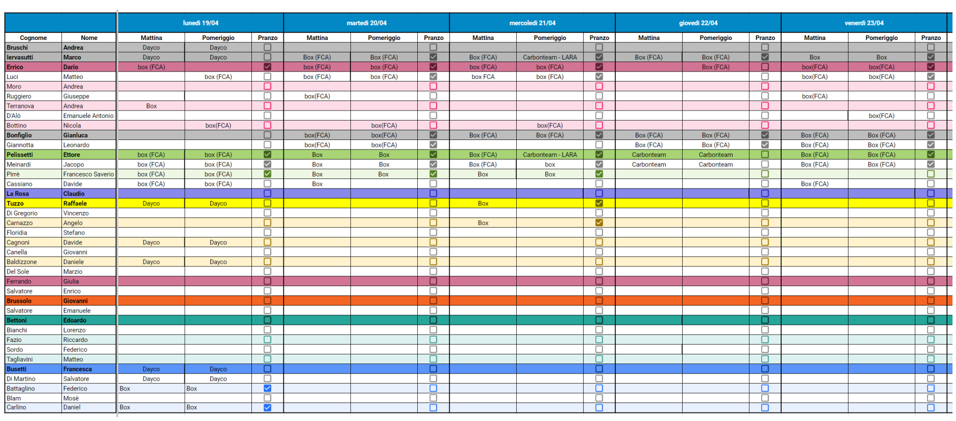


Figure 4.21: LV wiring harness production

4.3 Additional tools and documents

From an organizational and logistic point of view, a simple Google sheet is employed where, for each day of the week and for all the production duration, each Team member is entitled to write in which location he/she will be present. The datasheet serves both as an attendance check tool and as an organizational tool for the division leaders and board to better direct the human resources available day by day, in order to not create overcrowding or undercrowding situations in the workshop.



		lunedì 19/04			martedì 20/04			mercoledì 21/04			giovedì 22/04			venerdì 23/04		
Cognome	Nome	Mattina	Pomeriggio	Pranzo	Mattina	Pomeriggio	Pranzo	Mattina	Pomeriggio	Pranzo	Mattina	Pomeriggio	Pranzo	Mattina	Pomeriggio	Pranzo
Bruschi	**Andrea**	Dayco	Dayco	☐			☐			☐			☐			☐
Iervasutti	**Marco**	Dayco	Dayco	☐	Box (FCA)	Box (FCA)	☑	Box (FCA)	Carbonteam - LARA	☑	Box (FCA)	Box (FCA)	☑	Box	Box	☑
Errico	**Dario**	box (FCA)		☑	box (FCA)	box (FCA)	☑	box (FCA)	box (FCA)	☑		Box (FCA)	☐	box(FCA)	box(FCA)	☑
Luci	Matteo		box (FCA)	☐	box (FCA)	box (FCA)	☑	box FCA	box (FCA)	☑			☐	box(FCA)	box(FCA)	☑
Moro	Andrea			☐			☐			☐			☐			☐
Ruggiero	Giuseppe			☐	box(FCA)		☐			☐			☐	box(FCA)		☐
Terranova	Andrea	Box		☐			☐			☐			☐			☐
D'Alò	Emanuele Antonio			☐			☐			☐			☐		box(FCA)	☐
Bottino	Nicola		box(FCA)	☐		box(FCA)	☐		box(FCA)	☐			☐			☐
Bonfiglio	**Gianluca**			☐	box(FCA)	box(FCA)	☑	Box (FCA)	Box (FCA)	☑	Box (FCA)	Box (FCA)	☑	Box (FCA)	Box (FCA)	☑
Giannotta	Leonardo			☐	box(FCA)	box(FCA)	☑			☐	Box (FCA)	Box (FCA)	☑	Box (FCA)	Box (FCA)	☑
Pelissetti	**Ettore**	box (FCA)	box (FCA)	☑	Box	Box	☑	Box (FCA)	Carbonteam - LARA	☑	Carbonteam	Carbonteam	☐	Box (FCA)	Box (FCA)	☑
Meinardi	Jacopo	box (FCA)	box (FCA)	☑	Box	Box	☑	Box (FCA)	box	☑	Carbonteam	Carbonteam	☐	Box (FCA)	Box (FCA)	☑
Pirrè	Francesco Saverio	box (FCA)	box (FCA)	☑	Box	Box	☑	Box	Box	☑			☐			☐
Cassiano	Davide	box (FCA)	box (FCA)	☐	Box		☐			☐			☐	Box (FCA)		☐
La Rosa	**Claudio**			☐			☐			☐			☐			☐
Tuzzo	**Raffaele**	Dayco	Dayco	☐			☐	Box		☑			☐			☐
Di Gregorio	Vincenzo			☐			☐			☐			☐			☐
Carnazzo	Angelo			☐			☐	Box		☑			☐			☐
Floridia	Stefano			☐			☐			☐			☐			☐
Cagnoni	Davide	Dayco	Dayco	☐			☐			☐			☐			☐
Canella	Giovanni			☐			☐			☐			☐			☐
Baldizzone	Daniele	Dayco	Dayco	☐			☐			☐			☐			☐
Del Sole	Marzio			☐			☐			☐			☐			☐
Ferrando	Giulia			☐			☐			☐			☐			☐
Salvatore	Enrico			☐			☐			☐			☐			☐
Brussolo	**Giovanni**			☐			☐			☐			☐			☐
Salvatore	Emanuele			☐			☐			☐			☐			☐
Bettoni	**Edoardo**			☐			☐			☐			☐			☐
Bianchi	Lorenzo			☐			☐			☐			☐			☐
Fazio	Riccardo			☐			☐			☐			☐			☐
Sordo	Federico			☐			☐			☐			☐			☐
Tagliavini	Matteo			☐			☐			☐			☐			☐
Busetti	**Francesca**	Dayco	Dayco	☐			☐			☐			☐			☐
Di Martino	Salvatore	Dayco	Dayco	☐			☐			☐			☐			☐
Battaglino	Federico	Box	Box	☑			☐			☐			☐			☐
Blam	Mosè			☐			☐			☐			☐			☐
Carlino	Daniel	Box	Box	☑			☐			☐			☐			☐

Figure 4.22: Production Team members attendance

In order to correctly manage the material and items present in the workshop, an inventory has to be drawn up and constantly monitored and updated. All the items are catalogued in a single document where they are subdivided according to their types in different sheets as per the following subdivision:

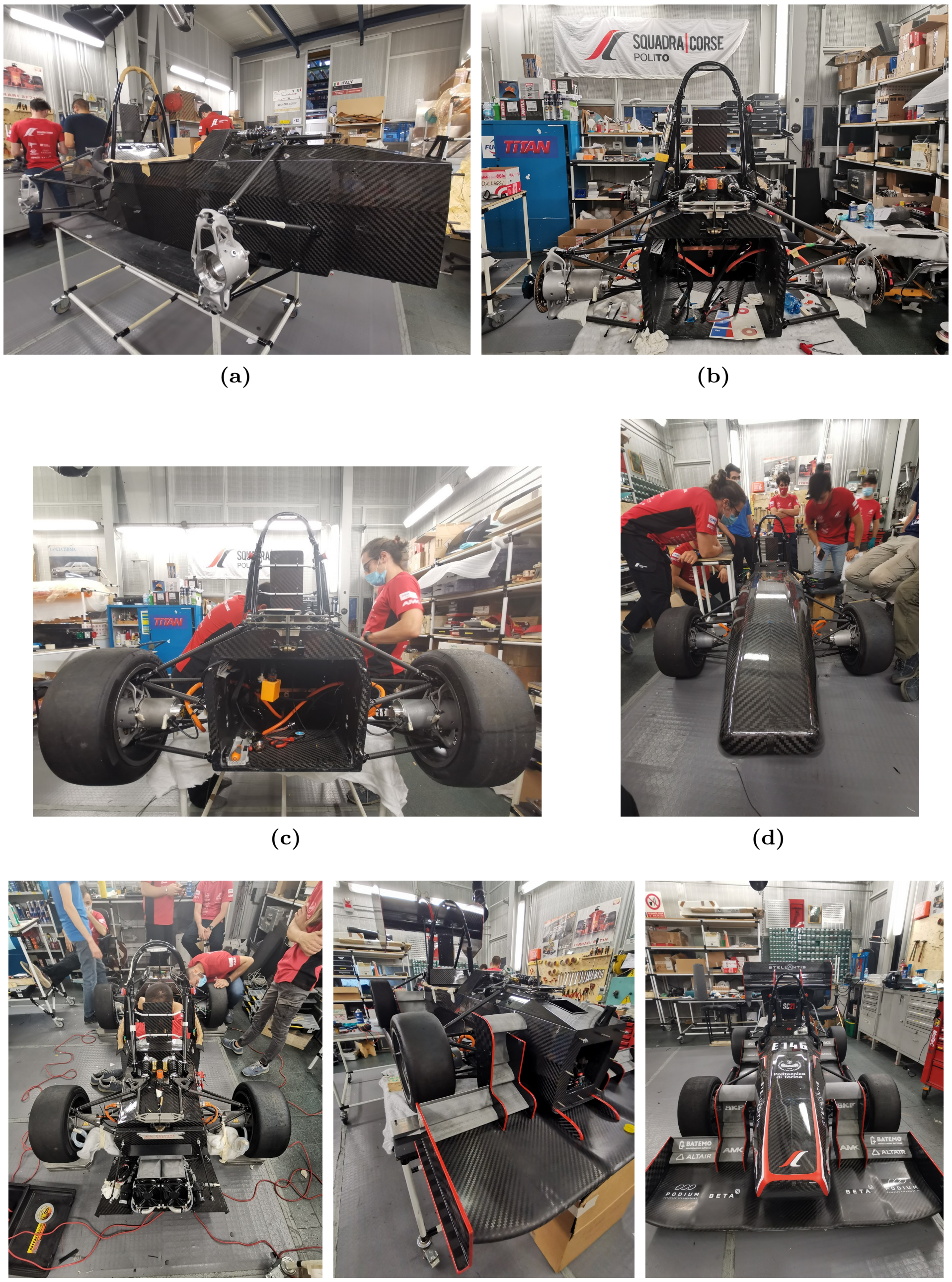
- Cars components (both for current and previous vehicles)
- Consumable
- Tools
- Fasteners
- Carbon fiber and cores

An example of Consumable sheet is reported in Figure 4.23. Simple and effective way of visualizing the current status of the item is done with colors.

Looking at the columns, starting from the left, each time an update is done in the items row, the date of update is updated. If the item is nearly finished or finished a flag "to buy" makes the whole row become red for faster recognition. If the item has to be verified in the inventory, a flag "to be verified" makes the whole row become yellow for faster recognition. Each item is then catalogued by its internal code, name, description, division belonging, class type of consumable, qty, format and consequent total qty available in stock, expiry date if any, supplier, supplier part No., link to the supplier datasheet or product description if any, location of the item inside the workshop. When inserting a new item, the user can select upon the different division belonging and class type of consumable available out of a predefined pop-up menu with automatic color distinction. The sheet has a filter on every column for easy reference.

Last updated	To buy	To be verified	Internal code	Division	Type	Item Name	Q.ta	Formato	Tot Q.ta	U.M.	Scad.	Box number	Supplier	Supplier part number	Link	Description
06 Jan 2021	☑	☐	C063	CHASSIS	Glues / Silicones	Loctite UK 3364	0	50	0	ml		Blu-3	Henkel	-	https://www.henkel-adhesi	UL94V0 Polyisocyanate - two component urethane (firewall)
06 Jan 2021	☑	☐	C032	CHASSIS	Glues / Silicones	Plexus	6	400	2,400	ml		Blu-3	ITW	MA300		Adesivo in metacrilato bicomponente progettato per l'incollaggio strutturale di compositi, materiali termoplastici e
06 Jan 2021	☐	☑	C029	Generic	Glues / Silicones	Anti-Seize Compound	1	85.0	85.0	g		Blu-3	ROCOL	14030		Composto anti-grippaggio a base di rame multiuso, rinforzato con grafite e bisolfuro di molibdeno per migliorare u
06 Jan 2021	☐	☑	C025	Generic	Glues / Silicones	Schiuma poliuretanica	1	750.0	750.0	ml		Blu-3	Spit	566930		Schiuma poliuretanica espansa ad alta resistenza ed isolamento manuale
03 Mar 2021	☐	☐	C021	Generic	Glues / Silicones	Silicone Termo-Resistente	3	310	930	ml	01/11/2021	Blu-3	ACE Silicones (RS)	892330		Silicone acetato per alte temperature
06 Jan 2021	☐	☐	C062	CHASSIS	Glues / Silicones	Butilico	10	1.0	10.0	pcs.		Blu-3	-	-		-
18 Feb 2021	☐	☐	C082	Generic	Glues / Silicones	Loctite mixer nozzle	50	1	50.0	pcs.		Blu-3	Henkel	1826921		-
18 Feb 2021	☐	☐	C009	CHASSIS	Glues / Silicones	Loctite HY 4070	12	50	600	g	23/03/2022	Blu-3	Henkel	-	om/it/it/prodotto/structural-	-
06 Jan 2021	☐	☐	C048	Generic	Hand wash	Top Gel 3	4	3.0	12.0	lt		Blu-1	Motul	108728		3 lt - sapone mani microgranuli
06 Jan 2021	☐	☐	C079	Generic	Lube	Loctite LB 8008	1	453	453	g	05/01/2023	Red-4	Henkel	-	https://www.henkel-adhesi	Pasta lubrificante antigrippante con una sospensione di rame e grafite in grasso d'alta qualità. Grado NLGI 0
06 Jan 2021	☐	☐	C043	Generic	Lube	P4 E.Z. Lube	12	0.4	4.8	lt		Red-4	Motul	102991		400 ml spray - Lubrificante multifunzione
14 Jan 2021	☐	☑	C040	PWT	Oil / Grease	Transmission oil (DA SMALTIRE)	4	1.0	4.0	lt		Blu-4	-	Motul SAE 80W90		-
14 Jan 2021	☐	☐	C080	PWT	Oil / Grease	Transmission oil (Fuchs)	2	5.0	10.00	lt		Blu-4	Fuchs	Sperimentale		-
12 Dec 2020	☐	☐	C001	MNS	Oil / Grease	Rack's grease	1	30	30	ml		Blu-6	ZRack	-		30 ml - Red grease for rack and pinion lubrication
06 Jan 2021	☐	☑	C012	CHASSIS	Paint	Diluente 352-91	1	1.0	1.0	lt		Blu-7	Glasurit	SV4103520005 / 50188192		Per trasparente e fondo
06 Jan 2021	☐	☑	C067	CHASSIS	Paint	Catalizzatore 929-33	1	1000	1000	ml		Blu-7	Glasurit	SC2900350105 / 5463942		Catalizzatore VOC 3.5 normale
06 Jan 2021	☐	☑	C078	CHASSIS	Paint	Catalizzatore 929-58	1	1000	1000	ml		Blu-7	Glasurit	SC2900580001 / 50366068		Catalizzatore per fondo
06 Jan 2021	☐	☑	C023	CHASSIS	Paint	Diluente 93-E 3	5	1.0	5.0	lt		Blu-7	Glasurit	AZ9302000110 / 50172104		Per base rosso (ritarda asciugatura) 2:1
06 Jan 2021	☐	☑	C056	CHASSIS	Paint	Trasparente 923-115	1	1500	1500	ml		Blu-7	Glasurit	AF2301150101 / 53145685		Trasparente HS universale VOC
06 Jan 2021	☐	☑	C034	CHASSIS	Paint	Vernice 93-M 363 Step 1	1	780	780	g		Blu-7	Glasurit	AJ9336300104 / 50546996		Rosso perlato
06 Jan 2021	☐	☑	C007	CHASSIS	Paint	Vernice 93-M 363 Step 2	1	780	780	g		Blu-7	Glasurit	AJ9336300104 / 50546996		Rosso perlato
06 Jan 2021	☐	☑	C089	CHASSIS	Paint	Catalizzatore H420	1	2000	2000	ml		Blu-7	RM Paint	1I50412201810		Catalizzatore per vernici
06 Jan 2021	☐	☐	C068	CHASSIS	Putty	SIKA APF 7 BLACK	1	2.0	2.0	kg		Blu-5	Axson - sika	-		Stucco stampi carbonio
06 Jan 2021	☐	☑	C006	CHASSIS	Putty	Stucco metallico poliestere	1	250	250	g		Blu-5	CFG	P00500		Usare con catalizzatore (2%)
06 Jan 2021	☑	☐	C066	CHASSIS	Putty	hardener RAKU TOOL EH-2934-1	2	1.0	2.0	kg	09/01/2021	Blu-5	Modelresine	-		Hardener per EP-2304 (Adhesive for epoxy boards)
06 Jan 2021	☑	☐	C065	CHASSIS	Putty	hardener RAKU TOOL EH-2936-2	1	0.5	0.5	kg	05/01/2021	Blu-5	Modelresine	-		Hardener per EP-2304 (stucco)
06 Jan 2021	☑	☐	C064	CHASSIS	Putty	Stucco RAKU TOOL EP-2304	1	5.0	5.0	kg	10/01/2021	Blu-5	Modelresine	-		Stucco/Adhesive for epoxy boards per WB a seconda del secondo componente
06 Jan 2021	☐	☑	C045	CHASSIS	Putty	Stucco elastico per plastica	1	120	120	g		Blu-5	Presto - Motildupli	601460		Ha bisogno del catalizzatore (2-4%)
06 Jan 2021	☐	☐	C038	CHASSIS	Resin	Mold tackyfire	1	500	500	ml		Marrone-4	-	-		Solvente per far rimanere incollato tessuto di carbonio sullo stampo. Marca non conosciuta
06 Jan 2021	☑	☐	C036	CHASSIS	Resin	Distaccante Chemlease PMR EZ	2		3.0	kg	06/01/2021	Marrone-4	Chem Trend	CA00079557		
06 Jan 2021	☑	☐	C003	CHASSIS	Resin	Otturapori Chemlease MPP 712 EZ	2	930	1860	g	07/01/2020	Marrone-4	Chem Trend	CA00107223		Scadenza 13/11/2019
06 Jan 2021	☐	☑	C005	CHASSIS	Resin	Accelerante SX8/10 EVO	1	250	250	ml		Marrone-4	Mike Compositi	ACSX810-025		Accelerante resine epox (4% della miscela)
06 Jan 2021	☐	☐	C002	CHASSIS	Resin	Catalizzatore Raku Tool EH-2952-1	1	3.0	3.0	kg	20/2021	Marrone-4	Rampf	539925		Catalizzatore per resina epox bicomp. Textreme
06 Jan 2021	☐	☐	C004	CHASSIS	Resin	Resina Raku Tool E-2203	2	5	10.0	kg	02/01/2020	Marrone-4	Rampf	541176		Resina Textreme con EH-2952-1 + 2/3 kg scandeza 11-2019 + 5 kg senza scadenza
06 Jan 2021	☑	☐	C037	Generic	Resin	Alcool Isopropilico	1	500	500	ml		Marrone-4	RS	567-890		Solvente per uso generico estremamente efficace per rimuovere sporcizia e grasso da molti materiali diversi
06 Jan 2021	☐	☑	C030	Generic	Resin	Resina siliconica	1	200.0	200.0	ml		Blu-3	RS	494-714		Rivestimento protettivo trasparente
06 Jan 2021	☐	☐	C075	Generic	Rust removal	Loctite LB 8018	8	0.4	3.2	lt	08/01/2021	Blu-7	Henkel	-		-
06 Jan 2021	☑	☐	C060	E&E	Scotch	Isolante	3	1	3	pcs.		Cassetto nastri	-	-		-
06 Jan 2021	☐	☐	C059	E&E	Scotch	Kapton	2	1	2	pcs.		Cassetto nastri	-	-		-
03 Mar 2021	☐	☐	C033	Generic	Scotch	Scotch di carta grosso 50mmx50m	6	1	6	pcs.		Cassetto nastri	-	-		-
03 Mar 2021	☐	☐	C085	Generic	Scotch	Scotch di carta sottile 19mmx50m	6	1	6	pcs.		Cassetto nastri	-	-		-
06 Jan 2021	☐	☐	C073	COOL	Sealant	Loctite 586	4	50	200	ml	10/01/2020	Blu-8	Henkel	-	https://www.henkel-adhesi	Sigillaraccordi ad alta resistenza formulato per il bloccaggio e la sigillatura di raccordi e tubazioni in metallo
06 Jan 2021	☐	☑	C039	COOL	Sealant	Filo Sigillaraccordi	1	1.0	1.0	pcs.		Blu-8	Loctite	483289		-
06 Jan 2021	☐	☐	C047	COOL	Sealant	Radiator Stop Leak	12	0.3	3.6	lt		Blu-8	Motul	108126		300 ml - turafalle radiatore
06 Jan 2021	☐	☐	C058	E&E	Solder	Flussante	2	1.0	2.0	pcs.		Kit saldatura	-	-		-
06 Jan 2021	☐	☐	C055	E&E	Solder	Solder past	1	35.0	35.0	g		Kit saldatura	-	TS391AX10		-
06 Jan 2021	☐	☐	C057	E&E	Solder	Stagno	4	1.0	4.0	pcs.		Kit saldatura	-	-		-
06 Jan 2021	☐	☐	C070	Generic	Threadlocker	Loctite 222	4	50	200	ml	11/01/2020	Blu-2	Henkel	123002	https://www.henkel-adhesi	Frenafiletti a bassa resistenza
06 Jan 2021	☐	☐	C071	Generic	Threadlocker	Loctite 243	4	50	200	ml	1x 05/020 3x 1/	Blu-2	Henkel	123000	https://www.henkel-adhesi	Frenafiletti a media resistenza
06 Jan 2021	☐	☐	C072	Generic	Threadlocker	Loctite 270	6	50	300	ml	06/01/2021	Blu-2	Henkel	-		Frenafiletti ad alta resistenza
06 Jan 2021	☐	☐	C074	Generic	Threadlocker	Loctite 648	4	50	200	ml	12/01/2020	Blu-2	Henkel	-	https://www.henkel-adhesi	Bloccante coassiale a bassa viscosità e ad alta resistenza, solitamente utilizzato per fermare gli ingranaggi e i pig
06 Jan 2021	☐	☐	C054	E&E	Zip ties	Fascettoni	100	1.0	100	pcs.		Fascettoni	Schnejder electric	-		
03 Mar 2021	☐	☐	C035	Generic	Zip ties	Fascette plastica 140mm	100	1	100	pcs.		Fascettoni	-	-		

Figure 4.23: Consumable inventory sheet



(a) (b) (c) (d) (e) (f) (g)

Figure 4.24: Stages of vehicle assembly

5 Validation and Testing

In the following section, a the description of the right hand side of the V-cycle, also called Validation, is reported. As already mentioned in Section 2.1, there is data and information exchange between the Verification and the Validation branches.

5.1 Component level validation

Staring from the very bottom hand of the validation branch, there is the component level validation. In the following, some examples are proposed.

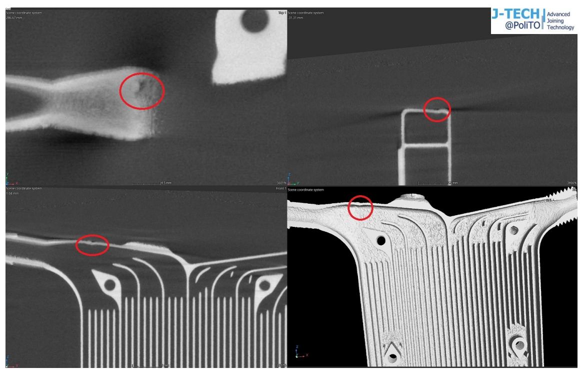
Non-destructive tests are used to assess the quality of a given component, assembly or material, by inspecting it without destroying or impairing its functionalities. Through different techniques, experts are able to identify defects, cracks, inclusions, discontinuities in the material or any other issue that makes the component non compliant with the technical specifications. Thanks to one of our sponsors, *J-Tech@PoliTO*, located inside our main campus, we had the opportunity to get access to a very expensive technology used for non-destructive testing: X-Ray Computer Tomography. The facility we had access to, showed a custom-built Computed Tomography with in-situ mechanical testing (tensile, compression, bending, load cell 10 kN), chamber size 3.5 m x 2.5 m x 2.5 m; samples up to 0.5 m x 0.5 m x 0.5 m resolution of about 5 μm [10].

We decided to analyze the inverters cooling coldplate, due to both an intricate internal geometry and the manufacturing technology adopted. Being printed with AlSi10Mg SLM powder, the component once manufactured, contains the powder from the powder bed, trapped inside the cooling channels. This technical solution could be contested, since simpler solution are available yet, requesting simpler geometries, but since we had the opportunity to validate our component once manufactured we decided to give it a try. After carefully removing the remaining powder and machining the component, the component is analyzed in a micro-ct.

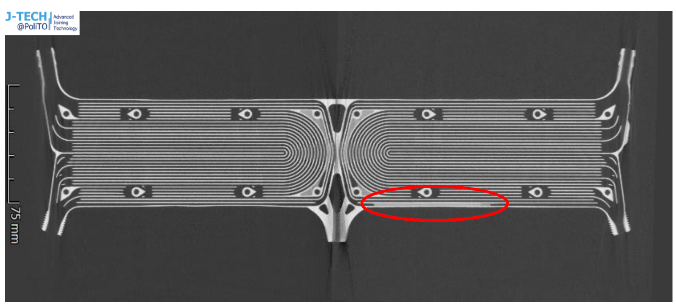
Different coldplates have been analyzed due to printing process defects and issues.

In Figure 5.1b the coldplate presented a tiny crack near to water outlet that caused water leakage during preliminary testing. This was probably caused by the printing supports removal not performed carefully enough, that combined with thin wall of the coldplate, led to a crack. For next versions the coldplate had increased thickness of the wall in supports area.

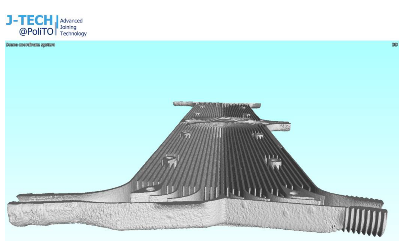
(a) Micro ct chamber



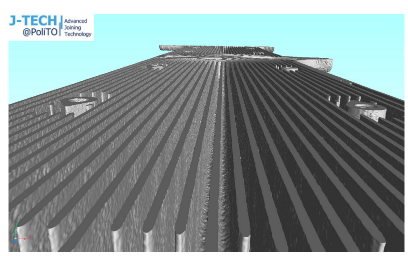
(b) Multiple views with tiny crack



(c) Section cut 2D view with small powder obstruction



(d) Section cut 3D view close up



(e) Channels close up

Figure 5.1: X-Ray Computer Tomography on cooling coldplate

In Figure 5.1c the coldplate showed an overall cleaned structure, with a small powder obstruction occurring in one of the external channels. This coldplate is still usable, with slightly lower cooling efficiency.

In Figure 5.1e we can appreciate a well cleaned coldplate with completely free channels.

5.2 Subassembly level validation

Going up in the validation branch, there is the subassembly level validation. In the following, some examples are proposed.

A particular interest was to characterize the carbon fiber tubes and the adhesive bonding used in the A-arms of the suspension, in order to have the right Young modulus for the FEM simulations. Four equal test specimens were fabricated using the same carbon fiber tube that goes into the final manufactured A-arms, with dedicated inserts to facilitate the clamping onto the tensile testing machine. The test showed an average Young modulus of 103 Gpa compared to the 115 Gpa declared of the datasheet, with a relative error of 11.7%.

Datasheet	Flexural modulus	Young's modulus	Tensile Strength	Density
	100 GPa	115 GPa	2900 Mpa	1.52 g/cm^3

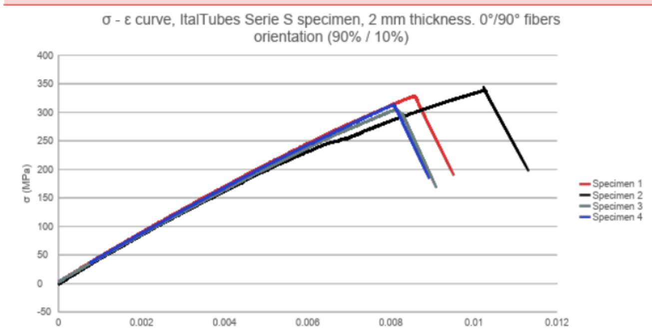
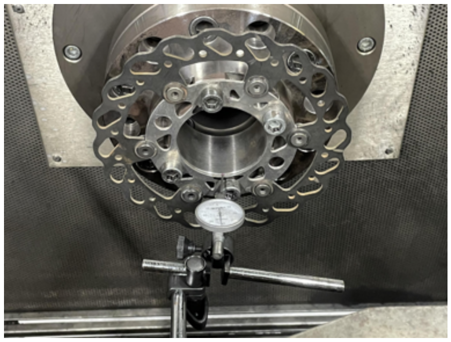


Figure 5.2: Suspension carbon fiber tubes and bonding validation

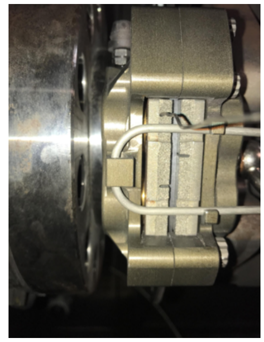
Another example is the brake system bench testing validation.

The brake system has been tested on a dynamometric bench test where a single quarter of the car is reproduced, both for the front and the rear. The bench test is able to simulate the vehicle inertia and to measure and evaluate several quantities such as disc temperature, pad temperature, brake pressure, braking torque, vehicle speed, friction coefficient. The braking system has been tested with two different pad compounds in order to better understand their performances. The tested cycles are the following:

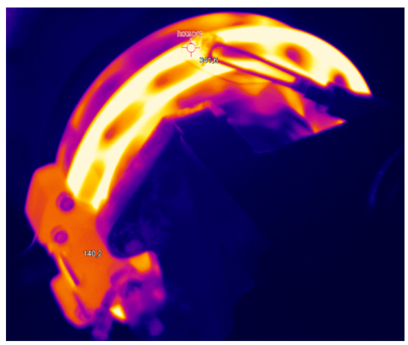
- initial bedding cycles



(a) Test bench centering controls



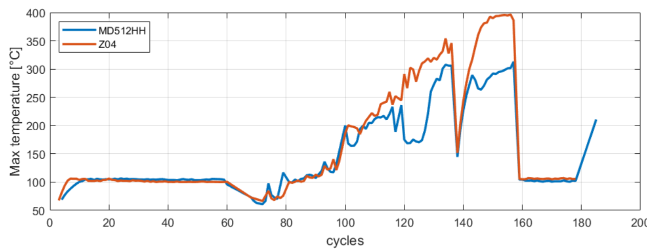
(b) Detail of pad temperature sensor



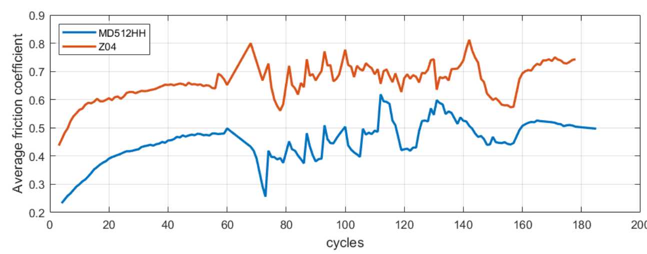
(c) Thermocamera image with disc and caliper temperatures

Figure 5.3: Brake system testing bench

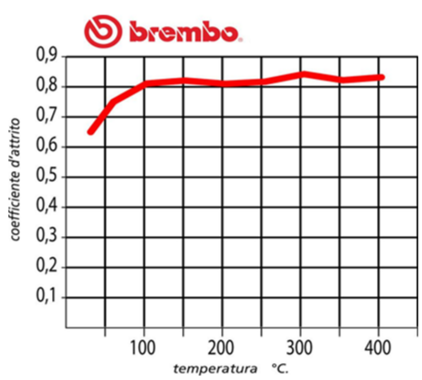
- 40-0 km/h deceleration with pressure sweeps of 2-60 bar at 50, 100, 200 and 300°C initial temperature
- 80-40 km/h deceleration with pressure sweeps of 2-60 bar at 50, 100, 200 and 300°C initial temperature
- 120-80 km/h deceleration with pressure sweeps of 2-60 bar at 50, 100, 200 and 300°C initial temperature
- fading cycles at variable pressures
- recovery cycles of 120 s each



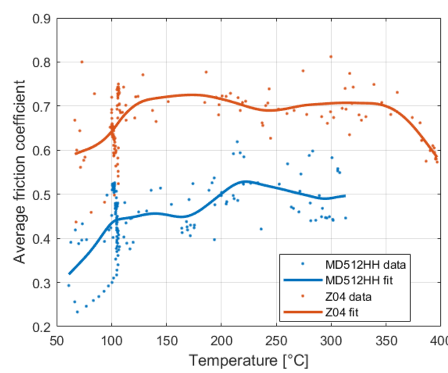
(a) Tested Max disc temperature per cycle



(b) Tested Average friction coefficient per cycle



(c) Brembo Z04 pad friction coefficient vs temperature



(d) Tested friction coefficient vs temperature

Figure 5.4: Brake system tests results

5.3 Assembly level validation

Going up in the validation branch of the V-cycle, we reach assembly level validation. In the proposed example the assembly validated is Aerodynamics.

SC21 racecar was tested in CRF wind tunnel facility located in Orbassano. The facility is a closed circuit type with ¾ open jet test section (10.5 m long, 12 m wide and 12 m tall), a 30.5 m^2 nozzle cross section (contraction ratio 4:1) and a maximum inflow velocity of 200 kph. The Rolling Road Simulation System (RRSS) is equipped with five belts, one central narrow belt (6 m long, 1.1 m wide), and four wheel spinning units. The balances present in the system are one integrated main balance with the RRSS and four additional balances under the wheel spinning units, in order to measure the tangential forces necessary to keep constant rotational wheel speed and the sum of drag forces. The system is equipped with a boundary layer suction system that, together with the moving belt, achieves an almost zero height displacement thickness ($\delta^* < 0.5mm$) along the entire main belt. In order to keep the car setup constant during the tests, the four vertical struts fixing the car to the platform were kept in a fixed condition with respect to the z axis. This has been preferred over the floating condition (more representative of the real driving conditions) simply because in CFD simulations it is more difficult to represent the car movements due to its downforce. Another note worth of mention is that the central moving belt is narrower than the car track, leading to leave the sidepods out of the belt, meaning that a significant aerodynamic contribution of the package is not taken in account as per real driving conditions. Despite the configuration, the tests have been extremely useful to validate the CFD model.

The tests were conducted with almost constant pressure, temperature and density:

$T \approx 25°C$
$p \approx 1.008 \cdot 10^5 Pa$
$\rho \approx 1.18 kg/m^3$

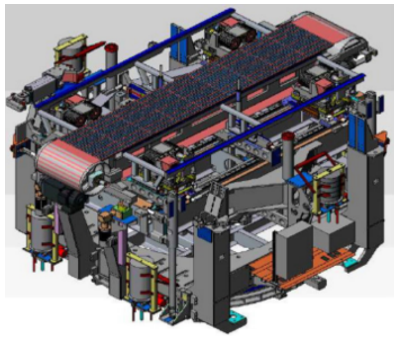
The turbulence level at the inflow is low, (0.1% turbulence intensity).

The first test is a Reynolds sweep plus pressure taps on the rear wing dorsal surface:

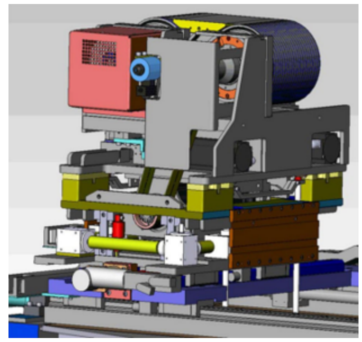
- Inflow velocity in a range of 20 - 100 kph (steps of 10 kph)
- 16 pressure taps: 4 for main, 4 for the first flap, 5 for the second flap and 3 for the third one one located at y = 306 mm from the xz plane of the car, as shown in the Figure 5.7

The second test is a wake measurement:

- Inflow velocity at 60 kph



(a) Aerodynamic balance and 5-belts system



(b) Wheel spinning unit with integrated balance

Figure 5.5: Wind tunnel system

- 16 total pressure probes, spaced 6 cm each other, connected to a rod. The traversing gear shown in the Figure 5.8 was responsible for the movement of the rod. Tests carried out starting from x = -0.3 m spaced 0.3 m one to another till +2.7 m, with the additional +0.75 m and +1.05 m measurements, where x = 0 m corresponds to the front axle coordinate.

The wake measurements were taken only for an inflow velocity of 60 kph, while the static pressure ones were taken during a Reynolds sweep (inflow velocity from 40 kph up to 100 kph). Thus, for the 60 kph case (estimated car mean velocity) there are two measures, while for the other inflow velocities just the measure on the configurations with pressure taps.

Data reported in the following consist of main aerodynamic coefficients, Cx and Cz referred to a frontal area of 1 m^2, as well as aerodynamic efficiency and aerodynamic load repartition. The relative errors between CFD results and wind tunnel data were calculated in post-processing.

The Table 5.2 shows that the presence of pressure taps on the rear wing surface reduces the downforce of that wing and therefore the aerodynamic repartition is shifted to the front compared to the WT* configuration 5.5. A relative error of 9.5% on Cx is present which is good, whereas the relative error on Cz is higher, around 15.1%, since the Cz measure is strongly influenced by underfloor aerodynamics and so by RRSS, which is not easy to simulate in CFD environment.

The error between CFD and WT decreases as speed increases, and this could be explained by the fact that the wind tunnel conditions become more representative of the real driving conditions as the air speed increases.

Figure 5.6: SC21 fitting to the Rolling Road Simulation System

	Cz	Cx	Cz/Cx	ΔCz	ΔCx	$\Delta(Cz/Cx)$	$\%front$
$\boldsymbol{WT}$	2.37	1.20	1.91				49.6%
$\boldsymbol{CFD}$	2.97	1.55	1.92	29.66%	28.75%	0.71%	39.9%

Table 5.1: WT-CFD Comparison, inflow velocity 40 kph, with pressure taps on the rear wing

	Cz	Cx	Cz/Cx	ΔCz	ΔCx	$\Delta(Cz/Cx)$	$\%front$
$\boldsymbol{WT}$	2.35	1.25	1.88				52.8%
$\boldsymbol{CFD}$	2.89	1.42	2.03	23.12%	13.95%	8.05%	43.3%

Table 5.2: WT-CFD Comparison, inflow velocity 60 kph, with pressure taps on the rear wing

	Cz	Cx	Cz/Cx	ΔCz	ΔCx	$\Delta(Cz/Cx)$	$\%front$
$\boldsymbol{WT}$	2.37	1.23	1.92				54.0%
$\boldsymbol{CFD}$	2.87	1.38	2.08	21.20%	12.32%	7.90%	44.6%

Table 5.3: WT-CFD Comparison, inflow velocity 80 kph, with pressure taps on the rear wing

Figure 5.7: Pressure taps on the rear wing

	Cz	Cx	Cz/Cx	ΔCz	ΔCx	$\Delta(Cz/Cx)$	$\%front$
$\boldsymbol{WT}$	2.40	1.22	1.96				55.0%
$\boldsymbol{CFD}$	2.85	1.37	2.08	19.04%	12.27%	6.04%	45.0%

Table 5.4: WT-CFD Comparison, inflow velocity 100 kph, with pressure taps on the rear wing

	Cz	Cx	Cz/Cx	ΔCz	ΔCx	$\Delta(Cz/Cx)$	$\%front$
$\boldsymbol{WT^*}$	2.51	1.30	1.93				49.8%
$\boldsymbol{CFD}$	2.89	1.42	2.03	15.14%	9.50%	5.18%	43.3%

Table 5.5: WT-CFD Comparison, inflow velocity 60 kph, without pressure taps on the rear wing

The figure 5.9 shows the pressure coefficient distribution for an inflow velocity equal to 60 kph. The black distribution is known from CFD, while the red one was obtained by experimentally collected taps data interpolation. The experimental measurement is affected by the taps their self. Hence, a correction was done by using data from wake measurement test at the same velocity (blue line). Moreover, this plot confirms that CFD estimates a higher aerodynamic load than the one calculated in the wind tunnel, as previously seen.

Good correlation between WT and CFD is present as well for total pressure probes measurements. On the side of the car, especially in tires wake region, not precise correlation related to tire flow field CFD modeling and to the presence in the WT of additional bars located to the side of the vehicle to fix the vehicle to the vertical struts which act as a turbulence source. Improvement in our CFD model in

Figure 5.8: Wake measurement system

this area is needed. Pretty clear flow field in front of the rear wing is measured, so pressure pressure coefficient measurements on rear wing surface are not affected by the incoming flow. There is also a strong correlation within the wake of the car between estimated CFD total pressure field and the WT measured one. This is also due to the SST $k-\omega$ Turbulence Model predicting flow separations from surfaces and turbulence regions.

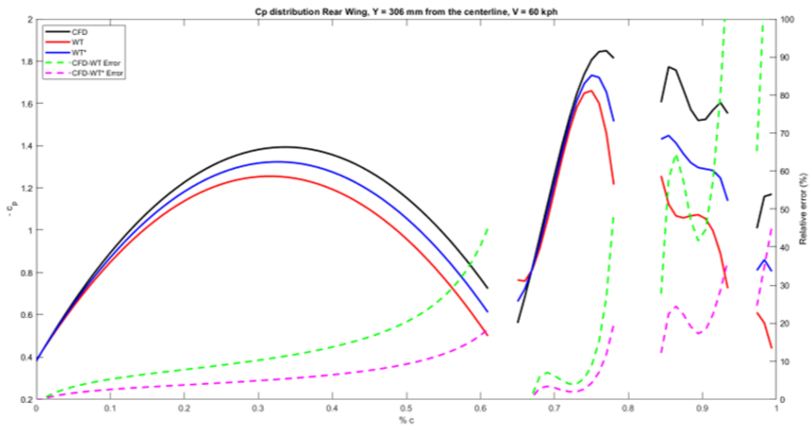


Figure 5.9: Rear wing pressure coefficient distribution at y = 306 mm from xz plane, inflow velocity = 60 kph

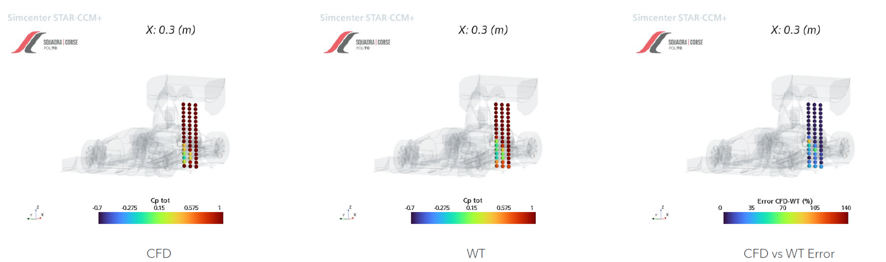


Figure 5.10: WT-CFD comparison total pressure coefficient measurements at +300 mm

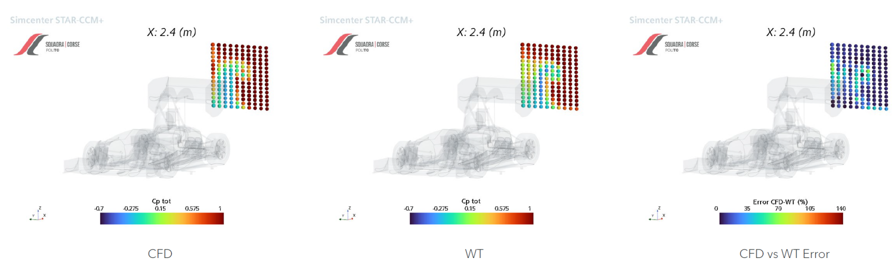


Figure 5.11: WT-CFD comparison total pressure coefficient measurements at +2400 mm

5.4 Vehicle level validation

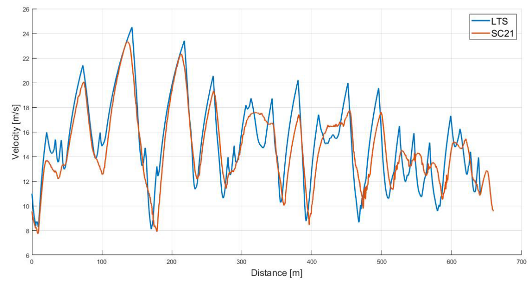
At the end of the validation branch, there is the vehicle level validation. When we refer to the vehicle level, the main metric used to validate the vehicle models are the logged data coming from the actual vehicle testing on track. These data are compared to the laptime simulators in order to validate them. In the following, the single point mass simulator is presented.

The single point mass simulator shows a pretty accurate behaviour in tracking the real logged data, with the main difference being that in single point mass simulator the driver is ideal, hence it brings the vehicle to its limit at any instant, leading to a faster laptime compared to real driver. At the same time, the real driver trajectory differs from the LTS one, by choosing a trajectory that gives less velocity variations over time, by smoothing the trajectory adopting more constant curvatures. For this reasons, the final distance is not the same in the two cases. In Figure 5.12, the LTS is compared to the real logged data in the Cerrina Race Track, where the Team usually tests the car. Pretty good correlation is showed in the lateral acceleration plot, where the real vehicle even achieves higher lateral accelerations than the LTS one, whereas in the longitudinal acceleration plot, the real driver lacks a bit of braking performance.

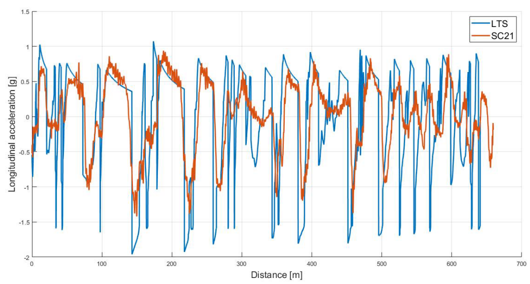
For what concerns the energy, similar trend is achieved aswell, but the real vehicle shows less energy consumption, for the same reasons as before, being the LTS driver an ideal one. Final errors between the simulators and the real car are reported in Table 5.6.

	Laptime [s]	Energy [Wh]	$\Delta Laptime$	$\Delta Energy$
LTS	43.7	243.5	5.4%	6.2%
SC21	46.6	207.7		

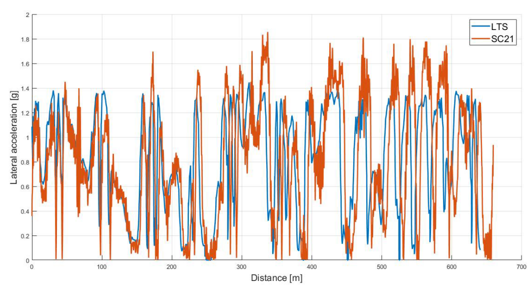
Table 5.6: Single point mass LTS and real car laptime, energy validation



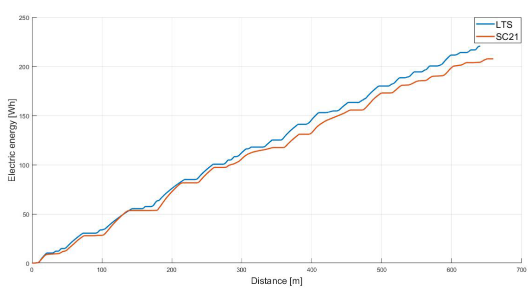
(a) Velocity plot



(b) Longitudinal acceleration plot



(c) Lateral acceleration plot



(d) Energy plot

Figure 5.12: Single point mass LTS validation

6 Operations and Maintenance

6.1 Operations

Operation activities of a Formula Student racecar can be classified by the purpose of the operation itself:

- **Service** operation: when the vehicle is not in driving condition, it is usually located on-stands to facilitate the disparate service operations in between track tests, or it is located on the ground with wheels mounted (to perform vehicle setup for example).

- **Ready-to-drive** operation: when the vehicle is in ready-to-drive and driving condition.

Ready-to-drive operation can be further subdivided into:

- **Chassis dynamometer** operation: the vehicle is tested on an automotive dyno.

- **Track testing** operation: activities performed on track where the vehicle is tested prior and after the events.

- **Official event** operation: the racecar is actually driven on track at the official events.

Usual service operations can be further subdivided into:

- Mostly used connectors connect or disconnect (such as HV and LV accumulators power and signal connectors, inverter to HV accumulator power connector, radiator and HV accumulator fans)

- HV Accumulator charging

- LV accumulator charging

- VCU software flash

- Data download from data loggers

- PCBs software flash

- Main switches operation
- Interlock and shutdown devices operation
- Measure electrical quantities through the measuring points
- IMD test
- Fuses replacement in fusebox
- Pedal box adjustments between driver changes
- Dampers and springs adjustments
- ARB adjustments
- Ride height adjustments
- Tire angles and pressure adjustments
- Seat mounting and dismounting
- Firewall mounting and dismounting
- HV accumulator air intake mounting and dismounting
- Front and rear wings mounting and dismounting
- Front and rear wing flaps for individual angle of attack changes
- Front end upper aerodynamic cover mounting and dismounting
- AIP mounting and dismounting
- Rear end cover mounting and dismounting
- Cooling system bleed
- Brake system bleed
- Brake pads replacement
- Brake discs replacement
- Tires replacement
- Gearbox oil change
- Cleaning operations

All the aforementioned operations include components that are usually crucial from the serviceability point of view, so careful design has to be taken into account according to DFMA practices seen in Section 3.9.1.

In addition or substitution other specific components may be identified.

To better manage the service operations off-track and on-track, dedicated sheets have been prepared in order to be consistent with data management of car preparation and setup, driver feedback, test objectives, test issues encountered and so on. In Figure 6.1 it is reported an example of off-track procedures for the unsprung masses division to be followed in order to prepare the car for the track.

After a first period of testing devoted to verify the reliability of the car, the tests begin to focus onto bettering the vehicle performance. An important tool is also the driver feedback. Dedicated sheets are prepared where the driver can fill in with their sensations encountered when driving, including both positive and negative aspects 6.3. The vehicle dynamics behavior of the car felt by the driver is further subdivided into driving aspects such as understeer, oversteer, steering effort, front grip, etc. standardized within a scale from 1 to 7. Also, the vehicle dynamics division is responsible for the data acquisition, storage and analysis, with dedicated packages, functions and sheets, that are not reported here, but are crucial in order to maximize the performance of both car and drivers.

The SC21 car competed into two official events, Formula Student Spain and Formula ATA in Italy. The Team scored average results in Static events and achieved a 2nd place in FS Spain Design Event, showing the strength of the project from a technical point of view. However, in both competitions, the car did not access the dynamic events due to issues encountered in the electrical tech inspections, which costed a good overall result. Fortunately, this point was already addressed in the following seasons (2022 and 2023) in order to arrive to the events with larger preparation and testing behind, and further work has to be done in 2024.

Event	**Formula Student Spain**	**Formula ATA**
Design	2°/19	4°/20
Business Plan	13°/19	9°/20
Cost	13°/19	13°/20
Endurance	DNS	DNS
Overall	12°/19	13°/20
Competitiveness index	0.85	0.85

Table 6.1: SC21 events results

Off Track Procedures

TRACK	
DATE	

Steering

Action	STATUS	RESPONSIBLE	NOTES
Steering-wheel centered and secured	✓		Note
Rack mount bolts tight	✓		Note
Rack ends tight	✓		Note
Rack movement length	✗		Note
Steering Lock-to-Lock	✓		Note

Front suspension

Action	STATUS	RESPONSIBLE	NOTES
Hub bearings play check	✓		Note
Upper ball joints checked	✓		Note
Lower ball joints checked	✓		Note
UCA brackets tight	✗		Note
LCA brackets tight	✓		Note
Pushrod tight	✓		Note
Rockers play	✓		Note
Rockers torqued	✓		Note
Dampers tight attachment points	✗		Note
Springs locked correctly	✗		Note
ARB-Rocker tight attachment points	✓		Note
ARB-Chassis tight attachment points	✓		Note
ARB correct movement	✓		Note
Race tire fitted and pressurized	✓		Note
ARB correct movement	✓		Note
Wheel nut tight	✓		Note

Front Brakes

Action	STATUS	RESPONSIBLE	NOTES
Brake pad wear check	✓		Note
Caliper bolts tight and wired	✓		Note
Discs centered	✓		Note
Disc checked for cracks	✗		Note
Brakes bleed, bleeders tight and dry	✓		Note
Seals and unions checked under pressure	✓		Note
Pedal and master cylinder bolts tight	✓		Note
Full reservoirs, caps tight	✓		Note

Rear suspension

Action	STATUS	RESPONSIBLE	NOTES
Hub bearings play check	✓		Note
Upper ball joints checked	✓		Note
Lower ball joints checked	✓		Note
UCA brackets tight	✗		Note
LCA brackets tight	✓		Note
Pushrod tight	✓		Note
Rockers play	✓		Note
Rockers torqued	✓		Note
Dampers tight attachment points	✗		Note
Springs locked correctly	✗		Note
ARB-Rocker tight attachment points	✓		Note
ARB-Chassis tight attachment points	✓		Note
ARB correct movement	✓		Note
Race tire fitted and pressurized	✓		Note
ARB correct movement	✓		Note
Wheel nut tight	✓		Note

Rear Brakes

Action	STATUS	RESPONSIBLE	NOTES
Brake pad wear check	✓		Note
Caliper bolts tight and wired	✓		Note
Discs centered	✓		Note
Disc checked for cracks	✗		Note
Brakes bleed, bleeders tight and dry	✓		Note
Seals and unions checked under pressure	✓		Note
Pedal and master cylinder bolts tight	✓		Note
Full reservoirs, caps tight	✓		Note

Cockpit

Action	STATUS	RESPONSIBLE	NOTES
Safety harness bolts secured	✓		Note
Switches working properly	✓		Note
Throttle pedal sensors working	✓		Note
Throttle pedal secured	✗		Note
Brake bias wheel functioning	✓		Note
Seat secured and locked	✓		Note

Figure 6.1: Off-track procedures for the unsprung masses division

(a) SC21 being prepared for setup

(b) Setup adjustments with vehicle on stands

(c) Track walk

(d) Data logged download

Figure 6.2: SC21 setup and track testing

Driver Log

LOG ID	
SCHEDULE	
ACTIVITY	
DATA LOG	
DRIVER	
TIRES	

TRACK	
DATE	
TIME	
AIR TEMP	
TRACK TEMP	
TRACK COND.	

CORNER ENTRY	
MID CORNER	
CORNER EXIT	

	SLOW	MID	FAST
BRAKING GRIP	8	6	5
TRACTION GRIP	4	6	6
FRONT GRIP	6	6	6
REAR GRIP	7	5	3
UNDERSTEER	4	6	6
OVERSTEER	7	4	2
STEERING EFFORT	5	5	5
STEERING HARSHNESS	6	5	2
ACCELERATOR SENSITIVITY	3	5	5
BRAKING EFFORT	6	6	6
BRAKE SENSITIVITY	7	6	4
WHEEL HOP	5	7	7
ROLL	7	7	7
PITCH	7	6	5

VEHICLE CONFIGURATION

MECHANICAL	FRONT	REAR
RIDE HEIGHT		
WING CONFIG		
TOE ANGLE		
CAMBER ANGLE		
SPRING STIFFNESS		
ARB DIAMETER		
BRAKE PADS		
TIRE PRESSURE (c)		
TIRES		
DAMPING LSC		
DAMPING LSR		
DAMPING HSC		
DAMPING HSR		
ACKERMANN		

CONTROL SYS	
POWER CONTROL	
REGENERATIVE	
TORQUE VECT	
TRACTION CONT.	
ABS	
LAUNCH CONT.	

Driver Mass [kg]

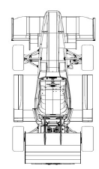
Vehicle Mass [kg]

Total Mass [kg]
0

FRONT
#DIV/0!

FL
DAMPER POT

FR
DAMPER POT



DIAG 1
#DIV/0!

DIAG2
#DIV/0!

RL
DAMPER POT

RR
DAMPER POT

REAR
#DIV/0!

TEST OBJECTIVE	
ENGINEER NOTES	

Figure 6.3: Track test driver log sensations

6.2 Maintenance

When operating a Formula Student race car, maintenance should represent only very short periods compared to the actual operative time of the vehicle. Maintenance actions can be divided into two types:

- Preventive maintenance (properly designed and scheduled for components prior their failure).
- Remedial maintenance (repairing or replacement of failed components).

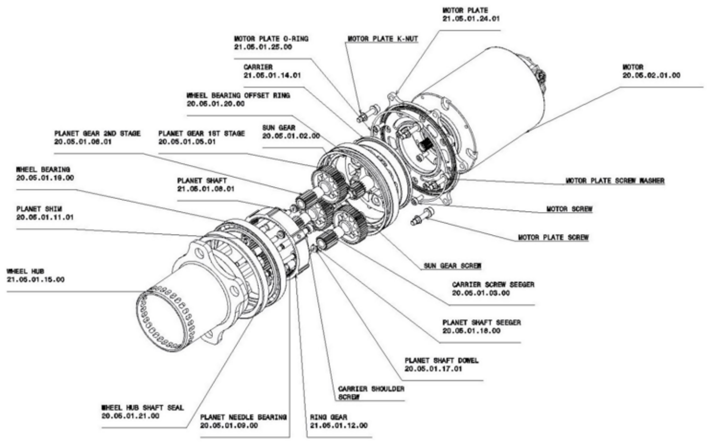
Preventive maintenance actions must be particularly considered during the design of the vehicle.

Considering where maintenance operations are likely to take place, three categories may be identified:

- 1st line maintenance: actions that can be performed on the track site (no special tools needed, requested time less than one hour). Example: brake disc replacement.
- 2nd line maintenance: actions that can be performed in the workshop by the Team (special tools required, requested time more than one hour). Example: wing repairing after crash.
- 3rd line maintenance: actions that involve third companies (either for repairing or for spare parts supplying). Example: HV BMS reprogramming.

A list of maintenance-critical items should be prepared in the early stages of the project and appropriate attention must be paid in their design.

An example of 1st line, preventive maintenance is shown in Figure 6.4, where an extract of the procedure to maintain the gearbox is presented.



2. Istruzioni di montaggio

2.1 Gruppo montante

1. Sgrassare tutti i componenti metallici di lavorazione (eccetto cuscinetti e paraoli) e soffiarli con aria compressa.
2. Mascherare con nastro carta la filettatura del mozzo (15) inserire fino a completa battuta il paraolio (21) nell' apposita sede sul mozzo, avendo cura di posizionare il paraolio in modo da avere la molla dal lato degli ingranaggi. Accoppiamento: interferenza.

Figure 6.4: Gearbox maintenance procedure extract

6.3 Post seasonal tests and retirement

Once the vehicle has participated to the official events, the season is not finished yet. Testing continues even after the events in order to test solutions that were not tested before or to further investigate and validate models that were not done before, in order to set the foundations of the new season. In fact, target setting of the new vehicle starts with the post seasonal tests with the current vehicle.

(a)

(b)

Figure 6.5: SC21 track testing

7 Conclusions

This work aimed to propose the project development of a Formula Student Racecar both from the technical and organizational points of view. Before the actual design begins, the project starts with the vehicle target setting where main vehicle concept and vehicle performance targets are defined. Main tool of analysis in this phase is the Laptime Simulator, which helps to run hundreds of different vehicle configurations in a restricted amount of time without having the need of developing and building real life prototypes. These aforementioned targets are further deployed into subsequent levels, respectively assembly, subassembly, down to the component level. The targets proved to be ambitious and challenging for the consequent phases. In the target setting phase are also defined the so called organizational targets, which are mostly related with the aspects that can improve the efficiency of the Team working to the Project.

The vehicle design is then deployed into assembly and subassembly levels, with the aid of both dedicated commercial softwares and programs/calculus sheets created by the Team. Along with these tools, additional technical documents are needed such as design books which are technical reports, BOMs, FMEA analysis for an effective management of the upcoming production phase and data management for the future generations of Squadra Corse. A correct time management is done with Gantt charts in order to correctly schedule and monitor the deployed tasks down to subsystem level. Design for Manufacturing and Assembly practices have been deeply analysed in order to drive the design in a consistent and oriented manner towards the following production and assembly phases.

Once the vehicle is designed, the production phase starts, both for the mechanical and the electrical areas. The tools needed for the manufacturing and assembly phases are provided. An effective time management with Gantt charts is necessary also in production phase.

After the vehicle is built, an insight on validation and testing phase is provided, subdividing it into four levels, that are component, subassembly, assembly and vehicle levels with their respective examples.

Final chapter on operations and maintenance described how the car is being operated during both track test days and race events, along with the maintenance required by the vehicle.

7.1 Final considerations and future developments

In this final thoughts I want to resume some considerations I came up with what Formula Student experience has left to me both from a technical and human sides, apart from the other I have already spoke about in the course of this work.

First of all Formula Student is about people, and then about machine. This is usually misunderstood when working on these projects but a the end of the day we are working together as a Team, and a Team is made up of people first. Everyone is different but everyone should work together and strive together to reach the same goals, as a Team, not as individuals. During the Formula Student experience some of the most intense friendships of the college period are born and still go on once the experience in the Team is finished. The real bonding experiences mostly happen outside of the office and it is extremely important to privilege those moments as a boost for the human relationships and the development of the car aswell. Passion is key when working in a Formula Student project, without passion of each Team member things could go wrong.

It is normal that in the Formula Student experience everybody has a different dedication to the Team in terms of hours put in the project. There will always be the core of the Team that puts extra hours to compensate for the work that has to be finished on time. As a division leader or board member you have to accept that, we all are different and all go through different things in life, both college and personal lives, so be emotionally intelligent, you cannot change the other, but you can optimize the resources you have in order to achieve better results.

As the technical lead in the first time of the season I used to check too much the other Teams member work, in order to make sure that everything was done properly and errors could be detected in the early phase of the design. Later on I understood that this is not the right approach to adopt. In fact, it is more about giving your colleagues better processes to follow, in all the project phases, that are more robust and allow to do a much more consistent and error-free job. This is a critical point where SC should to strive a lot for improvements. At the end of the day you, as a team leader or technical leader, you cannot control everything, you have to trust your Team mates and Division leaders, remembering that you cannot build the car on your own, but it is a Team effort. When you are one of the very few Team members that represent the Team, you have to realize that you are representing not only them as individuals, but also their countless hours and tears put in to make the project possible in real life. It is important to provide them with the right tools and processes in order to make their life easier, not harder.

Sometimes it happens that things do not go as planned, and also things have not been done according to what scheduled in advance. Amongst all the different possible causes it is important first of all that whenever you are telling, explaining something to one of your colleagues, the information has been received and understood. I know that this may sound so trivial but trust me, some problems may just arise by the misunderstanding of some information, both technical and non-technical.

Now I will briefly go through the tools that are important for the technical management of the Team where improvements should be done in my opinion.

Regarding Project Management activities, I would personally suggest to study and learn the basics of PM before going to use the PM tools, I would personally have found it much easier, efficient and profitable if I had done so, managing part of a project like Formula Student one. I think this applies as well for the Team Leader preparation since Project Management involves a lot of disciplines not solely technical. Countless errors could have been avoided and better results achieved if better preparation was dedicated from my side in the early phase of the season, without focusing too much on target setting and design phases. The definition of important metrics and KPIs to trace and monitor the project development should be implemented in the future. Another possible path could be to introduce the figure of a Project Manager that is fully dedicated to PM activities and relieves the burden of both Team Leader and Technical Director.

Design books are an amazing tool to correctly trace the work done in a season. Design books should be written with comparable effort by everyone in the Team, but unfortunately there has been quality difference in the redaction of those reports amongst the Team members. It should be clear that these reports are a useful tool for the future and should not be approached only as one of multitude of things you have to do. Furthermore, design books are useless if not read. I have seen some problems arise just by the fact that the members responsible for a subassembly have not gone through the previous seasons design books, just because they felt they did not have the necessity to do so. Some time should be dedicated in the first part of the year analyzing all the material available in order to understand the state of the art in that area of the car. Just imagine you spend some weeks thinking and designing a concept that in the end does not work, and you discover later on that this solution was already been discarded maybe two years before: is it worth to look at the previous years design books? Once everything is clear you can start to design, otherwise it is like grope around in the dark. This should be applicable as well for the division leaders and the technical director for the technical data management as well.

FMEA is a tool that should be vastly improved inside SC. Its use is not enough rooted in both the design and testing phases. Lots of failures should be traced in order to do not lose track during the years. Similar considerations as per project management tools learning process before the design phase starts are applicable to the FMEA.

For the production phase there should be implemented production books as well. Apart from the monocoque topic, all the subassemblies involved in the production should have consistent reports that go beyond of the pictures taken during the production phase, pictures only are not sufficient. We wanted to implement in 2021 season but did not have the physical time and human resources to do so.

Much more resources, better prepared and organized, should be dedicated to electric and electronics areas, since their lack of reliability and robustness could easily hinder the success of the project. It is useless at the end of the day to have a well designed race car from the mechanical and aerodynamics points of view if both HW and SW sides of powertrain and LV circuits do not follow the same trend. The car should be an embedded system of well-designed components rather than a set of outstanding parts not properly integrated with each other.

Regarding the data management huge improvements should be done, ideally adopting a PLM software. This was studied in between the 2020 and 21 seasons but did not come to life. The adoption of a PLM would drastically change the way data are stored inside the Team. In alternative to this, a Team's database or Wiki like website should be implemented for fast and effective data management, research and update, as other Teams have been doing for years. In 2021 season again, a Team's database was created but was not implemented correctly as dedicated people should have been devoted to develop properly that tool.

"Less is more" as Ludwig Mies van der Rohe once said.

Regarding the design phase I would suggest to do less stuff, but doing it in a controlled and effective way, following all the V-cycle phases, DFMA practices and avoiding potential troubleshooting. Time available in one season is very little considered all the stuff it has to be done. Much more time should be dedicated to the Validation phase, that usually is neglected. Let us say that the attention to the Project phases should be reversed in order of importance from what has been done for years: Validation should take the first place, followed by the production and then the design, not the other way around. In this way you will find out that very little time is actually dedicated to the design, such as some successful German teams do, they only design for three months, from September to December.

Another trivial but important thing is that a proactive approach should be used in each area of the Project. Several problems are avoided if both the design and production phases are approached with a mind that is not happy with the mere minimal work to be done, but instead strives for excellence and looks to different possible consequences to the actions taken. I cannot design a component without having in mind the constraints coming from my environment, and at the same time I cannot assembly a subassembly without knowing what goes around it in the car.

Being able to react quickly to the problems that may arise is crucial, especially in the production phase. Certainly things will not go as planned, but quick thinking in taking the right decisions can make the difference.

In the end, there is always room for improvement in every aspect of the Team and the car, there will always be ups and downs for sure, but the important thing to remember even when things do not go in the right direction is that you enjoy this wonderful experience, it happens only once in a lifetime!

Forza Squadra Corse!

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A Vehicle technical drawings

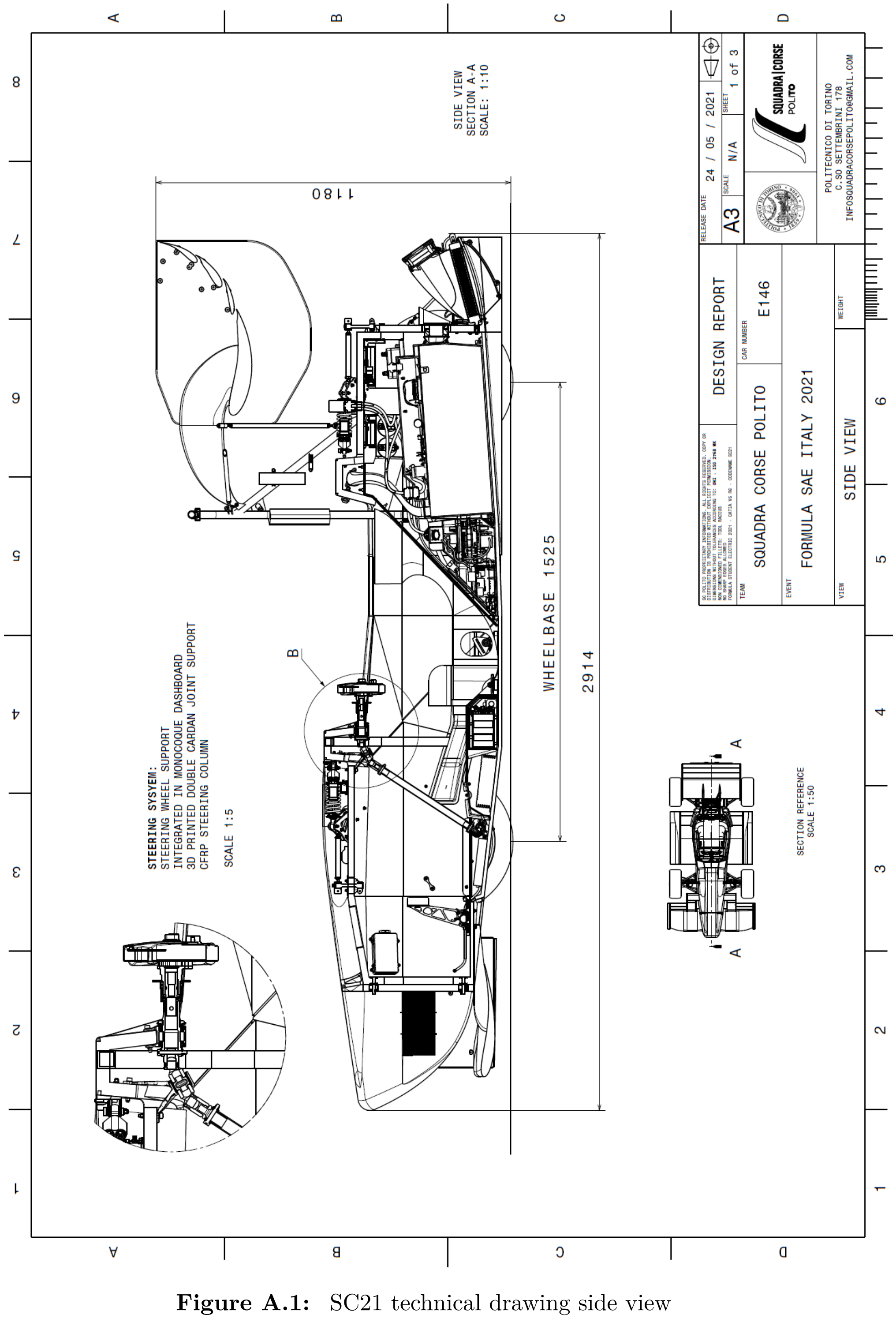

Figure A.1: SC21 technical drawing side view

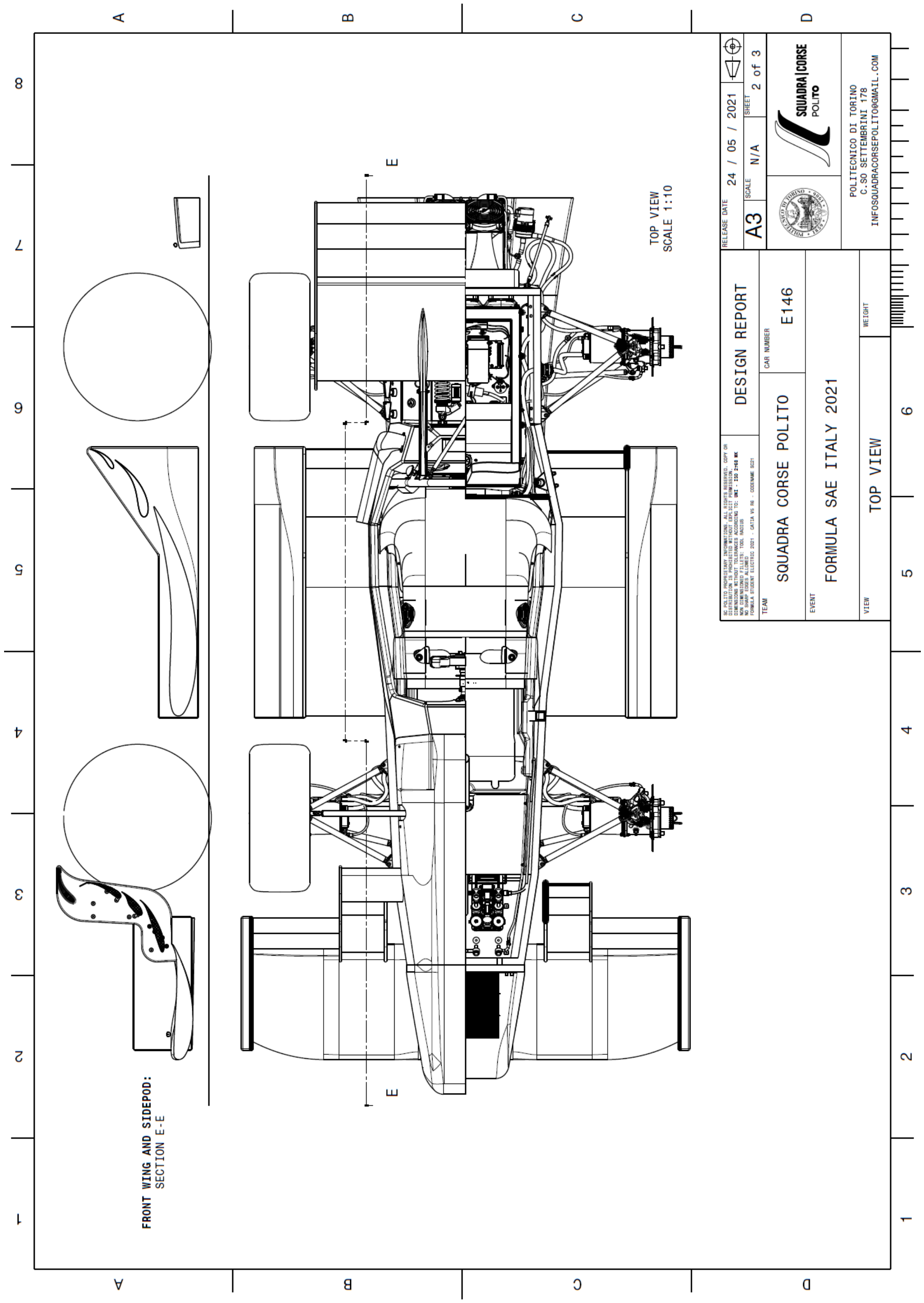

Figure A.2: SC21 technical drawing top view

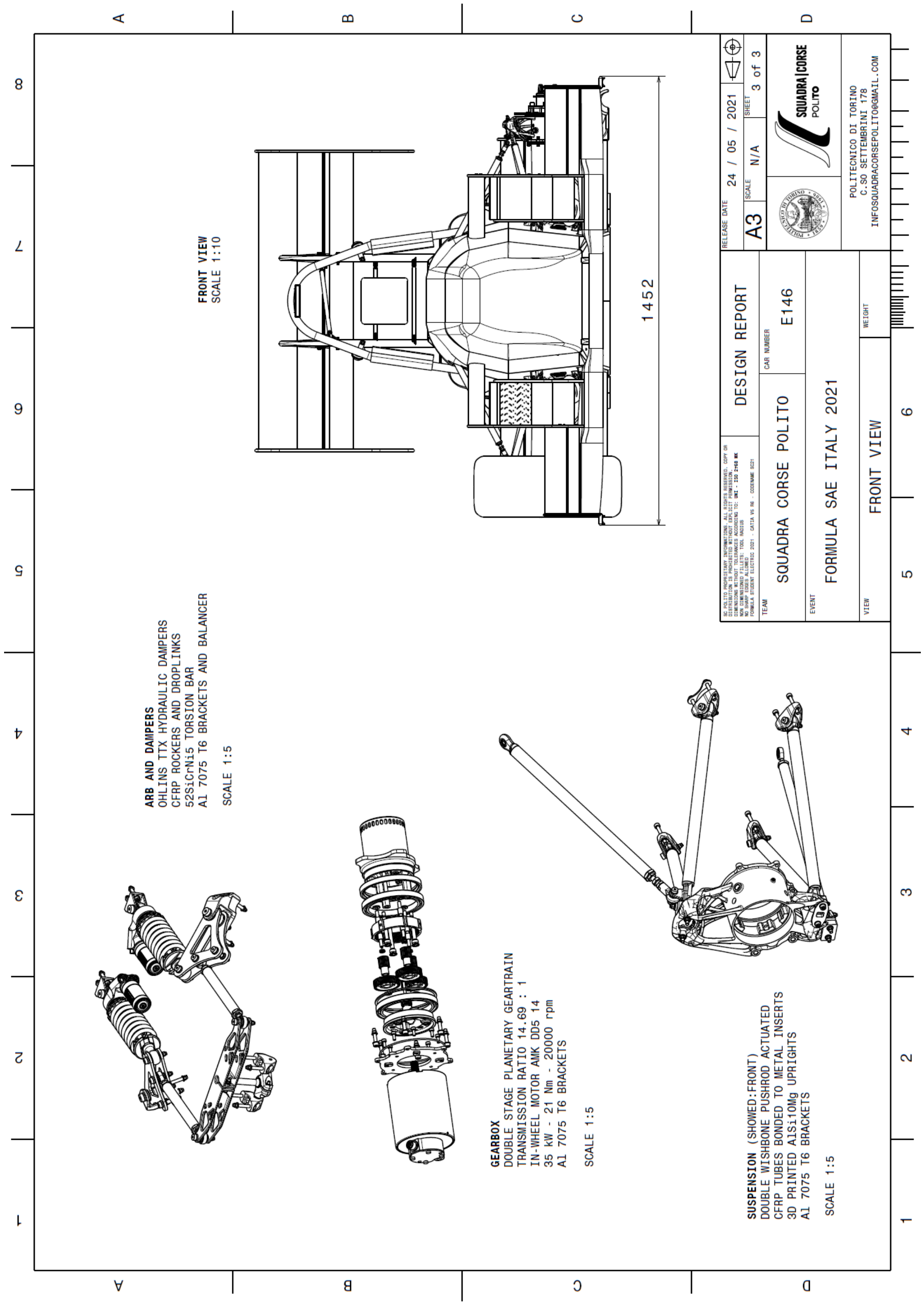

Figure A.3: SC21 technical drawing front view

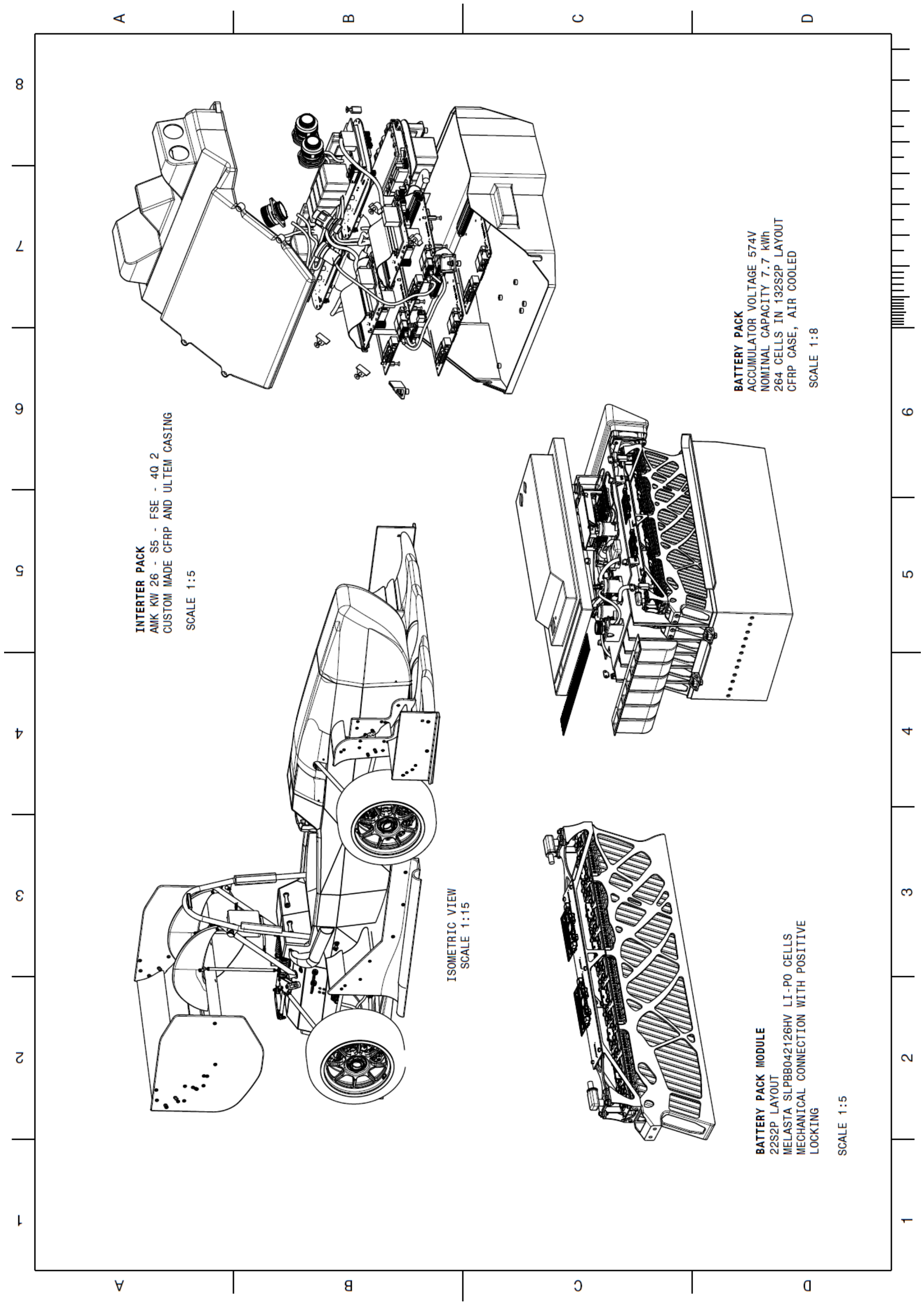

Figure A.4: SC21 technical drawing isometric view