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Design of a Radiator Assembly for a Formula Student Vehicle

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Abstract

The cooling of a racing car is an important aspect that has significant implications for both its reliability and performance. In an extremely competitive championship like Formula Student, a properly sized cooling system is essential for achieving excellent results in dynamic events.

The purpose of this master's thesis is to design a radiator assembly for the Politecnico di Torino SC26 Formula Student car. To achieve this, it was necessary to analyze the car's design targets in order to understand how the radiator assembly could help achieve them. The results were the targets of the cooling system and, as a consequence, the targets of the radiator assembly.

The project was then advanced using CAD software, thermal simulations, and CFD simulations. Once the radiator was sized, the next step was to find the correct position for the assembly within the car, taking into account three KPIs: air flow, interaction with aerodynamics, and influence on weight distribution. Subsequently, after selecting the best positioning, optimization was performed to improve its integration with the car's other assemblies.

The result was a component that, compared to the previous solution, is able to dissipate 39% more heat into the environment, respecting the car's new targets, while reducing weight by 29% .

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1 Introduction

1.1 What is Formula Student

Formula Student is an international design competition of speed, skills and spirit. Each year, teams made by university students from all over the world, develop and build a single seated formula style car to compete against each other. The winner team of the competitions is not the one that produces the fastest vehicle, but rather the team with the best overall package of construction, performance, and financial planning.

The competition takes place in several events during the summer. There is no institution that organizes the world championship but each race has its own organization and its own version of the rules. The rule book adopted by most competition is the one drawn up every year by the German one, Formula Student Germany (FSG), held each year at Hockenheim.

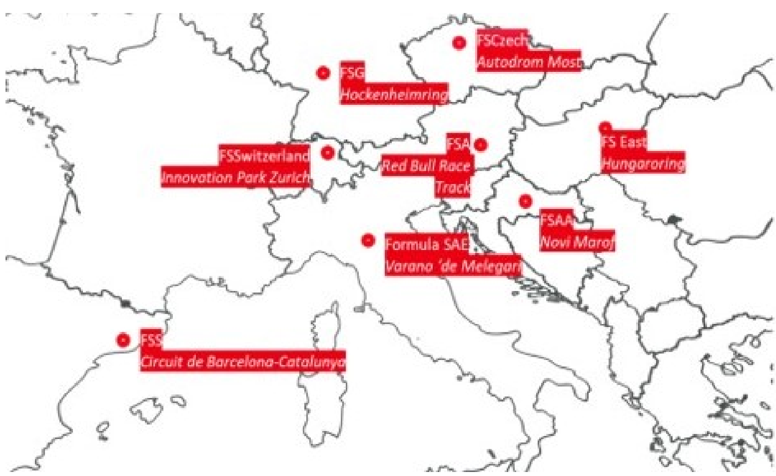

Figure 1: Map of the main European Formula Student competitions

Three categories are admitted at the majority of competitions: Electric Vehicles (EV class), Combustion or hybrid Vehicles (CV class) and Driverless Vehicles (DV class). The DV can be based on a EV or CV platform and the same vehicle can compete in both categories.

At each competition there are two kinds of events: static ones and dynamic ones

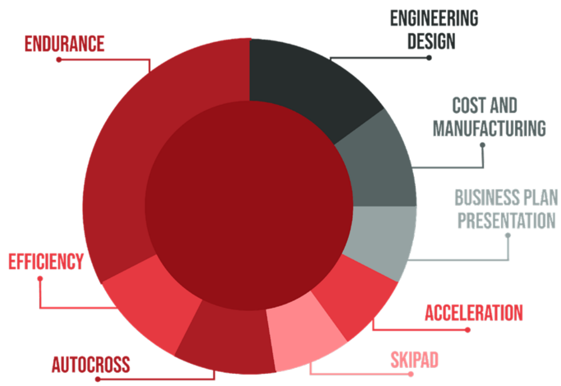

Figure 2: Points ditribution across the various Formula Student events

1.1.1 Static events

During the static events, a committee of experienced experts from the automobile, motorsport, and supply industries judge the performance of each team. There are three different events:

- **Engineering Design Event:** it consists in a discussion focused on clarifying technical details, exploring the thinking behind the chosen design and the corresponding technical understanding of the students. The evaluation will not only assess the quality of the technical solution in question but also the reasons behind it.

- **Cost and manufacturing:** it consists in a discussion about a written report that the teams must prepare with the calculative size of the vehicle, its components, and the necessary manufacturing steps. The students must then answer questions from the judges relating to the cost report on their prototype.

- **Business Presentation:** each team presents their business plan for the constructed prototype to the judges. During the presentation, the team must demonstrate why their design best fulfils the demands of their target group and show how their design can be successfully marketed.

1.1.2 Dynamic events

The performance on the track of the vehicles is tested during the dynamic events. For safety reasons, wheel to wheel racing is prohibited. So, a series of various event tests different features of the vehicles:

- **Acceleration:** the acceleration of the vehicle from a standing start is measured over a 75 metre straight. The goal of this event is to highlight the longitudinal dynamic of the vehicle.

- **Skidpad:** the cars must drive a figure of 8 circuit lined with track cones, performing two laps of each circle. The lap time gives a comparative value for the maximum possible lateral acceleration of the car. The goal of this event is to highlight the lateral dynamic of the vehicle.

- **Autocross:** the cars travel along a kilometre-long track with precise regulations:
  • Straights: No longer than 80m
  • Slaloms: Cones in a straight line with 7.5m to 12m spacing
  • Miscellaneous: Chicanes, multiple turns, decreasing radius turns, hairpin turns, etc.
  • The minimum track width is 3m
  • The minimum required turning diameter is 9m

- **Endurance:** the vehicles have to travel for 22 kilometres around a track similar to the autocross one. After the first 11 kilometres, a driver change must be completed. Due to logistic reasons, up to four different vehicles can run at the same time. The starting order of the endurance is decided considering the results of the Autocross. In this way, the vehicles that are running simultaneously have similar performances and the chances of overtaking are reduced. If an overtake is needed, there are dedicated parts of the track, with a double lane, to complete a safety operation.

- **Efficiency:** during the Endurance the energy consumed, for the electric vehicles, or the fuel burned, for the combustion vehicle, is measured and put in relation to the time required for completing the endurance.

To be eligible to participate in the various dynamic events, each car must pass a series of technical inspections to ensure its safety, compliance with the regulations, and good engineering practices.

Once compliance with the regulations has been verified, the car is subjected to three further tests

The car is put on the tilt table, a platform which tilts the car on both sides until 60 degrees to certify if there is any liquid loss.
The electric cars also have to pass the rain test. During it water is sprayed on the car in all directions for 120secs, simulating a rainfall.
The last one is the brake test. After an acceleration, the car has to be able to secure all four wheels at the same time without switching the engine off.
For each inspection passed, the team receives a sticker to apply to the car. Only after obtaining all the necessary stickers can the car participate in dynamic events.

Figure 3: Sticker application after the tilt test

1.2 Squadra Corse PoliTo

Squadra Corse PoliTo is the Formula Student team of Politecnico di Torino. It was founded in 2004 by a group of automotive engineering students, brought together by the same passion for motorsport. It is now a well-established organization, involving students from different engineering fields. The team deals each season with the design, production and testing of a full-electric single-seater open-wheel race car. The goal of the team is to compete in the European events of the Formula Student Championship against universities from all over the world.

Since the foundation, Squadra Corse competed in the CV category obtaining various podiums and the victory of the Formula Hybrid Championship in 2010. Since 2012 the team has been racing in the EV, becoming the first Formula Student team in Italy to build a full EV.

Figure 4: The 2025 Squadra Corse team at the SC25 presentation

The team is composed by eighty people divided into ten divisions:

- Aerodynamics and CFD
- Chassis
- Communication and media
- Electronics
- Management

- Powertrain
- Thermal management
- Unsprang masses and geartrain
- Vehicle dynamics and controls systems
- Drivers

Each division is managed by a division leader and the entire team is coordinated by three persons which form the eleventh division, the Board: the team leader, the technical director and the production director.

Here are some of the main features of the SC25:

Mass without driver	212 Kg
Front mass repartition	45%
Wheelbase	1.525 m
Track	1.202 m
Center of gravity height from ground	0.28 m
Tires	Pirelli PZero 185/40 R14 slick
Rims	R13 magnesium alloy
Aerodynamic lift coefficient	4.8
Aerodynamic drag coefficient	1.5
Front aerodynamic balance	58%
Nominal HV battery pack capacity	7.7 kWh
Nominal HV battery pack voltage	564 V
0-100 km/h	2.6 s
Maximum speed	122 km/h
Maximum lateral acceleration	2.5 g
Powertrain type	Electric 4WD in wheel (IMP motors)
Maximum motor power by data sheet	35 kW
Maximum regenerated power	40 kW
Transmission ratio	14.69

The car is entirely designed, built, and tested by team members. A new prototype is produced each year, striving to constantly improve its performance. Each assembly is analyzed at the end of the racing season to determine any potential development potential. If a component needs to be improved to increase performance, but its development has reached its end, a new one is redesigned to meet the targets.

In order to maintain the correct workflow inside the team, a particular attention on the integration of the various assemblies is required. To reach this goal, various useful tools are used, like a team Gannt in which there are all the tasks of the entire team. This organization permits to obtain the sufficient awareness of all the criticalities that can naturally rise in a numerous team.

Figure 5: SC25 during the test session

2 The current Cooling system configuration

The design of the cooling system of the Squadra Corse prototype was essentially the same since 2021.
It is divided into two different systems: an air-cooled system for the battery pack and a water-cooled system for the inverters and the motors. The first one is composed by two air ducts that bring external air directly inside the Battery Pack enclosure and by two fans that provide additional airflow if the passive one is not enough. The second one is composed by two identical branches, one for each side of the vehicle, made of a pump, a coldplate for the inverters and two cooling jackets for the motors. The two halves then flow into a single radiator. The air mass flow through the radiator is guaranteed by two fans.

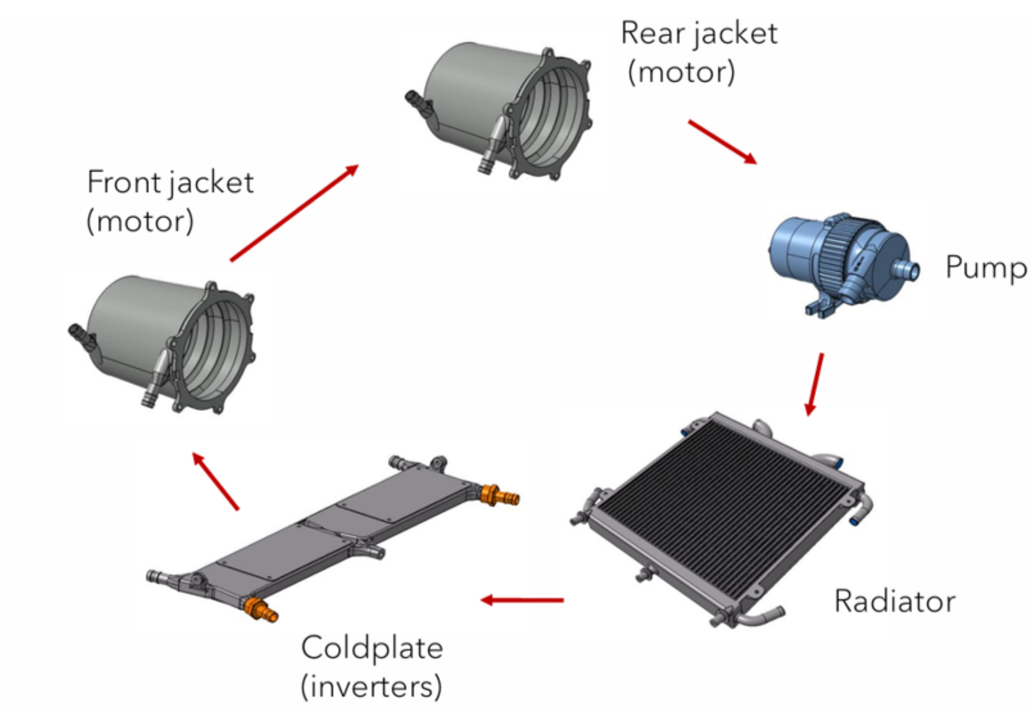

Figure 6: Water cooling system operating diagram

In order to set properly the cooling targets, the data of the two endurances events during the 2019 season were used: FSpain and FSCZ. The third endurance run during the 2019 season, FSATA, was not take into account because of the wet conditions occurred during the endurance. In addition, data from the autocross events in the two races were also considered. The power to be dissipated was calculated using the efficiency maps provided by our powertrain supplier AMK. As for the motors, AMK gives us three different maps at three different temperatures: 80°, 100°, 120°. Thanks to the temperature and power data it was possible to make an interpolation of the maps to obtain the efficiency values. As far as the inverters are concerned, the efficiency has a nearly constant value of 0.98.

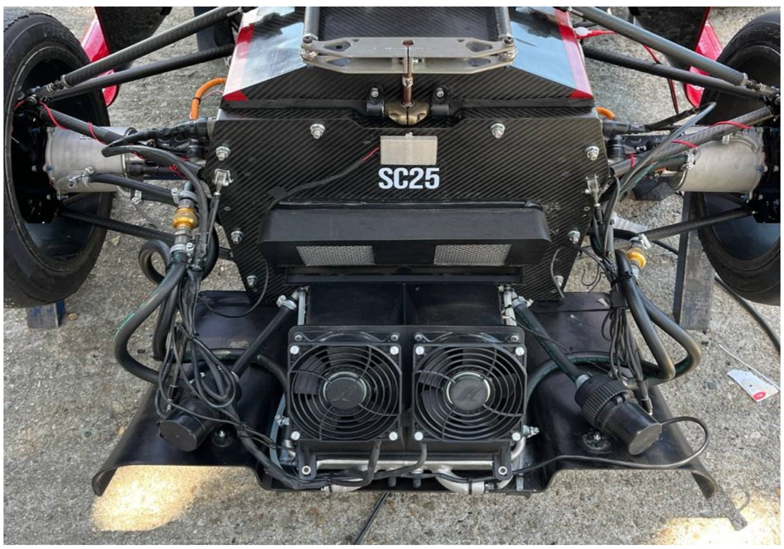

Figure 7: Radiator assembly of the SC25

The position of the radiator was chosen after some simulation performed by the Aerodynamics division. The final position, on the diffuser of the vehicle, was the result of a trade-off between the required air mass flow to dissipate the previously calculated thermal power and the improvement in downforce (Cz coefficient). The improvement in terms of aerodynamic performance depends on the improved design freedom, with respect to the SC19 solution, of the aerodynamic package in the sidepods zone. In fact, without the presence of the radiator assembly, the sidepod can be optimized without packaging limits.

Unfortunately, due to reliability problems, the prototype could not express the full potential for the next two seasons. The 2023 was a particular year for Squadra Corse: due to an unannounced budget reduction, the team could not participate in any competitions. Instead, the team focused on solving all the reliability problems that had arisen during the previous two seasons. Three different endurances were completed during the tests for the first time since 2019. During those runs, at a medium pace with limited regenerative braking, the cooling system performed well.

During the 2024 Formula Student season, Squadra Corse took part in three different competitions.

In Formula Student Austria (FSA) unfortunately the car did not pass the electrical inspection due to a component failure and the team competed only in the static events. In addition, the failure compromised part of the testing period.

Figure 8: The SC24 during the Endurance event at Formula Student Germany 2024

In Formula Student Germany (FSG) the team repaired the vehicle that successfully passed all the inspection. This race marked the return of Squadra Corse at the dynamic events of FSG after eleven years of absence.

The car performed well during all the dynamic events reaching the top 20 positions. Unluckily, due to extreme rain conditions during the event, the car did not finish the endurance: some drops entered into the Traction System Measurement Points during the driver change. This caused a loss of isolation, triggering a safety protocol that prevented the car from restarting.

At the end of the competition, we felt proud of what we had achieved in the most important and competitive race but, at the same time, we knew that with a free failure testing period and better luck we could aim to better results.

After two weeks of performance-oriented tests, we participated to the last competition of the season, Formula SAE Italy. During the entire race, the performances of the vehicle were pushed to the limit, improving the lap times in the Acceleration and Skidpad events with respect to FSG. Also in this race the endurance was held in wet conditions in incessant rain but, thanks to the experience gained in FSG, we managed to complete the event.

Figure 9: The SC24 during Formula SAE Italy 2024

It can be easily understood that the cooling system of the prototype never faced problems during those years. The lack of reliability did not allow the car to often show its full potential. Furthermore, considering that the event in which the cooling system is stressed is endurance, having only raced endurance in extraordinary weather conditions deprived us of being able to see the real limits in the race. On the other hand, during the simulated endurance events, we noticed that the temperatures of the inverters rose over the safety limit after the first five laps of a stint. This rise forces the Inverter control system to reduce the electrical power in order to avoid overheating.

3 Target Setting

Analysing the results of the 2024 season, it was clear to us that the vehicle had some characteristics that limit the maximum performance, with respect to the main competitors, and does not allow us to achieve better results. So, we decided to set new targets for the vehicle in order to aim for better results. Team targets:

- **Reach the top 10-15 in every dynamic event of a highly competitive race like FSG or FSA**

  The results of the 2024 season show us that the vehicle can perform well even in an extremely difficult competition like FSG. To be in the top 20 against the top 80 teams in the world is a source of great pride for us. But, at the same time, we want to do better. We acknowledge that aiming to better positions is doable. Obviously, in order to reach such target, the fundamental requirement is to have a reliable prototype.

- **Weight reduction**

  The weight of our vehicle is definitely one of our biggest limitations to improving the performance. The SC24 weights 212 kg, which is a lot compared to the top teams:
  - FS Team Tallinn Electric (1st World Ranking 2024) 178,8 Kg
  - Joanneum Racing Graz (2nd World Ranking 2024) 151,5 Kg
  - AMZ Racing Team (3rd World Ranking 2024) 173,8 Kg

  Each assembly of the car must be analysed to identify where we can reduce the weight of the car without affecting its reliability.

- **Improve the integration between the various assemblies**

  Each assembly can have some mechanical characteristics, requires a specific working temperature or may need special cables or packaging constraints. During the design of a new component, it must be clear how it will interface with the other assemblies to avoid inconsistencies. Improving the integration will also help the manual work on the vehicle during track days or the competitions, simplifying the operations and reducing valuable working time.

Those targets were decided by the Board and discussed with the Division Leaders. Later, the job of each division was to select the right design targets of each assembly in order to reach the general vehicle targets.

If any component is not compliant with the new targets, it will be modified or redesigned.

3.1 Radiator target setting

The identification process of the new targets for the radiator assembly started from the general targets.

- **Reach the top 10-15 in every dynamic event of a highly competitive race like FSG or FSA**

  The only dynamic event during which the cooling system plays a relevant role is the Endurance. In fact, the time duration of Acceleration, Skidpad and the Autocross is not long enough to justify a dedicated design.

  After the 2024 competitive season, we performed several track tests to obtain data for the new targets. In particular, we tried different Endurance paces to find the right trade off between lap time and energy consumption. Those tests were crucial for the Powertrain division to estimate the new High Voltage Battery Pack energy target and for the Thermal Management division to estimate the correct value of thermal power to dissipate.

  In this way, the Battery Pack would be dimensioned to complete the Endurance at the desired pace and the cooling system would be dimensioned to avoid any thermal power derating during the event. The power derating is the intentional reduction of the power of inverters or motors to ensure its safety and reliability.

  So, to achieve a top 10-15 position during the Endurance, the cooling system must dissipate enough heat to complete the event at the desired pace without occurring in thermal derating.

  After the tests performed on the track, we could identify the lap that correspond to the desired Endurance pace. The characteristics of this lap are:

- Maximum electrical power in traction = 75,5 kW
- Maximum electrical power regenerated during braking = 29,4 kW
- Electrical power (RMS value) = 40 kW

In order to obtain the right value of thermal power produced by the electric motors to dissipate, we developed a script that extracts different data from the track telemetry and, with the help of three different efficiency maps provided by our powertrain supplier AMK, finds the thermal power.

The three AMK maps correspond to three different motor operating temperatures: 80 °C, 100 °C and 120°C. For each timestamp of the telemetry log file, the code extracts three values:

· The temperatures of the four motors [°C].

· The motors currents intensities [A].

· The motors rotational speeds [RPM].

Depending on the motor temperature, the code selects the right efficiency maps. If the motor temperature is lower than 90 °C, it will use the 80 °C one, while if it is more than 90 °C but less than 110 °C it will use the 100 °C one. Otherwise, if the motor temperature is higher than 110 °C, the 120°C map will be used.

Interpolation was not considered because the temperature intervals are relatively close and there are not significant changes across different temperatures.

Due to regenerative braking, some current values are negative. In this case, the code takes the absolute value of the current, treating it as traction operation. This approximation, of considering the losses produced both in the regenerative phase and in the discharge phase as equal, is the only way we have to take into account the regenerative braking, since we do not have specific efficiency maps at our disposal for this case.

In the end the code provides the maximum and RMS values of thermal power for each motor. What we need for the radiator dimensioning are the RMS values:

	Thermal Power RMS [W]
FL	899,7
FR	891,4
RL	1402,6
RR	1385,7

Table 1: RMS values of thermal power produced by the four motors

The four motors are identified by their position: front left (FL), front right (FR), rear left (RL) and rear right (RR). In addition, it is also possible to plot the thermal power produced by the motors during the test

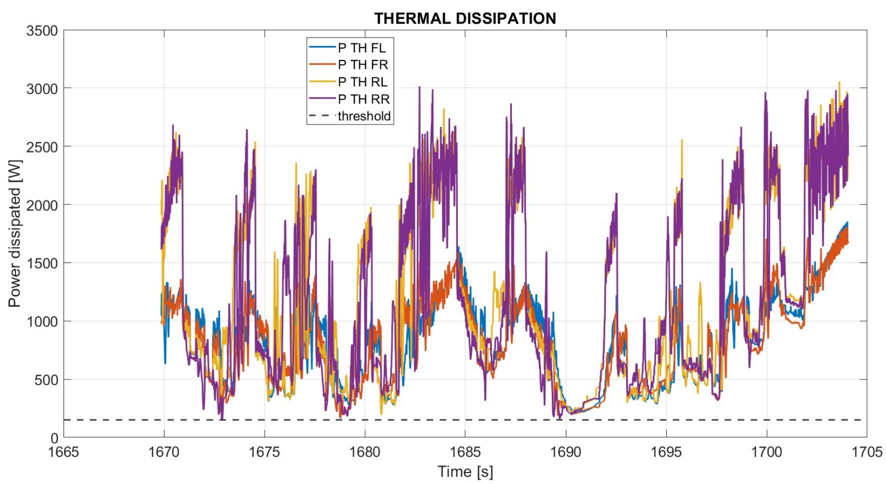

Figure 10: Thermal power dissipated by the motors during a lap

A similar script is used also for the inverters.

	Thermal Power RMS [W]
FL	107,4
FR	105,5
RL	200,2
RR	194,1

Table 2: RMS values of thermal power produced by the four inverters

The differences between left and right are due to the clockwise direction of travel on the track. The total thermal power on the most stressed side, the left one, is approximately 2600 W.

A safety factor of 1.2 is also considered, which increases the thermal power for each side to 3500 W. The safety factor was introduced with the expectation that the radiators could be used for multiple seasons. This allows for the development of the car's performance without being limited by the cooling system.

The final targets, considering the safety factor and the most stressed side are

Inverter	728,64
Front motor	1079,64
Rear motor	1683,12

Table 3: Design target of thermal power dissipation [W]

.

- **Weight reduction:**

  The cooling system of the SC24 is already the lightest one in the vehicle. Considering both the water-cooling and the air-cooling system, the total weight is around 8,36 Kg.

  In the next prototype, the Low Voltage Battery Pack, which is used to power the low voltage electronics, the cooling fans and the water pumps, will be replaced with a DC/DC converter. This converter requires

Part	**Mass [Kg]**
Front Jacket Assembly Right	0,20
Front Jacket Assembly Left	0,20
Rear Jacket Assembly Right	0,20
Rear Jacket Assembly Left	0,20
Radiator Assembly	3,36
Coldplate	0,60
Water Routing Assembly	3,00
HV Battery Cooling Assembly	0,60

Table 4: Mass of the various Thermal Management components in SC25

an additional cooling fan, which negatively impacts the weight of the assembly.

Additionally, the updated cooling targets are significantly higher in terms of power to be dissipated, which can bring to an increase of dimensions and weight of the radiator assembly.

So, it was considered unrealistic to aim for weight reduction in this assembly without reducing reliability. As a consequence, the target of the radiator assembly and of the entire cooling system is to maintain the same weight of the SC24 system, while increasing the thermal performances.

Another problem of the current vehicle, besides the high weight, is the high yaw moment of inertia which reduces the handling and responsiveness of the car during the numerous fast changes of directions. The Vehicle Dynamics division made some analysis to identify the assemblies that contribute the most in the increase of rotational inertia. Surprisingly, despite weighing only 3.2 kg, the radiator assembly is the third largest contributor to yaw inertia, behind only the HV Battery Pack and the rear wing. This is due to the elevated distance between the radiator and the car centre of mass.

So, in the next design, the reduction of the contribution to the yaw inertia of the radiator will be taken into account.

- **Improve the integration between the various assemblies**

  The cooling system has to interface with a lot of different other assemblies.

  The radiator assembly can have a significant impact on the aerodynamic components surrounding it. It needs the right amount of air, with high total pressure. The fans, which help ensure the necessary airflow even at low speeds, also have a significant impact on aerodynamics performances and can be used to energize the flow in certain areas.

In addition to the targets, other parameters must also be taken into consideration during the design. For example, it is necessary to take into account the maximum temperatures that inverters and motors can withstand before resorting to thermal derating, which are provided by our powertrain supplier AMK. For the inverter the maximum temperature is 50°C while for the motors it is 105°C.

Another key parameter for sizing the radiator is the outside air temperature. To find a value that is suitable for all European Formula Student competitions, research was carried out on the maximum temperatures recorded in the various race locations.

· Formula Student Germany (Hockenheim, Germany) = 33°C
· Formula Student Alpe Adria (Mičevec, Croatia) = 33°C
· Formula SAE Italy (Varano de' Melegari, Italy) = 32°C
· Formula Student Spain (Barcelona, Spain) = 32°C
· Formula Student East (Mogyoród, Hungary) = 32°C
· Formula Student Czech Republic (Most, Czech Republic) = 30°C
· Formula Student Nederland (Assen, Nederland) = 28°C
· Formula Student Austria (Spielberg, Austria) = 28°C

The temperature to be considered in the design phase was therefore decided to be 35°C.

4 Radiator technology and modelling

The radiator currently used on the SC25 is a radiator with louvered fins. This technology, introduced by Kays and London in the 1950s, is now widely used in various industrial sectors, including automotive and motorsport. Louvered fins do not have a smooth, continuous surface, but rather multiple interruptions. This increases heat exchange thanks to the continuous formation and destruction of the laminar boundary layer on the fin surface. The increase in heat exchange is notable, reaching up to approximately three times what would be obtained with smooth and continuous fins. The louvers have the further advantage that the enhancement of heat transfer is gained without increase in flow resistance that results from the use of turbulators.

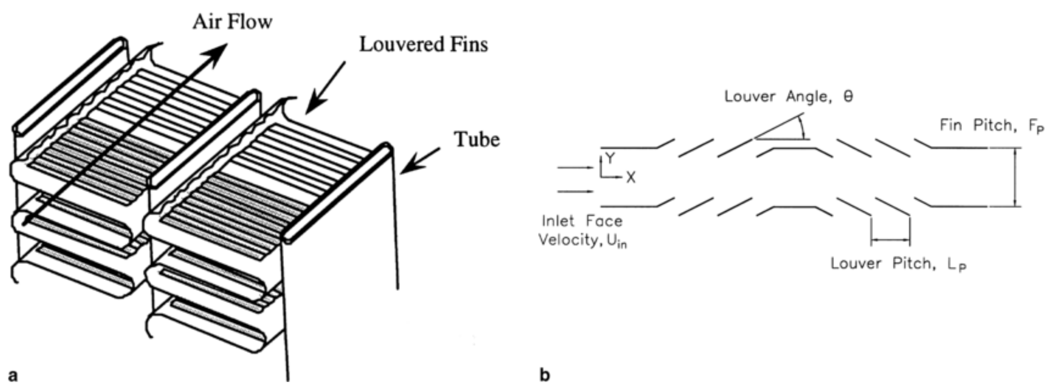

Figure 11: Louvered fin radiator section in axonometry (a) and along the airflow (b)

They are produced by cutting the fin and pushing the cut surfaces. This relatively simple system allows for rapid and economical production. Louvered fins can be produced with various fin, louver, and thickness sizes depending on the production method and customer requirements.

These characteristics make louvered radiators an excellent option for cooling a vehicle. Therefore, this technology will be used in this design.

4.1 Radiator thermal model

In order to correctly size the radiator, a model is needed that can simulate its performance by varying the main design parameters. A radiator model,

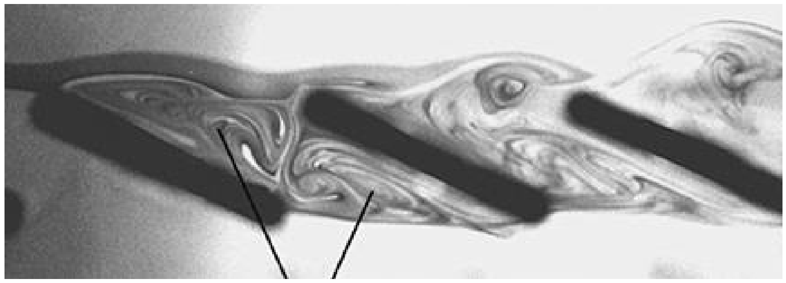

Figure 12: Detail of the turbulent flow generated by the louvered

in particular of the louvered fin type, was developed over the course of the various seasons in Squadra Corse.

4.1.1 Inputs

The first input part of the model concerns the radiator's geometric characteristics. This section contains both macro-characteristics such as height, length, and thickness, as well as characteristics more closely related to the exchanger type, such as tube wall thickness or geometric data on the louvered fins.

Major internal tube dimension (a)	Radiator wall thickness
Minor internal tube dimension (b)	Fin height
Tube wall thickness (s)	Fin length
Pitch between tubes	Fin thickness
Radiator length	Radiator height
Number of tubes per meter	Number of fins per length
Number of tubes in height	Radiator frontal area
Number of rows	λ_{tubes}
Internal hydraulic diameter of tubes	F coefficient

Table 5: Radiator geometric inputs

Then the thermodynamic inlet conditions of the two fluids must also be introduced: flow rate and temperature. By varying these parameters, under the same geometric conditions, the radiator's performance can be simulated under different operating conditions.

Water inlet temperature	Air initial temperature
Water mass flow	Air mass flow

Table 6: Radiator thermodynamics inputs

The properties of the two fluids, water and air, such as density and specific heat, are given as vectors because they depend on the thermodynamic properties of the system. A model function associates the correct value depending on the fluid temperature in the specific case.

Air	Water
ρ	ρ
c_p	c_p
λ	λ
μ	μ
	$\mu_{superficial}$
P_r	P_r

Table 7: Fluid properties

4.1.2 Water side calculations

To find the internal thermal resistance of a single tube, the first step is to calculate the flow rate in a single tube:

$$\dot{m}_t = \frac{\dot{m}}{n_{tubi}}$$

The velocity can be found:

$$v = \frac{\dot{m}_t}{\rho \phi_t}$$

Once the speed is found, the Reynolds number can be calculated:

$$Re = \frac{D_i v \rho}{\mu}$$

D_i represents the hydraulic diameter of the tube and μ dynamic viscosity.

The Reynolds number physically represents the ratio between the inertial forces and the viscous forces acting on a fluid particle moving within the same fluid.

Now it is possible to calculate Nusselt number in function of Reynolds number:

$$SeRe \leq 4000 \rightarrow Nu = 1,86(\frac{RePrDi}{L})^{0,33}(\frac{\mu_{sup}}{\mu})^{0,14}$$

$$IfRe > 4000Nu = 0,023Re^{0,8}Pr^{0,4}$$

The Nusselt number represents the increase in heat transfer through a layer of fluid by convection, compared to that transferred through the same layer by conduction.

From the Nusselt number it is possible to obtain the convective heat transfer coefficient:

$$h_w = \frac{Nu\lambda}{D_i}$$

In conclusion the thermal resistance for a single tube:

$$R = \frac{1}{h_w A_{int,tube}}$$

4.1.3 Air side calculations

The thermal resistance between the air and the external walls of the pipes can be expressed as:

$$R = \frac{1}{h_{air} A_{ext,tubo}}$$

Where the convective coefficient of the air is:

$$h_{air} = \frac{j\rho v_{eff} c_p}{Pr^{\frac{2}{3}}}$$

Wang theory - Round Tube Through the equations defined by the above theory we obtain the Colburn factor [j] which, in relation to the convective coefficient of the air, will provide an estimate of the thermal resistance between the air and the external walls of the radiator.

For $Re_{Dc} >= 1000$ Colburn number is:

$$j = 1.1373 Re_{Dc}^{J5} (\frac{F_p}{P_l})^{J6} (\frac{L_h}{L_p})^{J7} (\frac{P_l}{P_t})^{J8} (N)^{0.3545}$$

With:

- $J5 = -0.6027 + 0.0259 (\frac{P_t}{D_h})^{0.52} (N)^{0.5} \frac{L_h}{L_p}$
- $J6 = -0.4776 + 0.40774 (\frac{N^{0.7}}{ln(Re_{Dc}) - 4.4})$
- $J7 = -0.58655 (\frac{F_p}{D_h})^{2.3} (\frac{P_l}{P_t})^{-1.6} N^{-0.65}$
- $J8 = 0.0814 (ln(Re_{Dc}) - 3)$
- $D_h = \frac{4 A_{min} L}{A_{tot}}$

Wang theory - Flat tube The Colbur factor is obtained directly by relating the geometric data of the heat exchanger and the Reynolds number as follows:

$$j = Re_{Lp}^{-0.49} (\frac{\theta}{90})^{0.27} (\frac{F_p}{L_p})^{-0.14} (\frac{F_l}{L_p})^{-0.29} (\frac{T_d}{L_p})^{-0.23} (\frac{L_l}{L_p})^{0.68} (\frac{T_p}{L_p})^{-0.28} (\frac{\delta_f}{L_p})^{-0.05}$$

Where:

- $F_l \rightarrow$ Fin length;
- $L_p \rightarrow$ Louver pitch;
- $L_l \rightarrow$ Louver length;
- $T_d \rightarrow$ Tube depth;
- $T_p \rightarrow$ Tube pitch;
- $\theta \rightarrow$ Louver angle.

Chang theory - Flat Tube This theory aims to calculate the Colburn factor [j] through the *Fanning Friction Factor* [f]: The f coefficient is defined by the product of three coefficients.

- If $Re_{Lp} < 150$:

f1 $= 14,39 Re_{Lp}^{-0,805\frac{F_p}{F_l}} (ln(1,0 + (\frac{F_p}{L_p})))^{3,04}$

f2$=(ln((\frac{F_l}{F_p})^{0,48} + 0,9))^{-1.435} (\frac{D_h}{L_p})^{-3,01} (ln(0,5 Re_{Lp}))^{-3,01}$

f3 $=(\frac{F_p}{L_l})^{-0,308} (\frac{F_d}{L_l})^{-0,308} (e^{-0,1167\frac{T_p}{D_m}}) \theta^{0,35}$

- If $150 < Re_{Lp} < 5000$:

f1 $= 4,97 Re_{Lp}^{0,6049-\frac{1,064}{\theta^{0,2}}} (ln(0,9 + (\frac{\delta_f}{F_p})))^{-0,527}$

f2 $= ((\frac{D_h}{L_p}) ln(0,3 Re_{Lp}))^{-2,966} (\frac{F_p}{L_l})^{-0,7931(\frac{T_p}{T_h})}$

f3 $= (\frac{T_p}{D_m})^{0,0446} ln(1,2 + (\frac{L_p}{F_p})^{1,4})^{-3,553} \theta^{-0,477}$

$$f = \text{f1*f2*f3}$$

It is possible to estimate the pressure drops as:

$$\Delta p = \frac{2 f F_d \rho v^2}{D_h}$$

The relationship between the Colburn factor and the Fanning Friction Coefficient is as follows:

$$j = \frac{f}{2}$$

At this point, the thermal resistance between the air and the external walls of the pipes can be expressed as:

$$R = \frac{1}{h_{air} A_{ext,tube}}$$

Where the convective coefficient of the air:

$$h_{air} = \frac{j \rho v_{eff} c_p}{Pr^{\frac{2}{3}}}$$

4.1.4 Thermal resistance across the tube thickness

Tube thermal resistance = $\frac{ln\frac{D_{i,ext}}{D_{i,int}}}{2\pi\lambda_{tubi}l}$

4.1.5 ε -NTU method

In the ε -NTU method, the heat transfer rate from the hot fluid to the cold fluid in the exchanger is expressed as:

$$q = \varepsilon C_{\min}(T_{h,i} - T_{c,i}) = \varepsilon C_{\min}\Delta T_{\max}$$

where:

- ε is the heat exchanger effectiveness
- Ch is the heat capacity rate of the hot fluid, in this case water, and Cc the one of the cold fluid, air in this case.

$$C_h = \dot{m}_h c_{p,h} \quad \text{and} \quad C_c = \dot{m}_c c_{p,c}$$

- Cmin is the minimum betweeen Ch and Cc
- $T_{h,i}$ is the initial temperature of the water while $T_{c,i}$ is the initial temperature of the external air. Their difference, $DeltaT_{\max}$, is the maximum possible temperature difference between the two fluids, which occours at the start of the heat exchange process.

The heat exchanger effectiveness ε depends on the number of transfer units NTU, the heat capacity rate ratio C* and the flow arrangement.

- **Heat Capacity Rate Ratio C*** It is simply a ratio of the smaller to larger heat capacity rate for the two fluid streams so that C* ¡= 1.

$$C^* = \frac{C_{\min}}{C_{\max}} = \frac{(\dot{m}c_p)_{\min}}{(\dot{m}c_p)_{\max}}$$

C* is a heat exchanger operating parameter since it is dependent on the mass flow rates and/or on the temperatures of the fluids in the exchanger.

- **Number of Transfer Units NTU** It is defined as a ratio of the overall thermal conductance to the smaller heat capacity rate:

$$\mathrm{NTU} = \frac{UA}{C_{\min}}$$

Where UA is the reciprocal number of the sum of all the thermal resistances calculated before:

$$UA = \sum \frac{1}{R_t}$$

- **The heat exchanger effectiveness** ε is a measure of thermal performance of a heat exchanger. It is defined for a given heat exchanger of any flow arrangement as a ratio of the actual heat transfer rate from the hot fluid to the cold fluid to the maximum possible heat transfer rate qmax thermodynamically permitted:

$$\varepsilon = \frac{q}{q_{\max}}$$

While qmax is defined as:

$$q_{\max} = C_{\min}\left(T_{h,i} - T_{c,i}\right) = C_{\min}\Delta T_{\max}$$

In our case, where we have a crossflow heat exchanger in which air and water do not mix, the heat exchanger effectiveness is calculated as:

$$\varepsilon = \frac{1-\exp[-\mathrm{NTU}(1+C^*)]}{1+C^*}$$

It should be noted that the presence of louvered fins could suggest considering the air as a mixed fluid due to the turbulence induced by the louvered fins and the transverse movement of the air that is encouraged by them. The decision to consider the air unmixed is due to the fact that in both cases it would be an approximation since the flow is neither completely mixed nor unmixed. In the case of louvered fins, the flow can be considered mixed only locally and not globally. This makes the flow more approximate to unmixed flow.

So, at the end, the heat transfer rate can be calculated:

$$q = \varepsilon C_{\min}(T_{h,i} - T_{c,i}) = \varepsilon C_{\min}\Delta T_{\max}$$

The other important output of the model is the water temperature at the radiator outlet. It can be easily evaluated as:

$$\mathrm{T_{h,o}} = \mathrm{T_{h,i}} - \tfrac{q}{\dot{m}c_p}$$

4.2 Radiator CFD model

To design the radiator assembly, it's essential to be able to perform CFD simulations. These can be used to determine both the air flow rate through the radiator and its impact on the vehicle's aerodynamics.

4.2.1 Pre-processing

Once the CAD drawing of the radiator assembly is completed, it is initially simplified in the CAD environment. Specifically, the two faces of the radiator are replaced by two surfaces, and the radiator fan by a circular face with the same diameter as the blades.

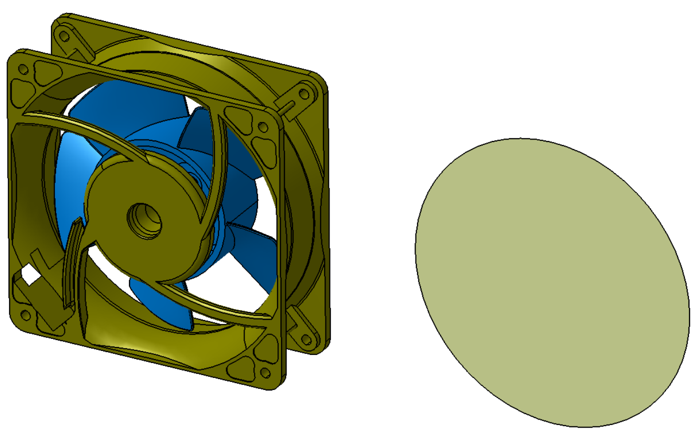

Figure 13: The CAD of the actual radiator fan and the circular surface that replaces it

After making these changes, the CAD drawing can be imported into BETA ANSA. Here, the various components of the radiator assembly are assigned to different PIDs. PID stands for Property Identifier and is a way to categorize the different parts of a model.

Once the file is imported into ANSA, the geometry is further cleaned of any hot points. Sometimes some surfaces need to be reconstructed using ANSA.

RAD Inlet	Front radiator face
RAD Outlet	Rear radiator face
RAD Walls	Edge between the two radiator's faces
RAD Fan	Circular surface of equal dimensions as the fan
MNQ RadiatorAssembly	Conveyor between the radiator and the fan

Table 8: ANSA PID component correlation

The goal of this phase is to obtain three different volumes to export to the CFD solver, SIEMENS StarCCM+.

Air volume	All the external air around the vehicle
Rad volume	The space between the two radiator faces and the walls
Conveyor volume	The space between the radiator outlet and the fan

Table 9: List of the three volumes of the model

In order to effectively create three distinct volumes, the PID cons that form the interfaces between the various volumes, i.e. RAD Inlet, RAD Outlet and RAD Fan, must be of the triple cons type.

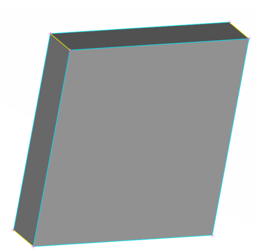

Figure 14: Radiator modellation in BETA ANSA

Figure 14 shows the RAD Inlet and RAD Walls PIDs. The triple cons is colored cyan. Its presence indicates the interface between two volumes: the external one, Air volume, and the one contained within the radiator core, Rad volume.

Interfaces play a very important role because they allow to easily model the behavior of the radiator and the fan.

Fan Modelling

As mentioned previously, the fan is modelled as a circular surface having the same diameter as the real fan.

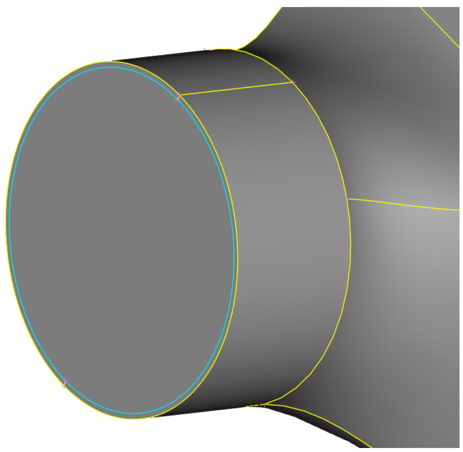

Figure 15: Fan model in BETA ANSA

Figure 15 shows the interface between the fan and the end part of the conveyor which simulates the real fan case. It is then possible to impose on Star CCM+ the properties of this interface in the form of a polynomial piecewise function
The function curve is a reproduction of the pressure difference/flow rate curve present on the fan's datasheet. The curve describes the fan's ability to generate air flow based on the various pressure differences between the two sides of the fan.

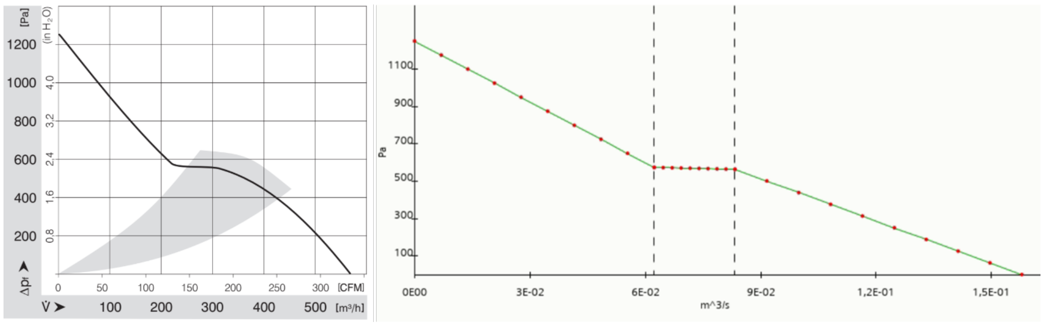

Figure 16: Differences between the fan curve provided by the producer and the reproduction in STAR CCM+

Radiator Modelling

The radiator core is not accurately simulated considering the fins and tubes. As previously seen in Figure 14, a parallelepiped with the same shape and dimensions is simulated instead. To take into account the radiator's physical properties, a porosity value is assigned to the Radiator volume. In this way, during the simulations, it will be possible to consider the resistance of the radiator on the air flow that passes through it.
To use this approach, a radiator was characterized and its porosity calculated. To make these measurements, it was necessary to use Pitot tubes and control the flow velocity with great precision.

Figure 17: Test rig used for the porosity characterization and detail of the Pitot tube

4.2.2 Post-processing

During the simulation, it is possible to monitor some fundamental parameters such as Cx, Cz, or the radiator flow rate. At the end, after 1000 iterations, different scenes are produced. All the scenes were standardized and printed at the last iteration of each simulation automatically.

In particular, scenes are produced for:

- Velocity scenes on plane sections (integral convolution)
- Static Pressure scenes on plane sections
- Total Pressure Coefficient scenes on plane sections
- Pressure Coefficient scenes on components' surfaces
- Wall shear stress scenes on components' surfaces
- Q-Criterion isosurfaces scenes

The X,Y and Z planes on which the scenes are printed are:

- 83 for X Axis: steps of 50mm (25mm near aerodynamics components);
- 28 for Y Axis: steps of 36mm (18mm near aerodynamics components);
- 49 for Z Axis: steps of 30mm (15mm near aerodynamics components);

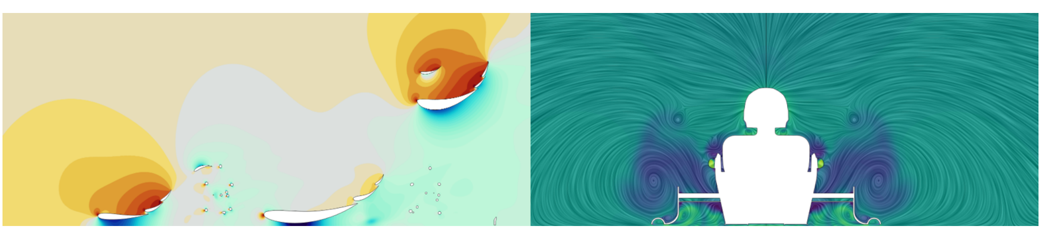

Figure 18: Example of a Cp scene along Y and a Velocity scene along X

A special scene is printed to monitor the airflow velocity entering the radiator. This allows us to assess the uniformity of the airflow and, if there are areas where the velocity is lower, locate them in order to intervene.

Figure 19: Velocity scene at the Radiator inlet

5 Radiator sizing

Once the targets have been defined and the models are available, we can proceed with the actual sizing of the radiator cores. In this phase, two different solutions will be compared: the first one that involves two symmetrical circuits, one for each side of the vehicle, and the second one that considers three separate circuits, two for the motors and one for the inverter.

For each of the two configurations, the temperature of the water exiting the radiator and the previously calculated power to be dissipated will be used as inputs. These two values are different for each configuration. The third input, constant between the two, is the water flow rate.

The results of this sizing will be the dimensions of the radiator core and the target air flow rate that must be achieved by correctly positioning the radiators in the vehicle and choosing the right fan.

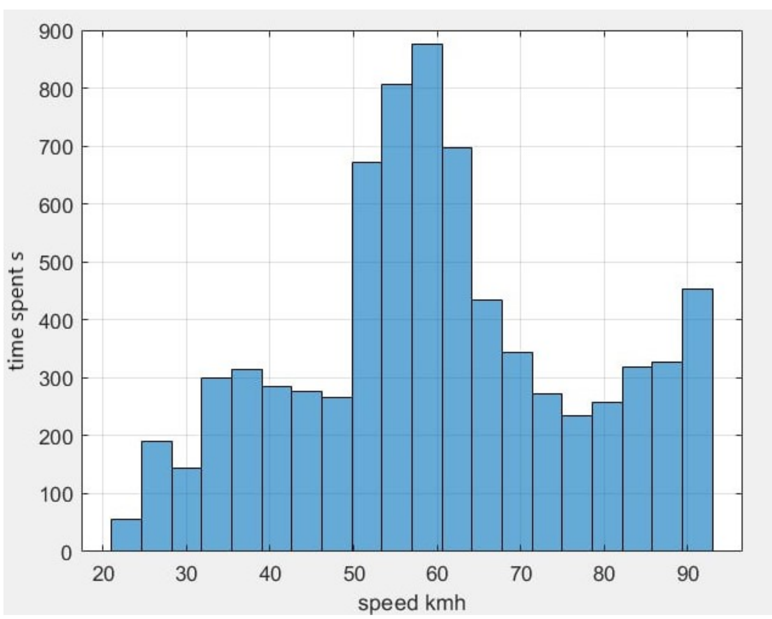

Figure 20: Speed distribution around a lap at FSG

The need for fans to ensure adequate airflow to the radiator stems from the very nature of the competition. Formula Student circuits, being tortuous by nature, with few straights and many slow corners, mean that the average speed is around 60 km/h. At these relatively low speeds, it's virtually impossible to ensure sufficient airflow to the radiator without a fan. This is even more critical in an electric car, where components like the inverter have low operating temperatures and cannot afford not to be properly cooled during some phases of their functioning.

To overcome these problems, the target air flow rate resulting from the sizing must be achieved, with the help of the fan, at an average speed of 60 km/h. At lower speeds, the fan's effect will predominate over that of passive aerodynamics, while still ensuring a sufficient air flow rate.

Another aspect to consider is the type of coolant used. Regulations require the use of only three types of it:

- Plain water
- Air
- Oil

As mentioned above, air is used to cool the HV battery pack, but it would not be possible to use it for the rest of the powertrain because the motors and inverters we have were designed to be cooled only with fluid cooling.

Although the regulations are very permissive regarding the types of oil to use, we didn't consider it appropriate as a coolant due to the difficulties that could arise during the design phase. The advantages of using oil aren't sufficient to justify all the special pump and pipe requirements that a system of this type would require.

The most conservative and reliable solution is certainly to use a distilled water system. Water has excellent thermal properties, such as a high specific heat, is easy to find, and is inexpensive. Furthermore, having a pressurized system eliminates the risk of boiling even at high temperatures. The use of distilled water is necessary to reduce wear on the components, avoiding the accumulation of mineral salts and other substances during system operation.

5.1 Water flow rate and pump choice

For the target water flow rate, it was decided to maintain the same value as the previous solution, 8 kg/min. This value provided in the previous seasons good thermal performances for both the motor jackets and the inverter coldplate. As a result, the current water flow rate was confirmed as the design parameter for the new jackets and coldplate.

The pump was therefore chosen to be the same model used in the current configuration. This pump has several features that make it an excellent choice for a Formula Student car:

Figure 21: Pump selected from GRI Pumps

- Low weight: this pump weights only 363 gramms.
- Great performances: It can deliver up to 28.4 litres/minute and its maximum head is 24.8 bar
- The power supply can be controlled using a PWM strategy to achieve exactly the desired flow rate value.

Furthermore, its small size allows considerable flexibility in their positioning, leading to advantages in the packaging of the car. The hollow sidepods are currently being designed, which will allow the pumps and part of the water routing to be positioned within the aerodynamic profiles.

This, in addition to improving the cleanliness of the car and the integration of the various assemblies, allows the pumps to be positioned at the lowest point of the circuit, reducing the risk of cavitation.

Another factor that convinced us to confirm the same product is its high reliability. The pumps have never encountered any problems during all the years of use.

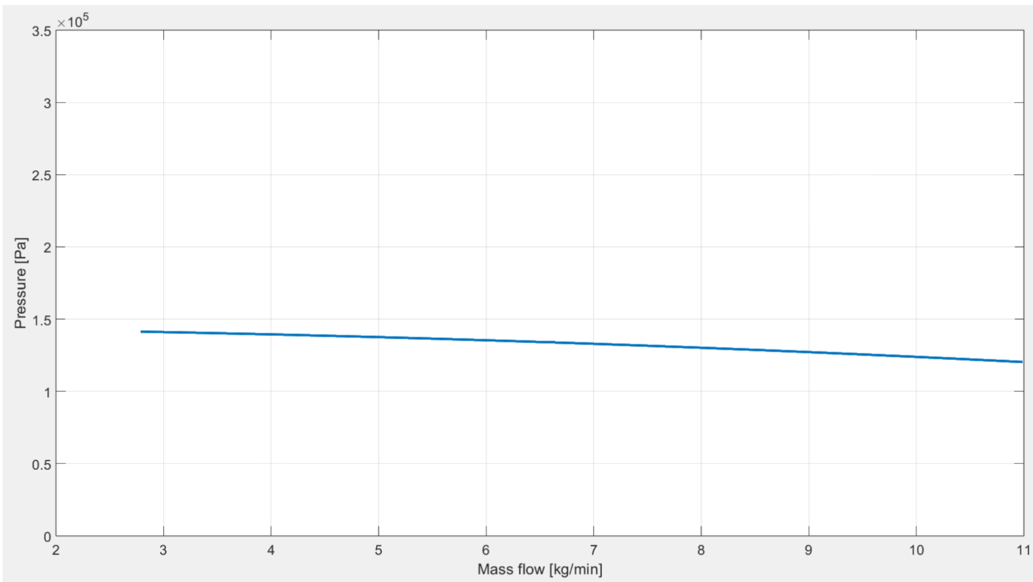

Figure 22: Pump operating curve

5.2 Two cooling circuits

The two-circuit symmetrical solution is already present on the current car. It requires a radiator for each side of the car, left and right, and the power-train components to be cooled are arranged in series.

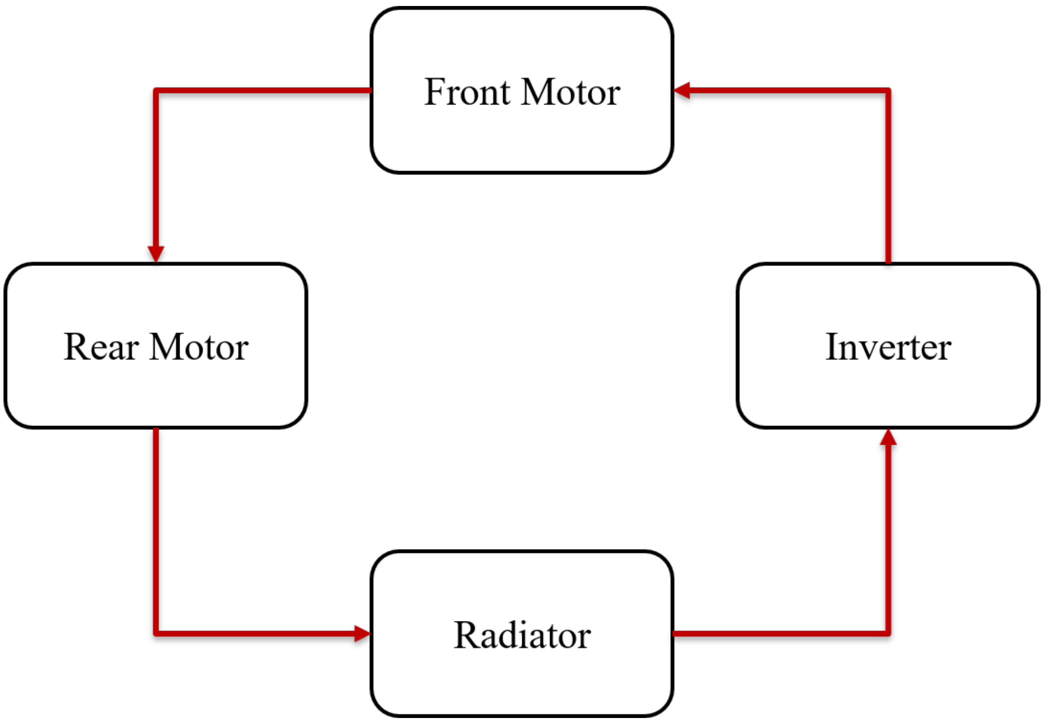

Figure 23: Single cooling loop of the two circuits configuration

- The inverter is the first to be cooled because it has the lowest maximum operating temperature, 50°C. The inverter case contains a coldplate, through which water flows, which has direct contact with the power modules to be cooled. In this configuration, the cold plate will be divided into two symmetrical parts to be able to connect to both circuits completely independently and without allowing water to mix between the two sides. The inverter temperature is the limiting factor for the entire system. Based on the heat exchange values of previous solutions, the temperature of the water reaching the inverter must not exceed 48°C.

- The second component to be cooled is the front motor. The choice to cool the front axle first stems from the lower heat it produces compared to the rear axle. This means that the temperatures of the front motors will necessarily be lower, and to cool them more effectively, it is necessary to use water that is certainly colder than if it did not pass through the rear axle first.

- The last component to be cooled is the rear motor. Due to the greater torque transmitted to the rear motors, it is the component that produces the most heat and tends to overheat the most. It is placed last in the series because of the high temperatures that can reach. We saw during testing it can heat up to 80°C. So, the difference in cooling it before the front motor is negligible. The temperature increase, due to cooling the front motor, is estimated at around 2.3°C, thus bringing the temperature of the water arriving at the rear motor to around 51.3°C, compared to the 49°C that would be achieved if it were cooled first. Given the large temperature difference between the water and the component, the advantage of cooling it first is less than cooling the front first, which operates at significantly lower temperatures, around 60°C.

The targets for this configuration are:

	Thermal power [W]	Max T [°C]
Inverter	364,32	50
Front motor	1079,64	105
Rear motor	1683,12	105
Total	3491,4	

Table 10: Radiator targets - two circuits

To achieve a sufficiently low temperature, 48°C, while simultaneously dissipating the heat target, the radiating mass must be:

Tube lenght	200 mm
Radiator height	180 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	54
Target air flow rate	0,336 kg/s

Table 11: Radiator features - two circuits

It is clear that both the dimensions and the required air flow rate are excessive. The large dimensions make it difficult to position it on the car.

A separate discussion must be made about the fan.
To ensure such airflow, it's necessary to use a type of fandifferent from the one currently used. To maintain the compact size, the only fan models capable of such airflow consume more power than those currently used: up to 180 W versus the current 120 W. Above all, the most significant increase is in weight.

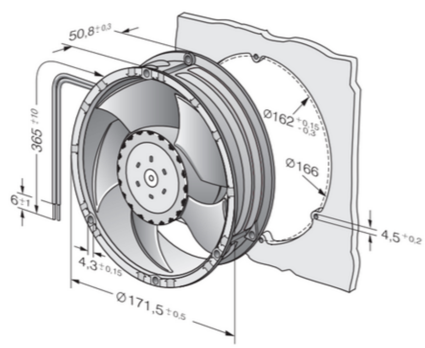

Figure 24: Example of heavier fan - Ebm-Papst 6318 /2 TDH4P

This type of fan, specifically the Ebm-Papst 6318 /2 TDH4P, weighs 0.91 kg, more than double the weight of current fans, which weigh 0.425 kg. When installing two fans in a car, the increase in weight is truly significant.

5.3 Three cooling circuits

This solution, unprecedented in the history of Squadra Corse PoliTo, includes two symmetrical circuits for the motors and a separate circuit dedicated solely to the inverter

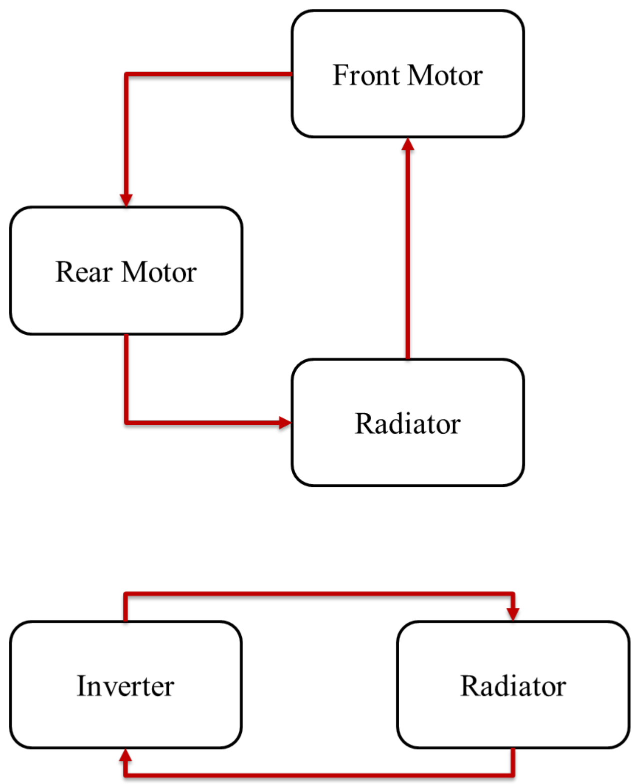

Figure 25: Single cooling loop of the motor circuit and inverter cooling loop

5.3.1 Motors circuit

The hot circuit, that cools the motors, is the one that must dissipate most of the system's thermal power. As regards the order of the motors to be cooled, the same considerations as in the previous solution are applied. The temperatures that can be reached by the water are significantly higher than the ones in the current solution, due to the absence of an inverter in the circuit. This increase in temperature facilitates heat exchange with the external air due to a greater temperature gradient between the two fluids. This allows the

large amounts of heat required by the motors to be exchanged with smaller radiators.
The targets for this circuit are:

	Thermal power [W]	Max T [°C]
Front motor	1079,64	105
Rear motor	1683,12	105
Total	2762,76	

Table 12: Hot radiator targets - three circuits

Although the engines can operate at temperatures up to 105°C without any problems, it was decided to limit the radiator outlet water temperature to 68°C. This is due to the lack of data, at this design stage, on the performance of the new motor cooling jackets. To reach this value and dissipate the right amount of heat, the radiator core must be:

Tube lenght	140 mm
Radiator height	85 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	26
Target air flow rate	0,104 kg/s

Table 13: Motors radiator features - three circuits

5.3.2 Inverter circuit

The cold circuit, which is dedicated solely to cooling the inverters, must dissipate the small amount of heat produced by the inverters. The thermal power targets is:

	Thermal power [W]	Max T [°C]
Inverter	728,64	50

Table 14: Cold radiator targets - three circuits

The most delicate aspect, however, is the operating temperature of this circuit. The radiator outlet temperature was chosen at 43.5°C. This value,

significantly lower than the previous limit of 48°C, was chosen given the possibility of having a dedicated circuit.
To reach this value and dissipate the right amount of heat, the radiator core must be:

Tube lenght	140 mm
Radiator height	80 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	26
Target air flow rate	0,098 kg/s

Table 15: Inverter radiator features - three circuits

It's clear, however, that for packaging reasons, it would be inconvenient to have three different radiators with three respective fans. Thus, the need to integrate the two circuits arises. The most reasonable solution is to separate the inverter radiator into two identical parts, in order to integrate each half with a motor radiator.

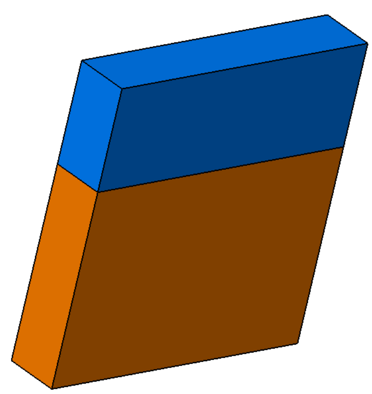

Figure 26: Integration between half of the inverter radiator (in blue) and a motor radiator (in red)

As can be seen in the figure, in this way the two radiators, one for the motors and one for the inverter, coexist and can be positioned and modeled as a single radiator core. This allows only two fans and maintains the symmetry of the car that would have been lost with a third radiator.

To make this change, two radiators are considered in series. The water will then pass through both before returning to the cold plate. The dimensions of each are:

Tube lenght	140 mm
Radiator height	40 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	12
Target air flow rate	0,049 kg/s

Table 16: Inverter single radiator features - three circuits

Since the target flow rate in this configuration is quite limited, 0.153 kg/s, it would be possible to use the same fan model currently in use. This fan has proven reliable even in adverse weather conditions such as heavy rain. It also offers excellent performance, with a flow rate of up to 185 kg/s, and a light weight of just 0.425 kg.

Figure 27: Ebm-Papst 4114 N/2H8P

5.4 Comparison and final choice

To recap what was said previously, we can first of all make a comparison between the various solutions based on the weight of the assembly.
To estimate the weight of the radiators, it was considered the weight of the current radiator, with water and divided by the volume.

	Two cooling circuits [Kg]	Three cooling circuits [Kg]
Radiators	0,956	0,465
Fan	0,910	0,425
Pump	0,363	0,545
Total	**2,229**	**1,434**

Table 17: Comparison between the weights of the two configurations

The weights considered refer to only one side of the car, left or right. For the fans, the two models previously described were used.
In the three-circuit solution, which requires the use of a third pump, the weight of the latter was considered as half of its weight, in order to be able to calculate its impact on a single side.

It is possible to see that the three separate circuit configuration has a significant weight advantage, resulting from a lower radiating mass and the use of a lighter fan.The disadvantage of having an extra pump is largely overcome.

These advantages arise from the ability to operate each exchanger within its ideal operating range. In the inverter circuit, the goal is to maintain a very low water temperature, especially considering the ambient temperature of 35°C. Since it only needs to dissipate the heat produced by the inverter, which is far lower than that produced by the motors, the radiator does not require excessive size or air flow, despite the low temperature gradient with the outside air.
Conversely, engines can operate at significantly higher temperatures, but need to dissipate much more heat. This allows for higher water temperatures, ensuring for easier heat exchange with the outside air, without requiring large radiating masses and air flow rates. For these reasons, it was chosen to use the three separate circuit configuration on the car.

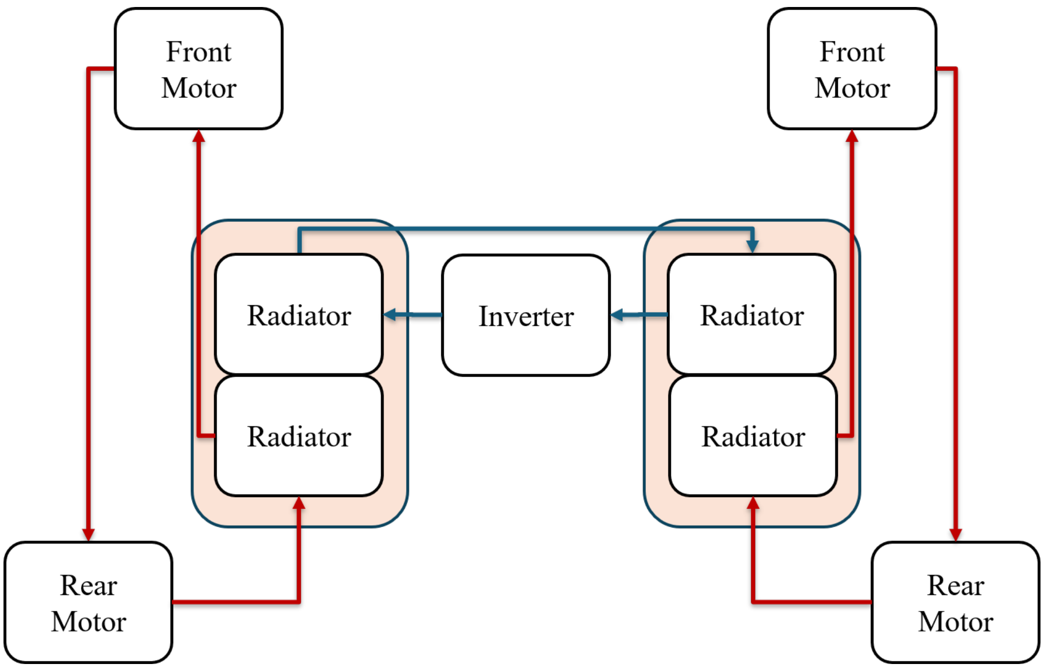

Figure 28: Diagram of the entire cooling system using three separate circuits. The two radiator assemblies are highlighted.

6 Radiator positioning

Once the target air flow rate has been fixed, the ideal positioning of the radiators in the vehicle can be determined. To achieve this, after an initial benchmarking step, the Key Performance Indexes for the radiator assembly will be defined. The three solutions will then be analyzed individually and, after a comparison, the best one will be chosen.
To analyze the various positions, several CFD analyses will be performed. This allows us to verify that the flow rate targets have been achieved and to see how the radiator interacts with the rest of the vehicle's aerodynamics. Some simplified CAD models have been prepared to simulate the radiator assembly. These include everything needed to correctly model the radiator on BETA ANSA as described in Chapter 4.

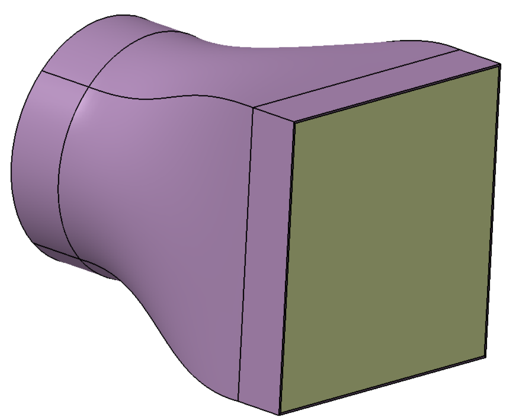

Figure 29: Simplified CAD drawing of radiator assembly

In particular, in addition to the radiator mass, there are also the fan and the conveyor that directs the air coming out of the radiator towards the fan.

6.1 Benchmarking

The first step was to analyze the most competitive cars during the last season. Thanks to the few regulatory restrictions regarding cooling, it is possible to observe several different solutions.Each team can make its own choices based on its needs
Three main positioning solutions have been selected.

6.1.1 Solution 1 - Radiator at the end of the footplate

In this configuration, the radiator is placed very externally to the car, at the end of the sidepod footplate.
From a packaging perspective, it seems to be a very convenient solution, as it is not an area of the car where other systems are present. Its proximity to the rear wheel may pose some problems, especially regarding how the fan flow can be directed. From a structural point of view, it should be fixed with specific supports to the sidepod.

Figure 30: Rennteam Uni Stuttgart

6.1.2 Solution 2 - Radiator over the sidepod

In this other configuration, the radiator is placed above the sidepod, on the sides of the cockpit.
In this position, careful integration between the radiator assembly and the sidepods is essential. The airflow coming out of the fan impacts the sidepod flaps and can improve or degrade their performance.
From a structural standpoint, the radiator can simply be fixed to the monocoque. Also, in this way, the mass of the radiator assembly should be closer to the car's center of gravity, improving weight distribution. Another aspect to consider is the influence the front wheel assembly has on the airflow arriving at the radiator. All teams using this configuration have a very clean assembly, with the various pipes and cables reaching the front engines covered by the suspension.

Figure 31: Rennstall Esslingen

6.1.3 Solution 3 - Radiator between the monocoque and the rear wheels

In this latter configuration, the radiators are positioned immediately behind the rear suspensions. From an aerodynamic standpoint, this solution is certainly the least impactful, being far from other aerodynamic elements. However, it is foreseeable that the turbulence generated by the suspension, so close to the radiator, could affect its flow rate.
From a structural standpoint, the radiator would require appropriately designed supports to secure it to the monocoque.
Before 2025, this type of solution could also be used to generate downforce

using fans. The use of very powerful fans helped draw air under the sidepod, improving its performance. With the new 2025 regulation, a 500W limit was set on the total power of fans mounted on cars to limit the significant performance gains of cars using this type of solution.

Figure 32: FS Team Tallinn Electric

6.2 Key Performance Indicators definition

In order to correctly evaluate which positioning is best suited to our application, it was decided to consider three different KPIs.

6.2.1 Radiator mass flow

The first KPI considered is the air flow rate reaching the radiator. This is a previously calculated target and it is crucial that it will be achieved. If the flow rate is greater than the target, given the same radiator core size, it will be considered a plus. At a later stage, it can be decided whether it is more advantageous to maintain a higher flow rate for greater cooling or to reduce the size in order to reduce weight.

6.2.2 Lift coefficient

The radiator has a significant influence on the aerodynamics of a racing car. It is therefore important to estimate its impact on performance. Specifically, the lift coefficient was chosen as parameter. This indicates the car's ability to generate downforce as speed increases. The variation in CL, based on the radiator's positioning, indicates its ability to negatively or positively influence the car's aerodynamic efficiency.
The fan can play an important role in this case. The air coming out of the fan has high energy and, if directed appropriately, can prove to be a valuable tool for improving the performance of other aerodynamic elements. Alternatively, the radiator may divert some airflow, preventing wings or other aerodynamic elements from functioning properly.

6.2.3 Moment of inertia of the vehicle

As seen previously, the current radiator assembly contributes to increasing the rotational inertia of the vehicle, compromising its responsiveness and handling. Therefore, the impact each positioning can have is considered during the comparison phase. To estimate the rotational inertia of the car, each component is entered into a spreadsheet. To each assembly the properties required for the calculation are assigned: assembly weight, positioning of the assembly's center of gravity relative to the center of the reference system, and its dimensions. This way we can evaluate the impact that the change in weight or the movement of each individual component has.

6.3 Position 1 - Radiator at the end of the footplate

In the first position, the one with the radiator on the sidepod footplate, the radiator was tilted forward to ensure that the air jet coming out of the fan did not impact on the rear wheel surface.

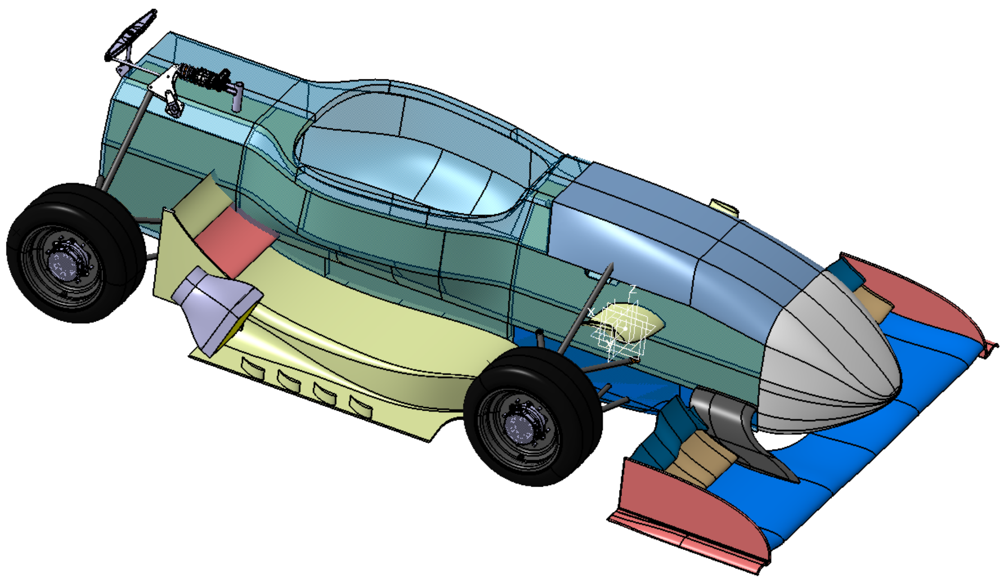

Figure 33: Radiator position 1

The first useful result is the air flow rate on the radiator, which is 0.158 kg/s, higher than the target of 0.153 kg/s.

In Figure 34 and Figure 35 it is possible to see how, despite the inclination of the radiator, the air flow coming from the fan still impacts on the rear wheel surface.

This jet, at high total pressure, CpT, and high velocity, is distinguishable in the scenes by its strong colors. In the following images, Figures 36 and 37, it is possible to see why the flow rate is sufficiently high. In Figure 36 in particular, it is possible to see the CpT before it reaches the radiator. On the footplate, despite there being no free flow, the CpT and therefore the flow energy is quite high. This is because, as can be seen in Figure 37, there is inwash caused by the wake of the front wheel. This inwash causes a considerable flow of air to reach the radiator.

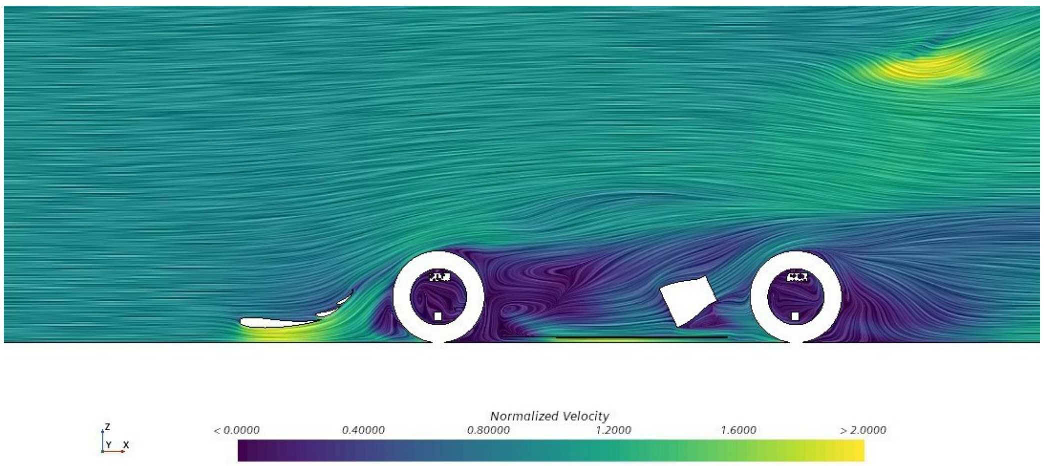

Figure 34: Position 1 - Velocity scene of the vehicle

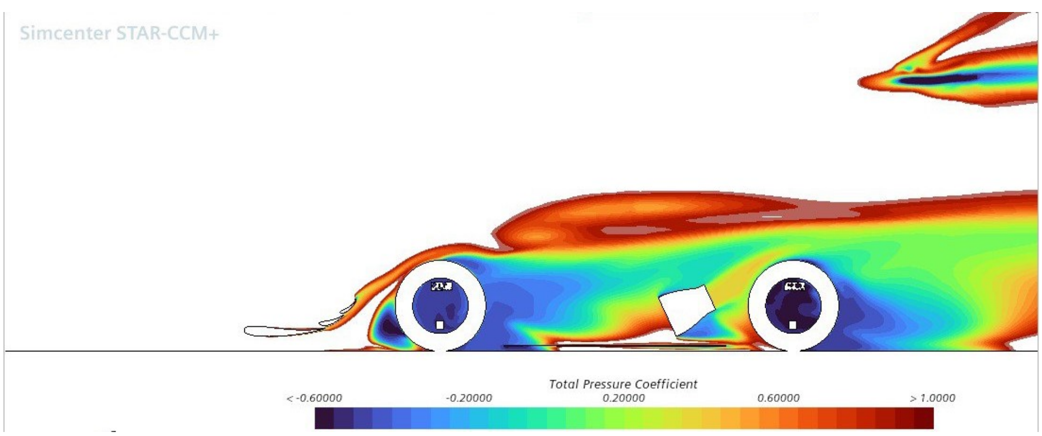

Figure 35: Position 1 - CpT scene of the vehicle, Y slice

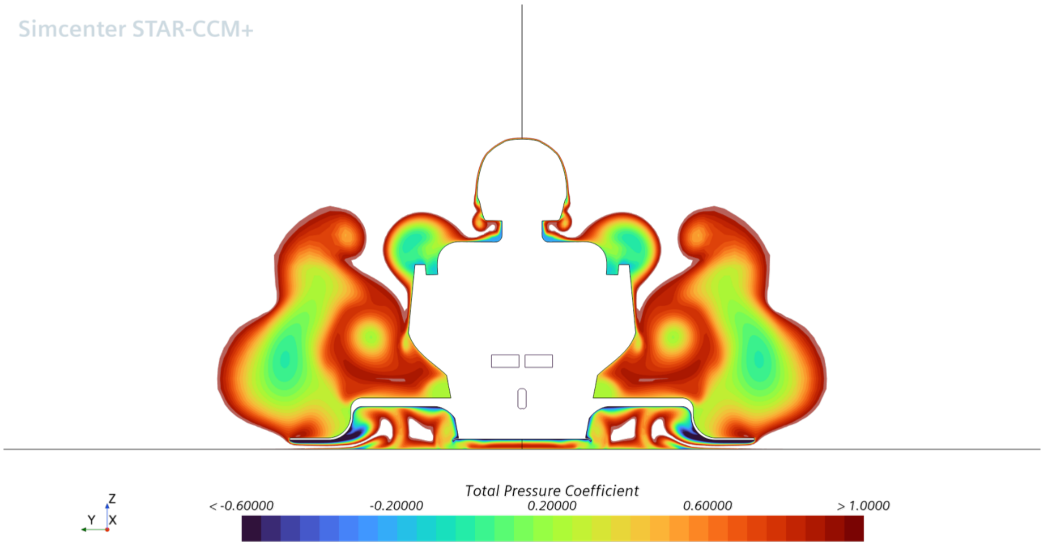

Figure 36: Position 1 - CpT scene of the vehicle, X slice

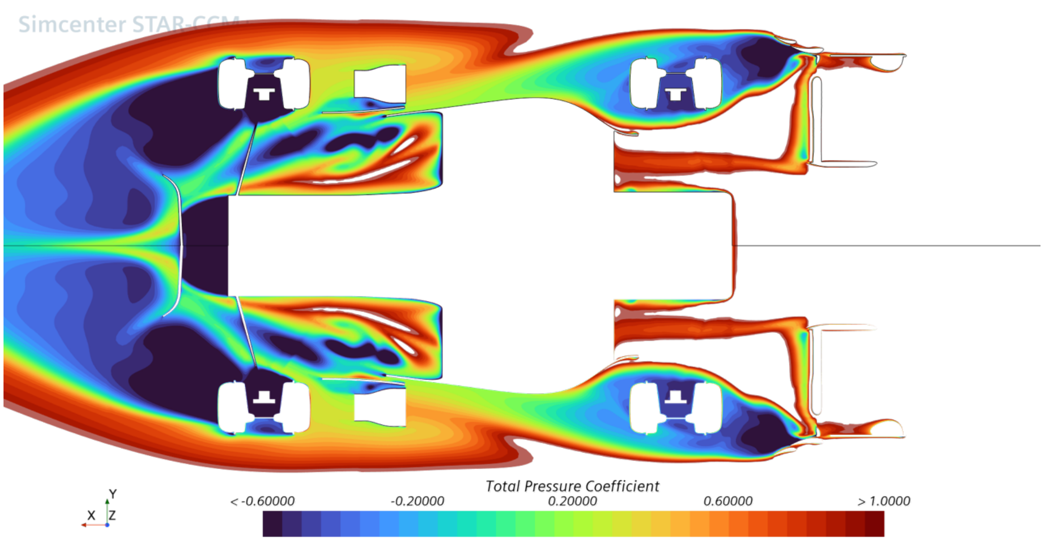

Figure 37: Position 1 - CpT scene of the vehicle, Z slice

6.4 Position 2 - Radiator over the sidepod

In the second position, the radiator was tilted forward to ensure that the air jet coming out of the fan is aligned with the sidepod main element.

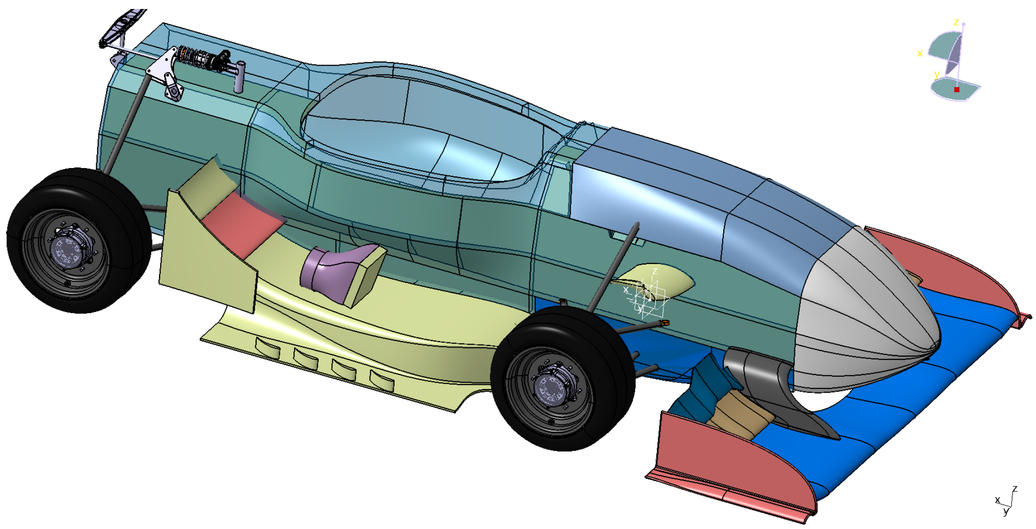

Figure 38: Radiator position 2

In this position, the radiator reaches its target flow rate again. The air flow rate is 0.154 kg/s. As can be seen in Figure 39 and in Figure 40, the fan has a preparatory effect on the sidepod's operation. This effect is also demonstrated by the increase in Cl compared to the previous positioning.
On some Formula Student cars, such as Rennstall Esslingen Figure 31, the fan angle is chosen by considering how the flow exiting the fan can favor the operation of the rear wing. In our case, however, it was decided to favor the flow around the sidepod elements. This choice arose due to a separation phenomenon that had been noticed by the Aerodynamics department. Thanks to the high-energy flow generated by the fan, it was possible to limit this problem.
Figure 39 also shows a low-pressure area in front of the radiator. This is caused by a vortex generated by the front wing. If this positioning proves to be the best one, improvements in that area of the vehicle will be necessary.

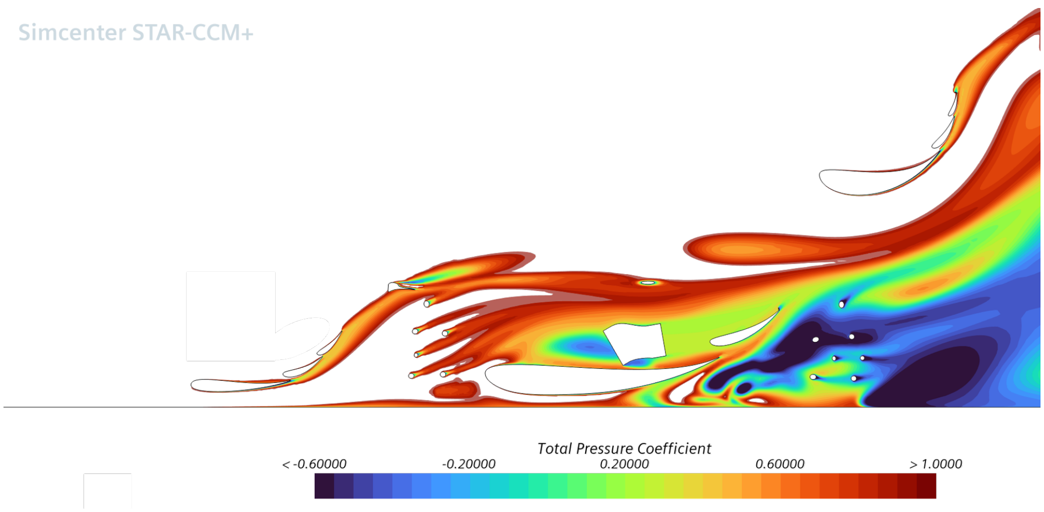

Figure 39: Position 2 - CpT scene of the vehicle, Y slice

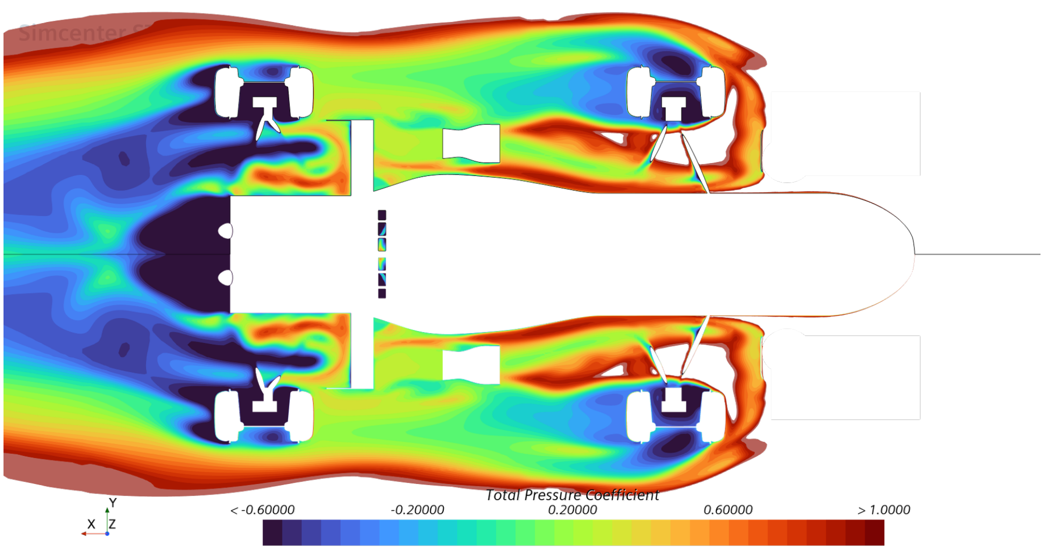

Figure 40: Position 2 - CpT scene of the vehicle, Z slice

6.5 Position 3 - Radiator between the monocoque and the rear wheels

In this last position, the radiator has been placed between the suspension elements to avoid disturbances in the air flow caused by the control arms.

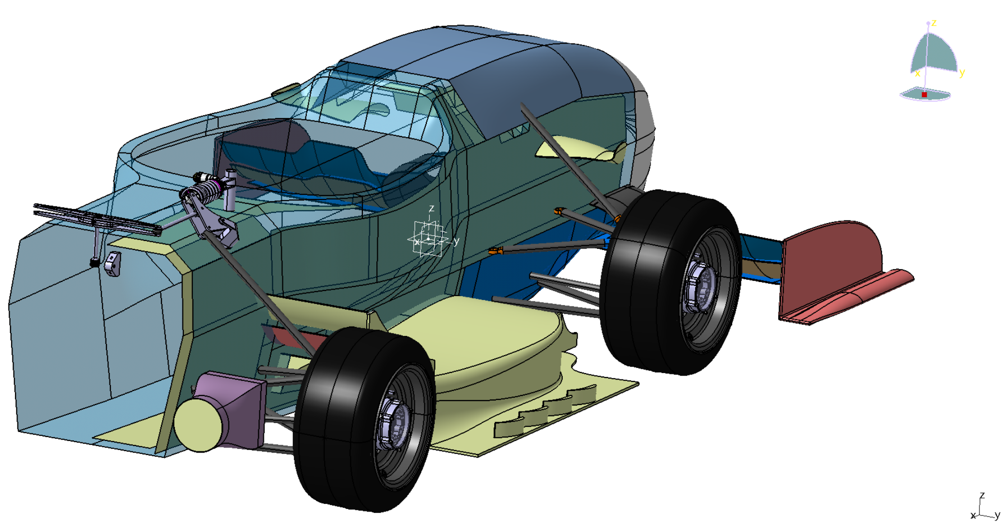

Figure 41: Radiator position 3

Unfortunately, the last position is the only one where the air flow target is not reached. The simulation result is 0.151 kg/s.
Figures 42 and 43 show that the area where the radiator is located has a low total pressure. This low pressure zone is caused by the normal operation of the sidepod. This low-pressure airflow prevents the required flow rate from being achieved.
From an aerodynamic standpoint, this solution is the most neutral, avoiding both advantages and disadvantages. This neutrality is due to the radiator's distance from any other aerodynamic appendages. In this way, the radiator cannot contaminate or interfere with any flow needed to generate aerodynamic load.

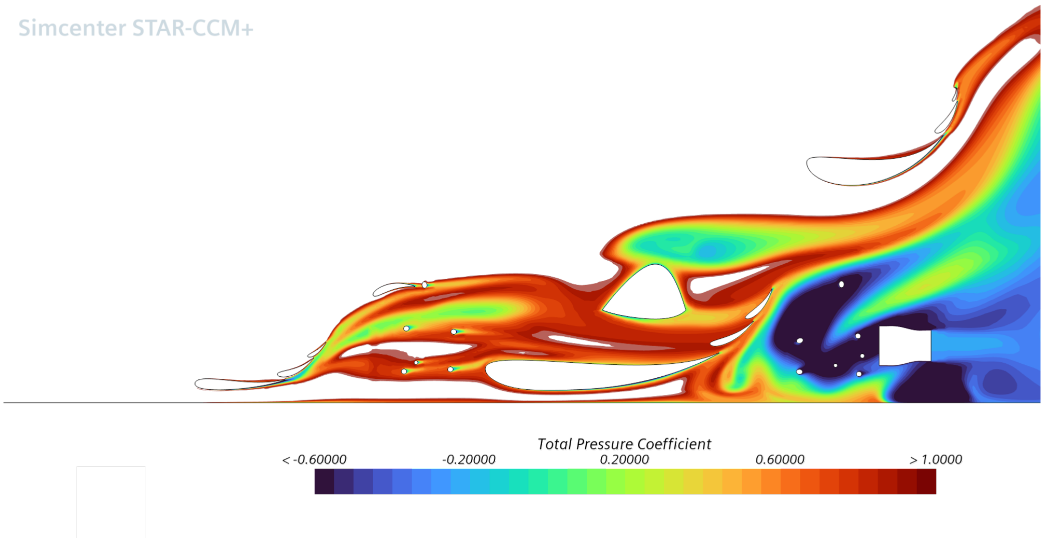

Figure 42: Position 3 - CpT scene of the vehicle, Y slice

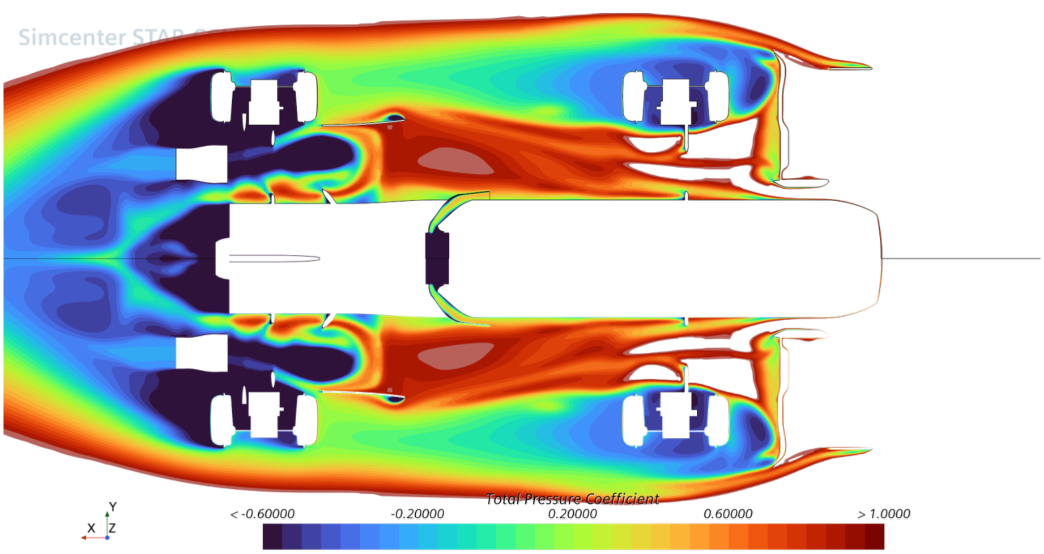

Figure 43: Position 3 - CpT scene of the vehicle, Z slice

6.6 Comparison between the three different positions

Once the different solutions have been analyzed individually, it is possible to make a comparison between them.

Starting from the air flow values, the first result to note is how solution number 3 is the only one that did not reach the minimum value. Conversely, position number 1 achieved the highest airflow, exceeding the target value. Position number 2 achieved a good air mass flow value, slightly above the target.

Regarding the downforce generated, evaluated through the Lift Coefficient, solution 2 contributes the most to the production of downforce. As seen previously, this is due to the improvements that the fan brings to the operation of the sidepod, reducing some separation phenomena. Conversely, position 1 has a disastrous effect on aerodynamic performance. Position 3, on the other hand, is confirmed to be, in relation to the others, the one that has the least influence on the aerodynamics of the car.

As for the moment of inertia, position 3 contributes the most to the car's rotational inertia. This is due to the radiator's position, which, along the car's longitudinal axis, is likely the component furthest from the center of gravity. Since rotational inertia is calculated as:

$$I_{zz} = \sum_i m_i r_i^2$$

and it depends on the square of the distance from the center of gravity, having the radiator assembly so far away is definitely detrimental to performance. The other two positions, however, have similar performance. This is due to the radiator assembly's lesser influence on the inertia calculation, as in both cases the masses are significantly closer to the center of gravity than in position 3.

	Radiator air mass flow [kg/s]	CL.A	I_{zz} [kg m^2]
Position 1	0.158	-4.96	107.81
Position 2	0.154	-5.05	107.06
Position 3	0.151	-5.03	109.71

Table 18: Comparison between the performance of the three different positions

Once the differences in terms of KPIs have been evaluated, it is clear that position 2 is the best solution.
In this case, the air flow target would be achieved satisfactorily, ensuring the necessary cooling for the vehicle.
The radiator assembly would be used effectively to improve the vehicle's aerodynamics. This way, an integrated design with the aerodynamic package can be carried out to extract further performance from the sidepods.
Finally, this positioning would help improve the dynamic performance of the car, contributing to its responsiveness.

7 Optimization

Once the ideal positioning is defined, it is possible to optimize the preliminary design to get closer to the finished design of the component.

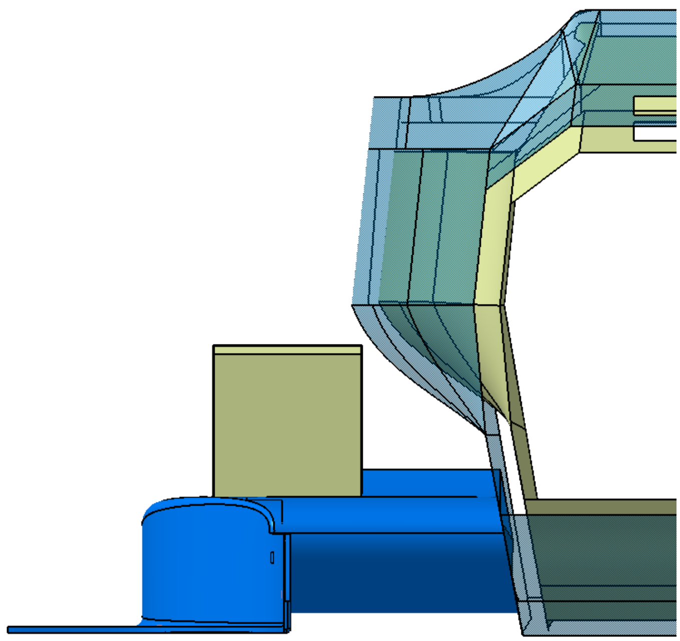

Figure 44: Front view of the chosen radiator

7.1 Analysis of criticalities

As can be seen from the CAD drawing in Figure 44, the shape of the monocoque prevents the radiator from being positioned closer to the body. This creates several problems:

- In order to fix the radiator assembly to the monocoque, it is necessary to have long supports. The possibility of fixing the radiator assembly to the sidepod was not considered feasible due to the difficulties that would have arisen during production phase. The only possible mounting point would be on the sidepod's rib, near the endplate. Considering that several components, such as water pumps and some electronic boards, must be secured inside the sidepod, the production and maintenance of these may be compromised by the radiator's supporting structure.
  By moving the radiator closer to the monocoque, it would be possible to use shorter and less slender supports.

- The air intakes for cooling the HV battery pack are located in this area of the car. This positioning was chosen to ensure sufficient airflow and to minimize the internal ducts carrying air to the battery pack.
  It would obviously be more convenient, in terms of packaging, to bring the two assemblies together as closely as possible to ensure a cleaner vehicle and minimize interference with the aerodynamic appendages. Moving the radiator assembly closer together would free up a portion of the sidepod flap from its wake.

- Between the radiator and the monocoque are the various pipes and cables that connect the radiator assembly to the rest of the systems. In particular, in addition to the water pipes, there are the fan power cables. Having the radiator so far from the monocoque means having longer pipes and cables, which themselves require support to avoid excessive movement during normal car operations. Furthermore, their presence constitutes an element of aerodynamic disturbance.

It is therefore clear how crucial it is to be able to bring the radiator assembly closer to the monocoque.

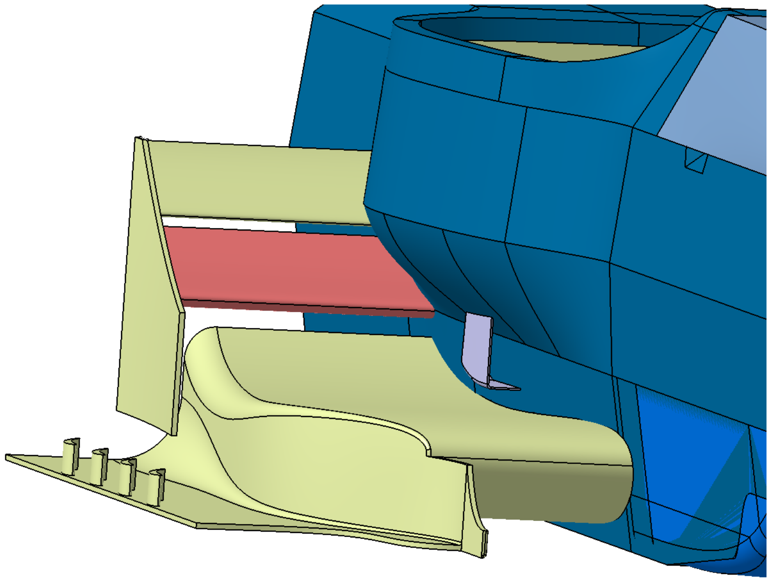

Figure 45: Detail of the air intake to cool the HV battery pack

7.2 Resolution and optimization

In order to position the radiator closer to the monocoque, it's important to consider its shape. The body's curves are determined both by the rules regarding the space dedicated to the driver and by maximizing aerodynamic performance. The rules, in fact, impose a minimum volume, strictly controlled, available to the driver, to guarantee safety and ergonomics.
The monocoque, as shown in Figure 44, has a curved shape. Since it was not possible to produce a radiator with a curved side, the result was a trapezoidal radiator. Thanks to these small modifications it is possible to bring the assembly significantly closer to the rest of the car, solving the problems seen previously.

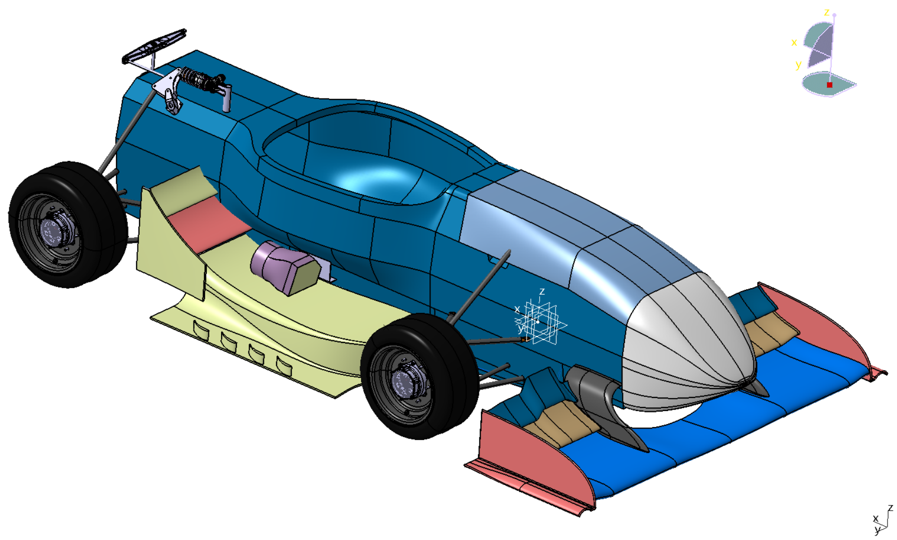

Figure 46: Optimized radiator assembly

Furthermore, considering that there are two different radiators, the only radiator that undergoes any modification is the one for the cold circuit. Conversely, the one dedicated to the engine circuit remains unchanged.

To achieve a trapezoidal shape for the inverter radiator without compromising its thermal performance, its dimensions had to be modified. The inclined side was chosen at a 45° angle to facilitate production. However, the inclined side reduces the length of the radiator tubing, reducing its heat exchange efficiency. To compensate for this effect, the radiator height was increased until the target values were reached again.

At the same time, as the design of the other cooling system components is under development, it has been possible to update the temperature targets for the motors and inverters.
Thanks to an inprovement in the jacket's effectiveness, the maximum possible inlet water temperature for cooling the motor is 76°C. The increase in temperature compared to the 68°C required by the previous solution, allows the use of a smaller radiator for the motors while maintaining the same heat dissipation.

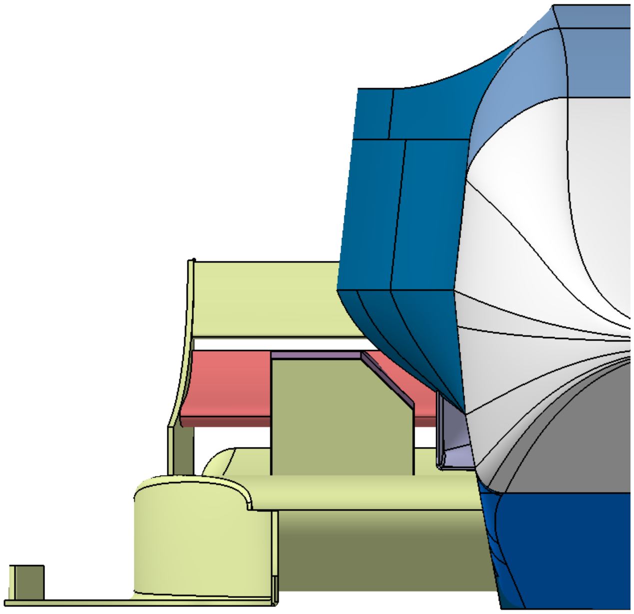

Figure 47: Front view of the optimized assembly

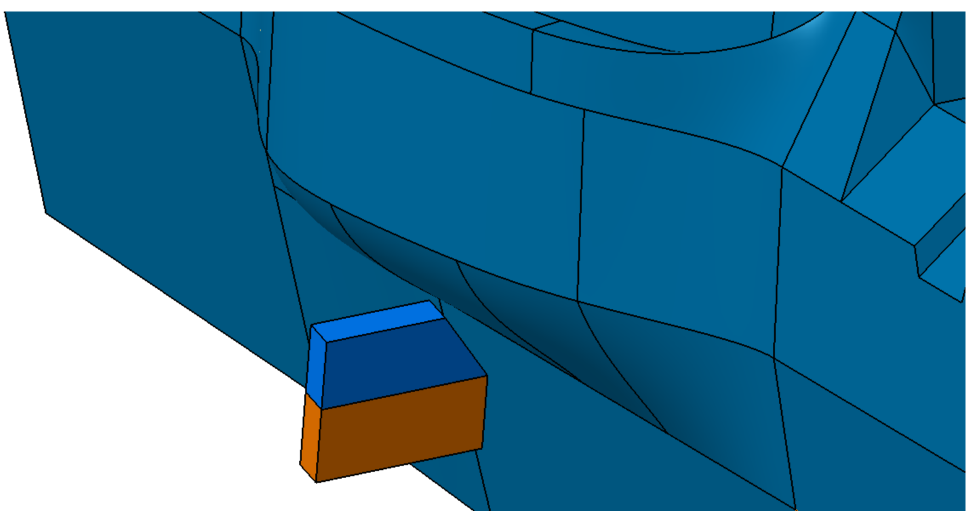

Figure 48: Division between inverter radiator and motor radiator in the optimized configuration

The 20mm reduction in height is also very useful considering the increased height of the inverter radiator. This way, the dimensions of the entire assembly can remain constant.

Tube lenght	140 mm
Radiator height	65 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	20
Target air flow rate	0,088 kg/s

Table 19: Optimized motors radiator features - three circuits

As previously mentioned, work has been done on the inverter radiator to compensate for the loss of exchange surface due to the inclination of part of the radiator.
The biggest approximation problem within the model is caused by the different lengths of the various tubes that make up the radiator. To overcome this problem, the average length value, equal to 110 mm, was assigned. To compensate for the reduction in radiating surface area, two tubes were added, arranged in two rows. This increased the radiator's height by 10 mm.
Considering the 20 mm reduction in height of the engine radiator, we can see how, following the optimization process, the overall dimensions have been slightly reduced.

Tube lenght	110 mm
Radiator height	50 mm
Radiator depth	27 mm
Row of tubes	2
Number of tubes	14
Target air flow rate	0,054 kg/s

Table 20: Optimized inverter radiator features - three circuits

7.3 CFD analysis

In order to verify the performance of the new optimized solution, it is necessary, as previously done, to carry out a fluid dynamics simulation. The process is similar to the one previously performed. The only difference was the shape and position of the radiator assembly.

The scenes show how the radiator continues to have a positive impact on the aerodynamic performance of the sidepod flaps. The high total Cp flow coming out of the fan surrounds the flaps, allowing the flow to remain attached to the aerodynamic surfaces.

Another positive effect of the optimization is the ability to benefit from the high total Cp flow present in the monocoque cavity. As can be seen from the scenes, in the area immediately adjacent to the monocoque, the flow is virtually undisturbed. It is not affected by either the front wing or the front wheels, reaching the radiator with plenty of energy.
It is also possible to see that, after the correct modifications to the front wing, the vortex that disturbed the air flow in front of the radiator is no longer present.

However, there is a low-pressure area, visible in Figure 50, caused by the radiator wake. This phenomenon occurs due to a high angle of attack between the external part of the radiator and the airflow. This angle is caused by an outwash flow in the area above the sidepod, which forces the airflow away from the monocoque. Fortunately, this vortex does not impair the sidepod's performance as it is pushed beyond the flaps.

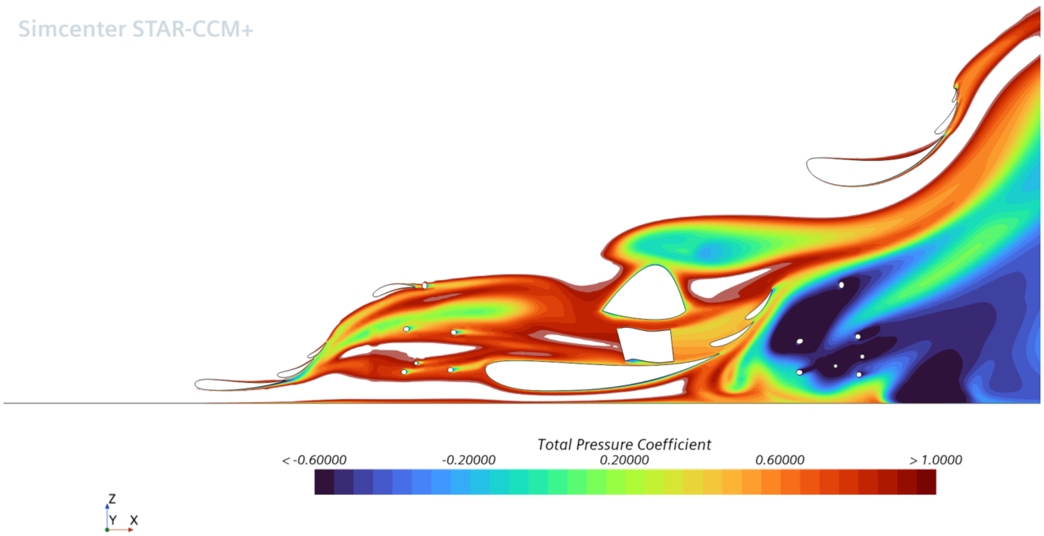

Figure 49: Optimized radiator - CpT scene of the vehicle, Y slice

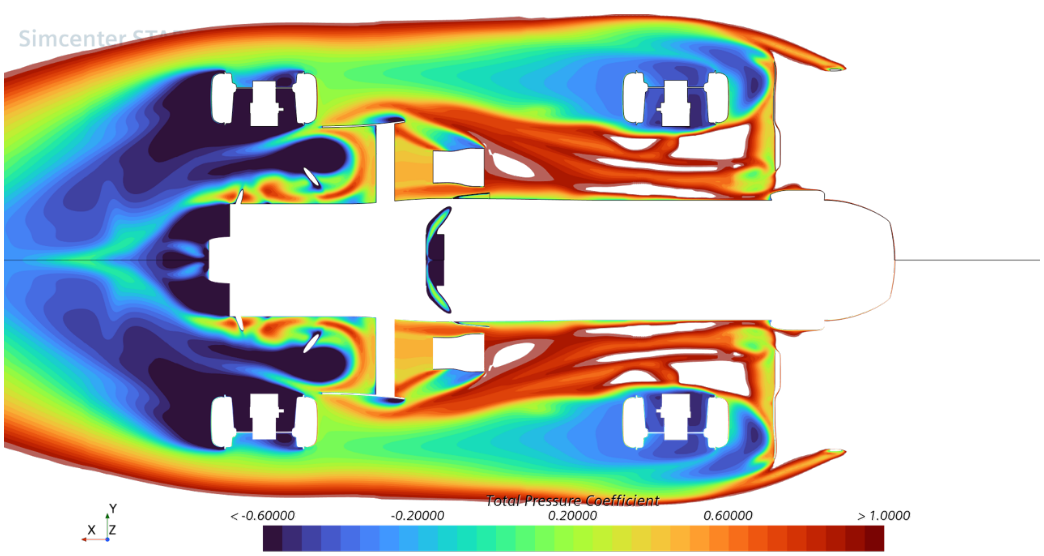

Figure 50: Optimized radiator - CpT scene of the vehicle, Z slice

In Figure 51, we can see the speed of the air passing through the radiator. It can be used to verify that the flow rate is sufficiently constant across the entire surface. Considering that the radiator is simulated as a porous surface, it is clear that the air flow rate is uniform across the entire surface, except for a negligible drop in the upper left corner.

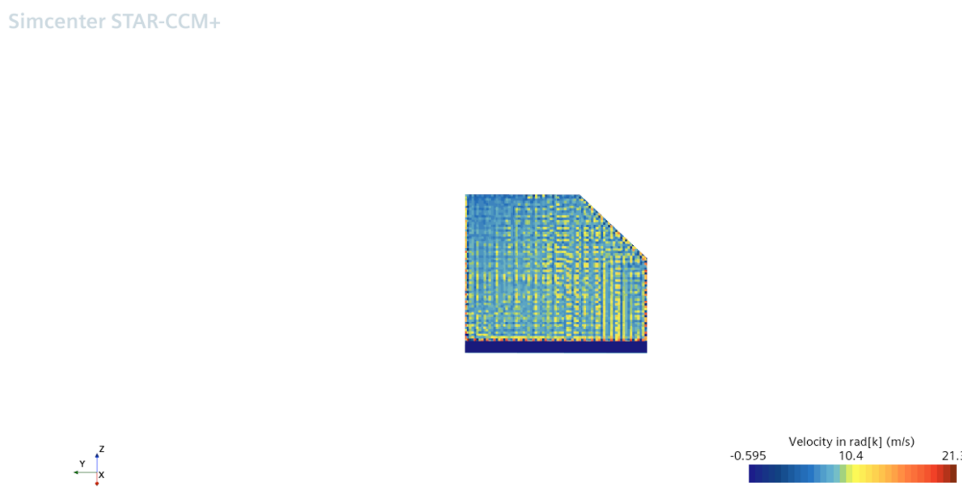

Figure 51: Air velocity through the radiator

To verify the effects of optimization, the same KPIs used to determine the ideal positioning can be used.

	Radiator air mass flow [kg/s]	CL.A	I_{zz} [kg m^2]
Baseline radiator	0.154	-5.05	107.06
Optimized radiator	0.146	-5.06	106.60

Table 21: KPIs of the optimized radiator

The CL and rotational inertia values are improved compared to those of the non-optimized solution. The flow rate is lower due to the smaller size of the radiant mass. Despite this, the air flow rate is higher than the target expected for optimization, confirming the effectiveness of the optimization process.

8 Finished product

At the end of the optimization process, once the shapes, dimensions and positions of the radiator assembly have been established, it is possible to design in detail the various components that make it up.

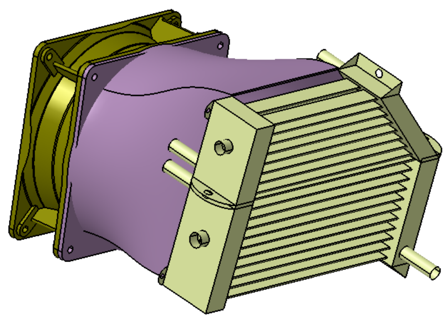

Figure 52: Radiator assembly of the SC26

1. The two radiators are connected to each other with two screws to form, from a structural point of view, a single entity. Both radiators also feature a structure that allows, thanks to the use of short brackets, to fix the radiator assembly directly to the inserts present in the monocoque.

   The direction of the pipes was chosen considering the path of the water routing.
   For the engine radiator, it is more convenient to have the inlet and outlet oriented differently, to facilitate the passage of water from the front to the rear axle.
   In contrast, the inverter radiator features an asymmetrical solution.

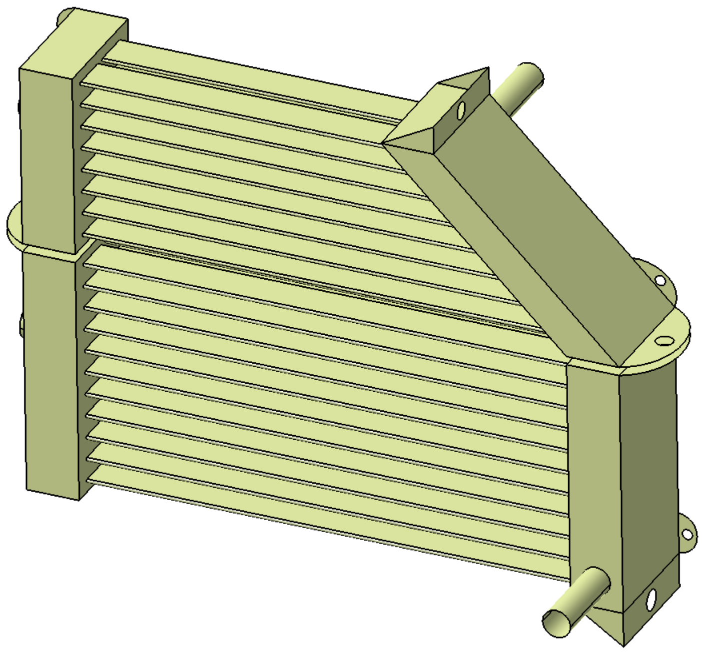

Figure 53: Finished radiator

On the right, both the inlet and outlet face the rear axle, while on the left, they point in different directions. This was desired because the cold circuit pump is located on the left, further forward than the radiator, while the inverter is behind it. This reduces the length of the pipes, reducing the quantity of water in the circuit and the weight, and improving packaging.

On the outside of the radiator, there are two threads for mounting Schrader valves. These valves are used to pressurize the water in the circuit before turning on the pumps. The purpose is to allow the pump to operate under better conditions and absolutely prevent cavitation. Since the system is pressurized from the start, even if pressure drops significantly reduce the inlet pressure of the pump, it will still be higher than atmospheric pressure, preventing cavitation that could damage the pump's mechanical components.

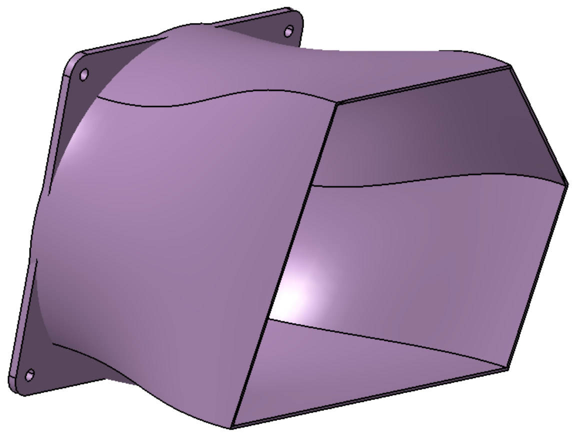

Figure 54: Radiator conveyor

2. The conveyor is produced in-house using plastic 3D printing. The material selected for production is simple PA 12, due to the low loads it has to bear. This allows for a lightweight and easily modified component. It is essential to make small adjustments if the radiator's production results in small differences from the CAD drawing. For this reason, the mounting points on the radiator are missing from the CAD drawing. The conveyor is connected to the radiator using four specially designed four-finned screws. The variations in the position of the fins led to the design of the mounting points on the conveyor being postponed until the end of radiator production.

3. As previously mentioned, we chose to use the same model of fans as previously used. This carryover, besides being technically convenient given the excellent performance of the component, also has another advantage. Using the same component already used, allows us to reduce costs, as we already have some new components as spares and to

maintain the same integration with the electrical system, given that a configuration already exists in the current system. The model in question is the Ebm-Papst 4114 N/2H8P.

Once the assembly design is defined, the total weight of the assembly can be accurately estimated. Can be seen that a great weight reduction is achieved.

	[Kg]
Radiator	0,393
Fan	0,425
Conveyor	0,220
Total	1,038

Table 22: Weight of the SC26 radiator assembly

9 Conclusions

The design process for a critical component like a radiator can be a tortuous one. In this thesis, I described my steps in designing the radiator assembly for the SC26, from defining the targets to designing the finished component. The result of this work was a component that fully met the cooling targets and, against all expectations, achieved a significant weight reduction. In fact, it was possible to reduce the weight of the assembly by 29% compared to the current solution. This reduction appears even more remarkable considering that the increase in heat to be dissipated, in accordance with the new targets, is 39% .

This is the result of both the optimization of the aerodynamic flows, which was carried out using CFD models, and the idea of separating the water circuits. In this way, it was possible to guarantee ideal operation for each of the two exchangers. Separating the large amount of heat that must be dissipated by the motors from the requirement for relatively very low temperatures for the inverter, allowed us to design two different exchangers, each optimized for its specific task. This practice, commonly used in the automotive or motorsports fields, is not usually considered in Formula Student due to its complexity. The idea of combining the two exchangers into a single assembly therefore minimizes packaging issues. In this way, the two separate radiators, in terms of packaging, occupy the same space as a single radiator. This assembly allows the car to compete throughout the entire Endurance race at a pace up to 35°C (95°F) in ambient temperatures. To date, few Formula Student cars can complete the entire Endurance race at the same pace as an Autocross race. The competitive advantage afforded to a team by achieving such performances, given the event's points, is significant. Allowing a racing car to fully express its potential without compromising reliability during a race is the primary objective of the cooling system.

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