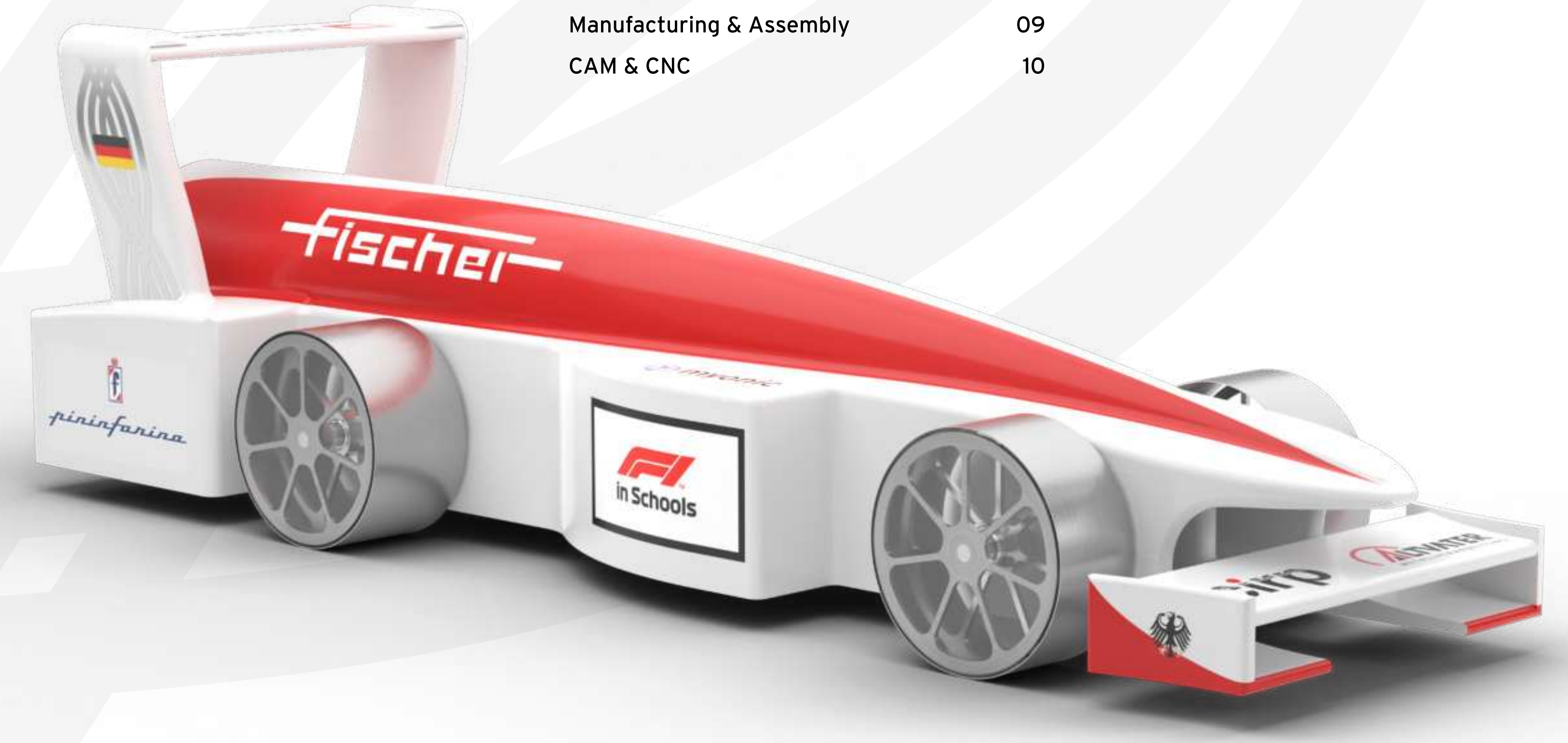
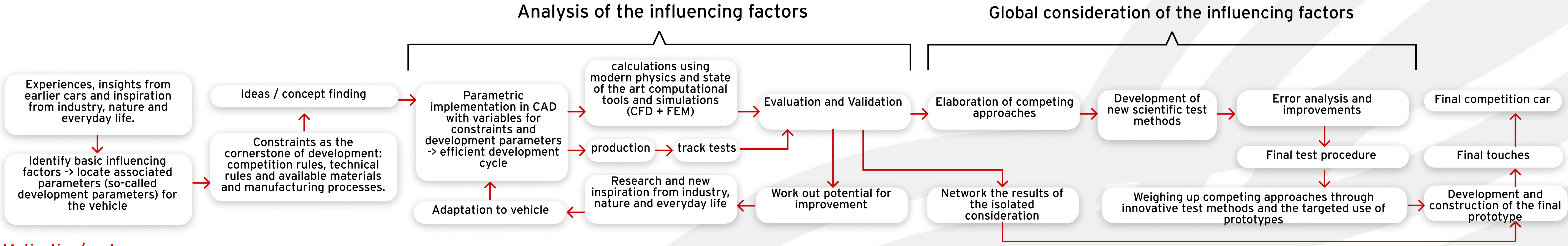
DESIGN & ENGINEERING

momentum
RACINGTEAM



INTRODUCTION - DEVELOPMENT PROCESS



Motivation/goal

Developing a car that is consistently as fast as possible and complies with the technical rules and regulations is essential for success in the competition (35% of the points are awarded for racing and compliance with rules). Since the world final rules differ strongly from the national rules, we decided to start the research and development process from scratch while utilizing our experience from the past years.

Design of Portfolio

This document is intended to be read in a chronological manner, from the beginning to the end, because the content of later pages often refers to the knowledge from earlier pages. This logical dependence is crucial to fully comprehend our development of the car.

Framework given by constraints

For every development project there are certain rules and restrictions that have to be followed. Therefore, we had to define and analyze the constraints that apply to us at the beginning of the development process. They form the basis for the entire research and development process and give us a framework in which we can work:

- Rules and regulations: Adherence to the rules and regulations has the highest priority in order to avoid penalty points and because of sportsmanship.
- Budget: Despite successful marketing strategies, a financial framework has to be considered, thus we were only able to perform 2 tests with official competition cartridges, as they are way more expensive than commercial gas cartridges. The facilities for real testing is expensive, therefore only allowing 5 track testing possibilities. This makes the efficient use of results obtained by track testing from past years essential.
- Manufacturing: By consulting with our manufacturing sponsors, we are able to determine the materials and processes available, thereby defining a precise development scope. Despite the use of a 5-axis CNC milling machine and additive manufacturing processes such as selective laser sintering, the technical possibilities are limited.
- Time: We have limited time, and thus we can only do finite amount of development.

Within this framework, the task now is to modify the variable vehicle properties in such a way that the race time is optimized.

Thrust

To start our development process we first have to understand our propulsion. Even though we can not influence our thrust, because it is NOT a constant force, it is important to precisely describe the force over time, so that we know in which parts of the race it is most important to reduce energy losses. As we will see later, it is not possible to optimize all stages of the race so a detailed understanding of thrust is crucial.

A mathematical model for a the thrust given by the puncture of a CO2 piston can be deduced by the application of the basic conservation laws of mass, momentum and energy. These laws can be imposed to a suitable control volume using the Reynolds transport theorem in a classical fluid mechanics approach.

We can consider a control volume (CV) which contains the car and intersects it at the nozzle of the cartridge (control surface (CS)). The absolute pressure and the air density at the nozzle are p_an and \rho_an, respectively, as indicated.
p_a0 is the absolute pressure of air before the launching and m_a is the mass of pressurized air. The mass of car with a empty race pack is m_b.

The mass conservation in the CV can be expressed in terms of the Reynolds transport theorem:

$$0=\frac{\mathrm{d}}{\mathrm{d}t}\int_{CV}\rho \mathrm{d}V+\int_{CS}\rho(v_r\cdot \mathrm{d}S)$$

This integral expression of continuity equation can be applied to our CV and yields

$$\frac{\mathrm{d}m_\mathrm{a}}{\mathrm{d}t}=V\frac{\mathrm{d}\rho_\mathrm{a}}{\mathrm{d}t}=-\rho_\mathrm{an}Sv_\mathrm{an},$$

where v_an is the velocity of the air at the nozzle.

The general expression of momentum conservation in the CV using the Reynolds transport equation is

$$\sum F=\frac{\mathrm{d}}{\mathrm{d}t}\int_{CV}\rho v\,\mathrm{d}V+\int_{CS}\rho v(v_r\cdot \mathrm{d}S),$$

Applied to our problem we get the following expression:

$$-F_\mathrm{D}-W_x-F_\mathrm{M}=\frac{\mathrm{d}}{\mathrm{d}t}(m_\mathrm{b}v_\mathrm{b}+m_\mathrm{a}v_\mathrm{a})+\rho_\mathrm{a}(v_\mathrm{b}-v_\mathrm{an})v_\mathrm{an}S.$$

The conservation of energy in the CV leads to the following relation:

$$\frac{\mathrm{d}Q}{\mathrm{d}t}-\frac{\mathrm{d}W}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}t}\int_{CV}\rho e\,\mathrm{d}V+\int_{CS}\rho\left(e+\frac{p}{\rho}\right)(\mathbf{v}_r\cdot \mathrm{d}S),$$

where $e=u+v^{2} / 2+g h$ is the specific energy, u is the specific internal energy, g is the gravity, h is the vertical position and p is the absolute pressure.

From this we get: $-v_\mathrm{b}(F_\mathrm{D}+F_\mathrm{M})=\frac{\mathrm{d}}{\mathrm{d}t}(m_\mathrm{b}e_\mathrm{b}+m_\mathrm{a}e_\mathrm{a})+\left(e_\mathrm{an}+\frac{p_\mathrm{an}}{\rho_\mathrm{an}}\right)\rho_\mathrm{an}v_\mathrm{an}S.$

Now the preceding 2 equations can be expanded and combined, and led to

$$m_\mathrm{a}\frac{\mathrm{d}u_\mathrm{a}}{\mathrm{d}t}+\left(u_\mathrm{an}-u_\mathrm{a}+\frac{v_\mathrm{an}^2}{2}+\frac{p_\mathrm{an}}{\rho_\mathrm{an}}\right)\rho_\mathrm{an}v_\mathrm{an}S.$$

The absolute pressure of the air at the nozzle p_{an} is not equal to p_{atm} in the present case because the flow is compressible. If an adiabatic expansion for the air is considered

$$m_\mathrm{a}\frac{\mathrm{d}u_\mathrm{a}}{\mathrm{d}t}=\rho_\mathrm{a}V\frac{c_v}{R}\frac{\mathrm{d}T_\mathrm{a}}{\mathrm{d}t}=-\rho_\mathrm{an}v_\mathrm{an}S\frac{p_\mathrm{a}}{\rho_\mathrm{a}},$$

and the difference of specific internal energy can be expressed as

$$u_\mathrm{an}-u_\mathrm{a}=c_v(T_\mathrm{an}-T_\mathrm{a})=\frac{1}{\gamma-1}\frac{p_\mathrm{a0}^{1/\gamma}}{\rho_0}\left(p_\mathrm{an}^{(\gamma-1)/\gamma}-p_\mathrm{a}^{(\gamma-1)/\gamma}\right).$$

After further simplification one obtains a system of equations with one algebraic equation and 3 ordinary differential equations.

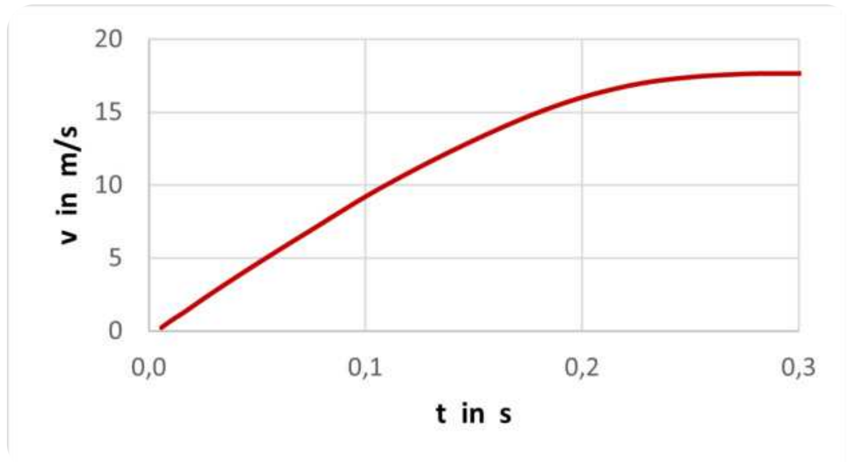
$$v_\mathrm{an}^2=\frac{2\gamma}{\gamma-1}\frac{p_\mathrm{a0}^{1/\gamma}}{\rho_0}\left(p_\mathrm{a}^{(\gamma-1)/\gamma}-p_\mathrm{an}^{(\gamma-1)/\gamma}\right)$$

$$\frac{\mathrm{d}v_\mathrm{b}}{\mathrm{d}t}=\frac{S}{m_\mathrm{b}+m_\mathrm{a}+m_\mathrm{w}}\frac{2\gamma}{\gamma-1}\left(p_\mathrm{a}^{(\gamma-1)/\gamma}-p_\mathrm{an}^{(\gamma-1)/\gamma}\right)p_\mathrm{an}^{1/\gamma}-\frac{1}{m_\mathrm{b}+m_\mathrm{a}+m_\mathrm{w}}(F_\mathrm{D}+F_\mathrm{M}+W_x)$$

$$\frac{\mathrm{d}m_\mathrm{a}}{\mathrm{d}t}=-Sp_\mathrm{an}^{1/\gamma}\left[\frac{2\gamma}{\gamma-1}\frac{\rho_\mathrm{a0}}{p_\mathrm{a0}^{1/\gamma}}\left(p_\mathrm{a}^{(\gamma-1)/\gamma}-p_\mathrm{an}^{(\gamma-1)/\gamma}\right)\right]^{1/2}$$

$$\frac{\mathrm{d}p_\mathrm{a}}{\mathrm{d}t}=-\frac{S}{V}\left(\frac{2\gamma}{\gamma-1}\right)^{1/2}\left(\frac{p_\mathrm{a0}^{1/\gamma}}{\rho_0}\right)^{1/2}p_\mathrm{a}^{(\gamma-1)/\gamma}p_\mathrm{an}^{1/\gamma}\left(p_\mathrm{a}^{(\gamma-1)/\gamma}-p_\mathrm{an}^{(\gamma-1)/\gamma}\right)^{1/2}$$

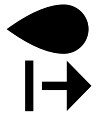
These equations can be solved with numerical methods. We used a computational tool called Matlab to solve this system of equations. After dividing by the mass of the power pack and integrating over time we got the following graph of velocity, if no energy losses are considered:



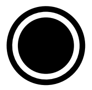
ANALYSIS OF INFLUENCING FACTORS 1

AVAILABLE ENERGY

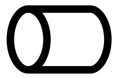
We have a certain amount of energy available to drive our car, which is contained in the gas cartridge (pV). We want to convert this energy as much as possible into movement energy / kinetic energy (W= 1/2 m*v^2). Therefore, when developing vehicles, we must ensure that energy losses are minimized. In order to realize this, we have to recognize and analyze the fundamental influencing factors. During the last few years we have gained a lot of experience and found out the fundamental aspects that affect the race time. These are:



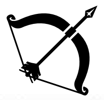
- Aerodynamics: By optimizing the aerodynamics of the race car, we can reduce energy losses caused by air resistance. For this, the vehicle shape (with the air attack surface) must be adjusted. A teardrop shape, for example, is optimal.



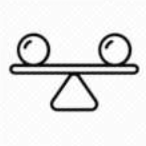
- Wheels: With the help of the rotation of the wheels, the vehicle is enabled to move forward; this can result in large losses due to friction and high moment of inertia of the wheels.



- Tether line guides: The optimization of the guide eyelets is important in order to keep the energy losses caused by unsteady driving behavior and friction as low as possible.



- Directional Stability: The shape not only determines the air resistance, but also the aerodynamic stability of the car. The lateral tilting results in large energy losses. An aerodynamically stable car counteracts this tilting.



- Stability: The geometry of the car should be rigid, this means it should not change during the deacceleration process of the race. Due to the large forces which the car experiences during the deacceleration process, we performed strain tests and FEM to avoid mechanical failure.

ANALYSIS OF IFS & GLOBAL ANALYSIS

The determined development parameters are defined as IFs (influencing factors) and initially analysed one by one, completely in isolation. For our development, we used design concepts from industry, nature and everyday life, and adapted them to our car through research and precise analysis. This enables us to solve problems that arise during the design phase of the isolated considerations in the best possible way.

For the analysis of influencing factors, physical considerations, calculations, computer simulations (CFD and FEM) and real tests are used to validate the theory derived by physics. The results of these considerations reveal contradictions which we can be resolved through global analysis afterwards. For a successful global assessment, innovative test methods must be developed and applied to compare the importance several IFs. Further prototype tests then determine the direction of development. By combining the constraints, the analysis of influencing factors and global considerations, we get the final prototype. After that, the parameters are fine-tuned to get the final car. In addition, individual components and their materials are examined in parallel using test procedures, and manufacturing processes and assembly devices are analyzed and optimized.

In the following, the findings of the isolated considerations are derived and then the test methods and results of the global considerations are presented. The design of our car is dedeuced from this and thus fully explained. Finally, we explain the selection of manufacturing processes and functionally optimal materials. The conclusions drawn from the analysis of influencing factors and global considerations are shadowed in GREY. The implementation of these conclusions is again framed in RED.

TEST CONCEPT

The basics of experimental statistics are essential to increase the validity of the track tests. We always made 10 runs so that most of the values scatter around the mean and a standard deviation of 0.15 seconds is almost always achieved. However, there were statistical outliers that we did not take into account. Through multiple error analysis, we were able to optimize our experimental setup to minimize systematic errors (continuous, repeatable error related to inaccurate equipment or a flawed experimental design). However, since we test for relative results, systematic errors have almost no influence. Because of the financial limitations, we could not use standardized competition cartridges for the tests. However, we weighed the cartridges in order to create the same conditions as possible. We also controlled the temperature of the cartridges and the room to get meaningful results.

TRACK TESTS

Because we only had limited opportunities to perform track tests, we had to ensure to make the most out of them. We used a drone and multiple camera angles to record the races. This way we gained much more information than the race times. We could extract the exact race behaviour and cause of a fast or slow race. This was possible by modern Computer Vision technology used to extract accleration and velocity of car and also which angle the car tilted.

Using static cameras, the background subtraction algorithm is commonly used to generate a foreground mask, which is a binary picture containing the pixels belonging to moving objects in the scene. The foreground mask is calculated by subtracting the current frame from a backdrop model that contains the static component of the image. We used the GMG algorithm.
The GMG algorithm uses a bank of Kalman filters and Gale-Shapley matching to combine statistical background image estimate, Bayesian segmentation, and a solution to the multi-target tracking problem. It uses a probabilistic foreground segmentation algorithm that uses Bayesian inference to identify probable foreground items. To reduce undesired noise, several morphological filtering processes such as shutting and opening are performed.
Detecting features is easier now that we have removed the backdrop from the image and have a bitmask of the scene's objects. To discover the corners or spots of interest in the frame, OpenCV's version of Good Features to Track was employed. Feature detection takes a picture and generates a vector of points that it considers "nice to track."

We can now calculate how much each pixel moves between neighboring photos using this data. The image sequences utilized in this project are created using perspective projection and the relative motion of the scene's objects. Moving patterns create temporal variations in visual brightness, and all temporal intensity changes are presumed to be due to motion alone. The Lucas-Kanade approach was utilized. All 9 points exhibit the same motion when considering a 3x3 matrix or a window of pixels selected around the central point. The problem thus becomes one of solving nine equations with two unknown variables which is a overdetermined situation.

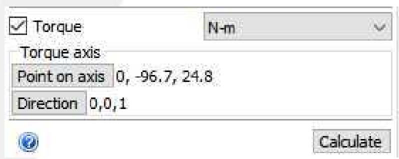
Other types of optical flow, such as dense optical flow, are more accurate. Because it performs computations on practically all of the pixels, this method can be computationally demanding, which may be overkill for our needs. There is only one moving object in the scene, which is filtered out using background subtraction.

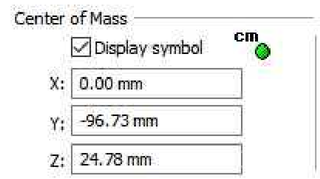
Directional stability

Minimal differences in braking forces on the wheel suspension, off-centre position of the center of mass and a slightly skewed alignment at the start mean that the cars unfortunately never exactly start straight. This causes lateral pivoting, which not only enormously increases the friction on the tether line, but also results in very large energy losses, since the thrust cannot be fully used to drive the car. In order to minimize these losses, it is not only necessary to take measures to ensure that the car starts straight from the start (see axle design), but also to design a car that does not reinforce this behavior due to its geometry (aerodynamics), but counteracts this behaviour. So we tried to create a car which counteracts this pivoting.
Vertical surfaces in front of the COM form an airfoil when pivoted sideways, which generates a torque in the direction of diegression. Vertical surfaces behind the COM, on the other hand, generate a torque that counteracts this digression.

Our goal is to maximize: $T_{net} = T_r - T_f$
- where T_r summarizes all torques behind the COM
- where T_f summarizes all torques before the COM

In order to have a benchmark that can be used as a guide during development, we need a scalar. We first did empirical experiments to find out what the average angle of the car to the track is when a human tries to align the car. Using our Computer Vision technology and our drone recordings we found out that the average angle is 1,5 %. Therefore, we simulated the car in Autodesk CFD Ultimate at a 1° angle and 2° angle towards airflow and calculated the mean value of the Torques
Our goal was to maximize this value. For this we computed the coordinates of the COM with Solid Edge.

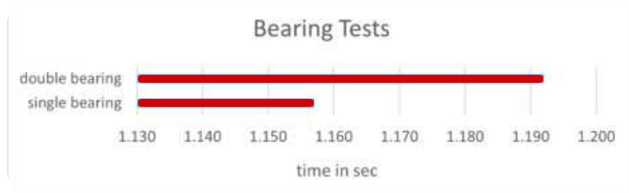




Wheel Suspension

Ball bearings
In order to keep the friction between axle and wheel small, we have used Ceramic ball bearings because their coefficient of friction is the lowest of the bearings we could afford. The rolling friction coefficient is primarily determined by the hardness of the components.

The track tests showed us that two ball bearings per wheel significantly increase stability, which has a positive effect on race time, even if the moment of inertia increases as a result.
Because we didn't have the time and resources to do track tests with ball bearings with different dimensions, we relied on our physical calulations:



The force F_b required to overcome the rolling friction of the ball bearing is given by:

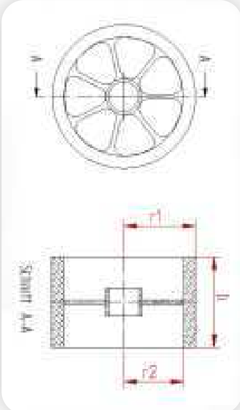
$$F_b = \frac{d_b}{d} F_r$$

where F_r is the Ball bearing friction, d is the diameter of the wheel and d_b is the diameter of the beearing. This means

we should use double ceramic ball bearings with the smallest diameter available
=> we used two 5/2/2.3 ceramic ball bearings in each car

analysis of influencing factors 2

Moment of Inertia



Setting a wheel in motion requires energy. The moment of inertia is a measure of this energy. Thus our goal is to reduce the moment of inertia. The moment of inertia of our wheel can be compared to that of a hollow cylinder because the moment of inertia of the spokes is about 300 times smaller than that of the outer surface.
The spokes have been optimized in such a way that a certain degree of stability remains and the lowest possible mass can still be achieved.
moment of inertia of the outer surface:

$$J = m\left(\frac{r_1^2 + r_2^2}{2}\right) = \rho V\left(\frac{r_1^2 + r_2^2}{2}\right) = \rho\pi b(r_1^2 - r_2^2)\left(\frac{r_1^2 + r_2^2}{2}\right) = \frac{1}{2}\rho\pi b(r_1^4 - r_2^4)$$

- minimum width and radius of the wheel => 28mm diameter, 15mm/12mm width
- wheel should be as thin as possible

Problem: Inertia vs. Stability
If the Wheel is to thin or has to thin spokes, it can break or deform which leads to big energy losses

Rolling friction of the wheels

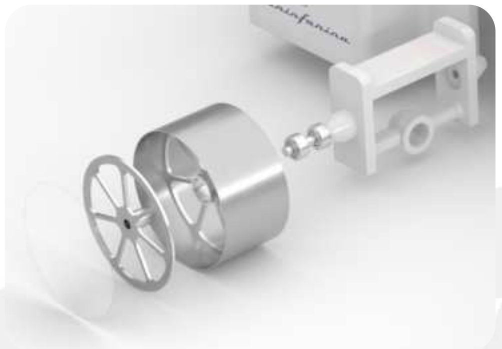
The rolling friction is the deformation resistance of a rolling body. The formula is: $F_R = vC_R$
where C_R is the coefficient of the rolling friction => C_R should be as small as possible (=> material of wheels is titanal, which has a low coefficent).

Taking these results into account, we determined the number of spokes, the thickness of the rolling surface based on real tests. To do this, we only changed one variable at a time in order to achieve comparable results
Results:
optimal number of spokes: 7
optimal rolling surface thickness: 0.1 mm (perfect balance between stability and moment of inertia)

Axle suspension

We had the following requirements for the axle suspension:
- Accuracy to minimize friction losses and avoid side-to-side panning
- little mass, in order to affect the center of mass and the launch behavior as little as possible
- easy assembly while guaranteeing that all 4 wheels touch the road
- should not allow space for the wheel to move laterally
- high stability to avoid deformation

We couldn't use one axle, because our car is designed like a catamaran and then it would be very unstable. We still had to somehow attach the wheels to the car body. It was logical to connect the Wheel to the nearest part of the car body with a semi-axle. This semi-axle needed to be robust so that the it wouldn't deform when experiencing immense forces during the launch, but it also couldn't weigh a lot to not compromise the launch behaviour. This is why we manufactured the semiaxle out of the alloy Titanal which is light and sturdy. That is how our wheel suspension satisfied the first 2 conditions. The problem with semi-axles is that because the wheels aren't connected with each other it is almost impossible to ensure that all wheels touch the track, because manufacturing tolerances lead to different positions of the sime-axle holes. Another big concern was that the connection between the semi-axle and car body (which was made of the porous, deformable material of the F1 in Schools Model Block) would break during the launch.



We could solve both problems by using innovative bridge structures made of PA 12 which is far more sturdy than the car body and still light.
This way perfect axle alignment both vertically and horizontally was ensured so that all wheels touch the track and the vehicle drives exactly straight.
We also added extensions to the bridge and the hubcap to lock the wheel laterally.

This way we were able to combine the benfits of a single axle wheel suspension with the catamaran concept.

In order to meet the last requirement, we thought about which factors can lead to deformation:
- the extremely high acceleration at the beginning
- Steps and bumps in the track
- the extreme deceleration after the race by braking cloths

Then, we first measured acceleration and deceleration with a small accelerometer over several races. After that we measured the y-vibration over several races. We were able to insert the y-vibration as a periodically occurring event and the acceleration and deceleration as force vectors in the FEM program and derive improvements for the stability of our chassis from this.

Stability

From experience we know that the only truly critical structure that can deform or even break during racing is the front and rear wings. That's why we checked the entire nose for stability using physical calculations and FEM simulations. We will get to rear wing later. Here we have considered the deceleration process, since this is where the greatest forces are at work. During the deceleration process, the total mass of the vehicle is the sum of the mass of the vehicle and the empty cartridge: 55.5+19.5g=75g. The braking distance is 20 cm long, the initial speed is 23 m/s, the final speed is 0 m/s. So the force that acts is:

$$a = \frac{v^2}{2s} = 1322,5m/s^2 \Rightarrow F = ma = 1322,5m/s^2 * 55,5g = 100N$$

If you look at the stresses, you will find that bending and shearing stresses act. Therefore we checked the failure against fracture and yield with the following calculations. We can neglect the notch effect number since the width of the front wing is reduced by a maximum of 1% within the profile.

bending stress

$$M = F * h_f = 100N * 22mm = 2200Nmm, W = b * h^2/6 = 80mm^3 \Rightarrow \sigma_{bf} = \frac{M}{W} = 27MPa$$

shear stress $\tau = \frac{F}{A} = 4Mpa$

Equivalent stress according to the shear stress hypothesis

$$\sigma_{vF} = \sqrt{\sigma_{bF}^2 + 4\tau^2} = \sqrt{(27MPa)^2 + 4 * (4MPa)^2} = 28MPa$$

breakage resistance

$$\sigma_{WirkF} \leq \sigma_{Zul}, \sigma_{Zul} = \frac{Rm}{S}, \sigma_{vF} = \sigma_{Zul} \Rightarrow S_B = \frac{Rm}{\sigma_{vF}} = \frac{120MPa}{28MPa} = 4,28 \geq 2$$

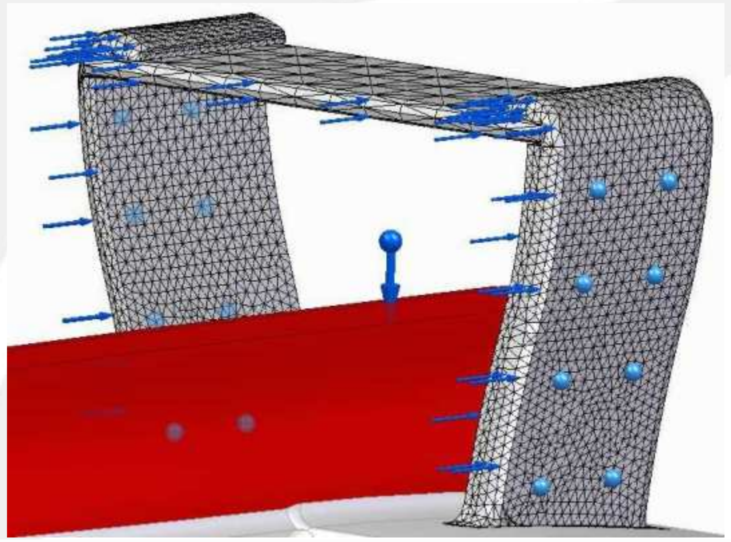
flow security

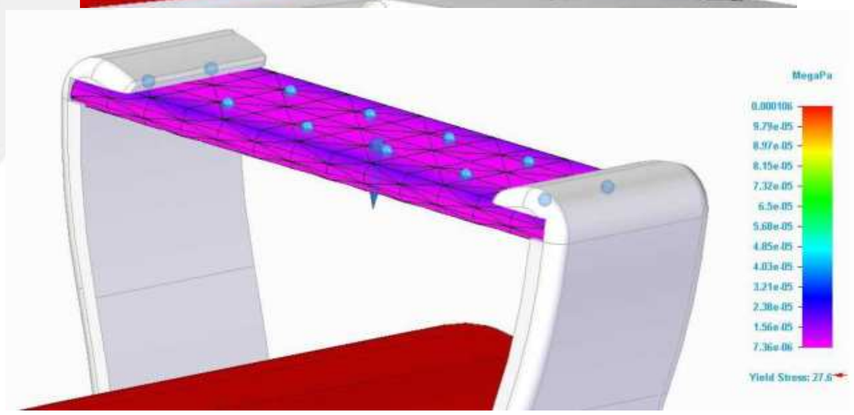
$$\sigma_{WirkF} \leq \sigma_{Zul}, \sigma_{Zul} = \frac{Re}{S}, \sigma_{vF} = \sigma_{Zul} \Rightarrow S_F = \frac{Re}{\sigma_{vF}} = \frac{40MPa}{28MPa} = 1,43 \geq 1,2$$

FEM simulation

Solid Edge Simulation is an integrated finite element analysis (FEA) solution that allows us to digitally validate part and assembly designs within the Solid Edge environment. Based on proven Femap finite element modeling and NX Nastran technology, Solid Edge Simulation significantly reduces the need for physical prototypes, reducing our material and testing costs and saving design time. We made a linear static simulation with tetrahederal mesh. We were able to adjust the force vector and define the degrees of freedom. This is how we got the best and most meaningful results.

We knew that only the rear and front wings would experience the most stress from past years. this is why we first simulated the rear wings and because of the robust material from which we made the rear wing: titanal, there were no problems





Even though our calculations showed that our nose cone wouldn't break during the race, we wanted to be 100% sure that this wouldn't happen.

To improve the stability of the front wing, we curved our front wing. The stability improves because of the second order axial moment of area. We used this same concept in the rear wing support structures.
Hereby we were inspired by a technology from skis.

Design concept

A similar concept was used in the amphibio 4d technology for downhill alpine skis. In the case of the skis, the shape is used to reduce vibration and prevent deformation.

ANALYSIS OF INFLUENCING FACTORS 3

Launch Behaviour

High-speed footage showed the rear of cars from previous competitions lifting off the track during takeoff. This must be avoided, otherwise the thrust force F is not fully used for the horizontal acceleration. Because the thrust is largest at the beginning it is crucial to have an optimal start behaviour.
Our car has a mass M and a thrust in the direction of travel, which acts on the height H. The center of mass (COM) is at the height h from the track. In our case =0.61g. Source: Article "Static friction coefficient of some plastics against steel and aluminum under different contact conditions" by Habib S. Benabdallah in Tribology International, Volume 40, Issue 1, 2007".
The cause for the rear lifting off is a torque acting around the centre of mass. The total torque around the centre of mass in the vertical reference plane is given by:

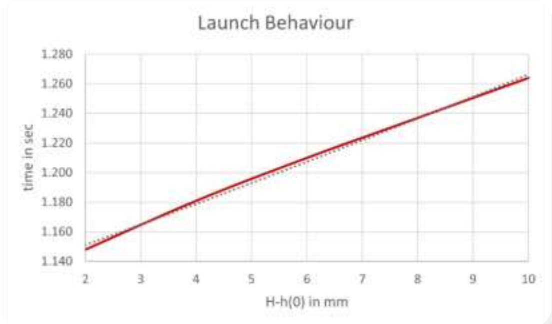
$$\tau_{com}(t) = F(t)(H - h(t)) - M(t)gh\mu(t) \qquad \mu = \begin{cases}\mu_{static} & t \le c \\ \mu_{kinetic} & t > c\end{cases}$$

We want to minimize this torque and in the optimal case it should be zero. This means:

$$\tau_{com}(t) = 0 \Rightarrow H - h(t) = \frac{M(t)gh\mu(t)}{F(t)}$$

- COM has to be between the front and rear axle, so that car doesn't tip over
- h(t) must be maximum = the center of mass must be as high as possible
- H must be minimal = the cartridge chamber must be as low as possible, permitted by the rules => H=30mm

We were able to prove these conclusions with a car with an adjustable center of mass in track tests.

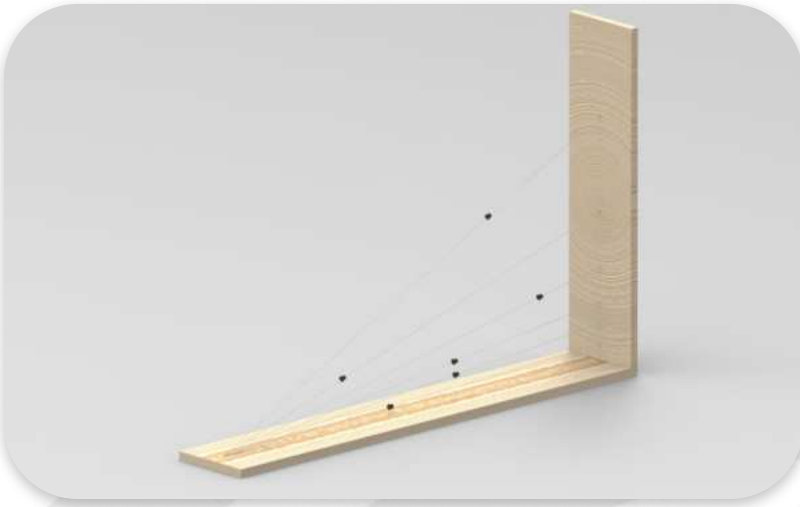


- The rear wing has its maximum dimensions and is as high as possible with 2 huge support structures for the optimal COM
- lightweight concept adapted from technology and nature to the car in order to save weight and shift the center of mass upwards

Friction of the tether line

The friction between the guides and the nylon cord is caused by 3 forces:
F_1: the Force necessary to lift the mass m of the tether line.
F_2. the Force necessary for the vertical acceleration of the tether line.
F_3: The force caused by the friction between the .
To minimize F_3 we have to maximize the directional stability minimize the coefficient of sliding friction. Because we can't influence the properties of the thread, we can only place the tether line guides as low as permitted by the rules (T3.8: track clearance: 1.5mm) to minize these forces.

To minimize the friction of the tether line, we wanted to use special sleeves in our guides. We ordered several sleeve bearings made of different materials as well as with different coefficients of friction from Igus and compared them with each other.
As an experimental setup, we built a simple wooden structure, attached a piece of guide cord, and then gradually changed the angle of inclination of the cord until the sleeve moved. We performed 10 tests with each sleeve then compared the respective angle of inclination.



Results: We used the sleeves from Igus Igildur X.

Drag

Drag is the physical quantity that describes the force that the air opposes to movement. A body moving relative to air experiences air resistance, a force opposing velocity.
The formula of drag is given by:

$$F_W = \frac{1}{2} c_W A \rho v^2$$

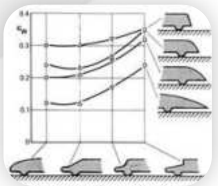
where F_W:=Drag in [Newton], A:=Cross-sectional area in [m^2], p:=Density of medium (in our case air) in [kg/m^3], v:=Velocity of the air in [m/s]

Of all the factors on which the drag depends, we can only influence c_w and A. Because we want to minize drag, we should minimize c_w and A.

We have minimized the cross-sectional area (A) by using the catamaran principle. We also made the car as narrow as possible without violating the rules to further this cause.

C_w value

Turbulences have a negative impact on the c_w value, which is why a high-quality surface must be sought. We used high-quality paint to reduce turbulences on the surface. In addition, CFD simulations can be used during vehicle development to determine the effects of geometry changes on the c_w value and thus improve the design.
From previous wind tunnel tests we know that it is also important:
- not to have too large pressure differences
- to reduce the vacuum area behind the car



Turbulences

Turbulences are highly accelerated air. They increase drag and consume a lot of energy, so we have them minimized by adapting the vehicle design.

Virtual mass of air

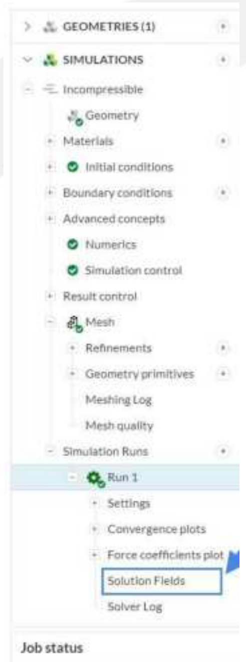
Slowly moving air (relative to the car) has a certain virtual mass: it cannot be measured, but it increases the mass m to be accelerated. Therefore we fill these areas with existing volume/mass. This way we can minimize the mass that has to be accelerated and the car will go faster. We used this principle primarily for the side pods and the wheel block.

CFD

CFD simulations are extremely useful for guiding the development process and gaining important insights without having to prototype for track testing. Unfortunately, due to COVID-19, we were not able to validate these simulations in the wind tunnel. Therefore, we used wind tunnel test data from previous teams to assess the validity of the software. Simscale has been found to be the most accurate (free for students) software compared to Flow Design, Autodesk CFD and FloEFD.

Method

- Export from Solid Edge to SimScale and create flow volume
- Assign topological entity sets
- Assign boundary conditions, material, and other properties to the simulation
- Set the Numerics & Simulation Control
- Mesh with the SimScale standard meshing algorithm and add Region Refinements
- Simulate with k-omega SST turbulence model and evaluate results

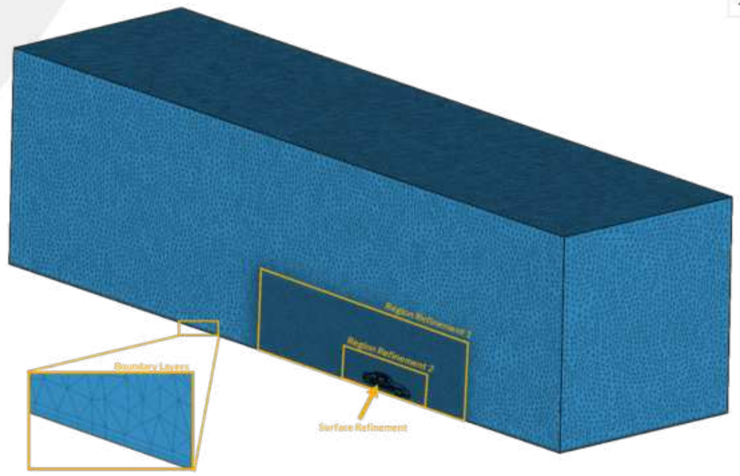


Direction of optimization

Adjustments to the geometry lead to a change in the flow around the vehicle. Optimizations at the front of the vehicle have a significant influence on the airflow around the car. So that such changes do not invalidate the previous simulations, we optimize from front to back.

Mesh refinements

The local element size varies between areas with complex airflow and simple airflow. Because the velocity and pressure gradients are so high in such places, finer cells are required to accurately resolve them.



Evaluate results using Force and Moment coefficients, surface visualization, cutting planes and streamlines

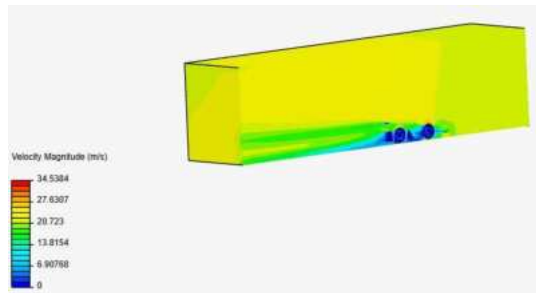


photo source: https://www.simscale.com/docs/tutorials/aerodynamic-simulation-vehicle/

3D MODELING

CAD Software

We decided to work with Solid Edge, because we have 6 years of experience and it would take to much time to learn a new CAD software. Furthermore Solid Edge gives you complete design freedom, including the ability to create synchronous parametric components, which allow you to add design intent through parametric control.

Parametric design

Parametric design is critical for ensuring a time-effective development process. Parametric design allows you to specify logical rules characterizing the model and the interconnections between its components, as well as a set of parameters to drive the logic, rather than manually adding and modifying every part of the model. Based on your specifications, the design tool calculates and builds a dynamic 3D model. PMI dimensions can be used to change the model, with locking and unlocking dimensions governing the impact of adjustments. This way we could quickly produce new geometry after examining the results of a test by just altering the variable's value. By eliminating manual input, the model may be generated considerably quickly, resulting in a significant decrease in the time required for one development cycle. We were able to execute as many development iterations as needed in a short amount of time as a result of this. Aother big advantage is that we could forget the rules and manufacturing tolerances because these were automatically incorporated in the variables.

Rules incorporated in parametric design:
Technical Rules and Regulations: as this was one of our contraints we included this in our variables so that we didn't have to worry about memorizing the rules for the development process
Manufacturing considerations: To ensure a smooth manufacturing process we had to consider a few things, which we integrated into our variables:

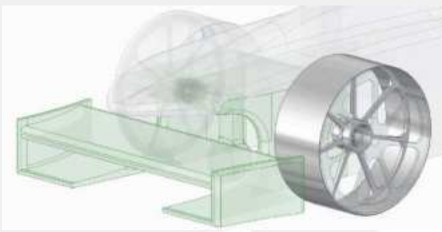
- Minimum Wall Thickness in Car body: 2.5 mm
- Minimum Wall Thickness in SLS parts: 1 mm
- Minimum Wall Thickness in wheels: 0.1 mm

Hybrid modeling

For a favourable results, a hybrid approach that combines freeform surfaces with ruled geometry is ideal. It allows extremely complex geometry while requiring minimal computing time when changes are made.

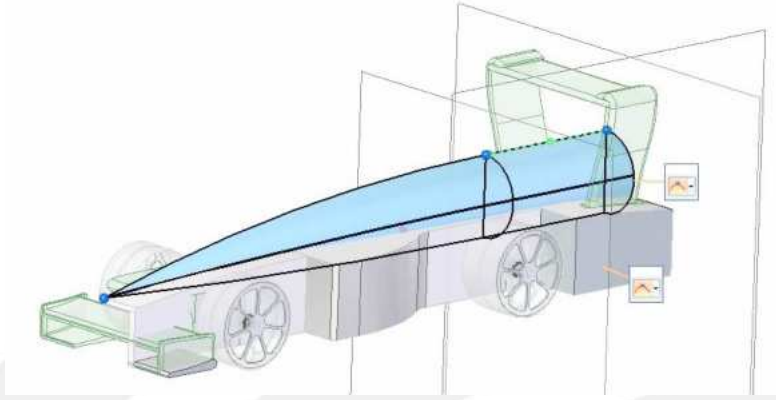
Ruled Geometry

Ruled geometry is the optimal choice for easily designing simple geometries. Solid Edge allows us to create three-dimensional solid bodies out of two-dimensional sketches with the features: extrusion, rotation, cutout and rotated cutout. These are extremely stable, precise, and can be calculated quickly following geometrical changes. For example, creating the wheel, we used ruled geometry.



Free-form surfacing

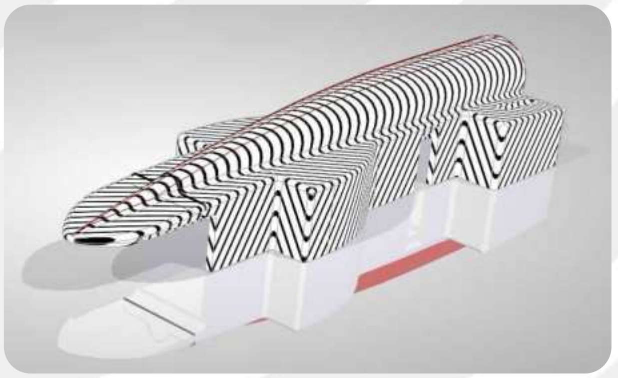
For more complex geometries like the volume encompassing the cartridge chamber we used freeform surfacing. We were able to parametrically model highy complex geometries by using two-dimensional sketches to generate three-dimensional cross-curves which in turn define our geometry.



We employ a variety of tools to increase our productivity and efficiency.

Quality assurance (zebra stripes)

We employ tools like zebra-stripes to control the surface of the geometry. This aids in the detection of uneven surfaces and structural flaws prior to manufacturing.



Properties Manager

We used the tool Properties Manager to accurately compute volumes, surfaces and mass. This aided the choice of materials and planning of painting so that we could obtain our aspired car mass.

Material	Density	Accuracy	Mass	Volume
			0.045 kg	121952.737 m...
Aluminum, 1060	2712.000 kg/m...	0.99	0.005 kg	1850.288 mm^3
ABS Plastic, high impact	930.000 kg/m^3	0.99	0.008 kg	8265.016 mm^3
Teflon	2200.000 kg/m...	0.99	0.000 kg	91.892 mm^3
ABS Plastic, high impact	1024.000 kg/m...	0.99	0.005 kg	4802.086 mm^3
Polyurethene	163.000 kg/m^3	0.99	0.017 kg	102051.875 m...
			0.001 kg	540.582 mm^3
			0.002 kg	706.046 mm^3
Aluminum Alloy:3.1355, AlCu4Mg1, EN-AW 2024	2780.000 kg/m...	0.99	0.000 kg	83.252 mm^3
Aluminum Alloy:3.1355, AlCu4Mg1, EN-AW 2024	2780.000 kg/m...	0.99	0.000 kg	73.827 mm^3
ABS Plastic, high impact	930.000 kg/m^3	0.99	0.002 kg	2306.434 mm^3
Aluminum Alloy:3.1355, AlCu4Mg1, EN-AW 2024	2780.000 kg/m...	0.99	0.001 kg	257.992 mm^3
Aluminum Alloy:3.1355, AlCu4Mg1, EN-AW 2024	2780.000 kg/m...	0.99	0.001 kg	231.602 mm^3
Aluminum, 1060	2712.000 kg/m...	0.99	0.001 kg	201.278 mm^3
ABS Plastic, high impact	930.000 kg/m^3	0.99	0.000 kg	0.000 mm^3

Variables

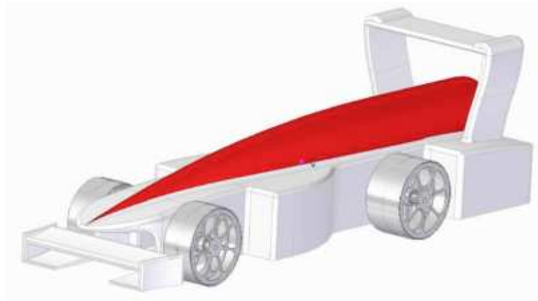
In a familiar spreadsheet style, Solid Edge can use a Variable Table to help develop and edit functional relationships between variables and dimensions of a design. These variables are created automatically by Solid Edge when you define dimensions or a surface, for example (calculation). Of course, you have the option of creating your own variables.

Variable limits allow you to restrict the values of a value in your design, such as the thickness of a part or material. This is similar to the options you have when printing a document, where you may pick whether to print the entire document, the current page, a range of pages, all odd or even pages, and so on.

Type	Name	Value	Units	Rule	Formula	Range	Expose	Exposed Na...	Comment
Va.	MinFlügelDic...	1.50	mm						Regel 7b
Va.	ÖsenTiefe	4.00	mm						R&D Parameter
Va.	PKS	4.00	mm						Regel 5d
Va.	PKTiefe	46.00	mm						Regel 5b
Va.	LängeÜberAl...	208.00	mm						Regel 3a
Va.	FreiesVolumen	16.00	mm						Regel 3h
Va.	BreiteBasis	15.00	mm						
Va.	BAMitte	3.50	mm						BodenAbstandMitte, ...
Va.	PKD	18.20	mm						Regel 5a
Va.	Breite	60.00	mm						R&D Parameter
Va.	Lichtschrank...	26.00	mm						
Va.	RadD	28.00	mm						Regel 4b
Va.	MinFlügelBre...	40.00	mm						Regel 7b
Va.	BohrKopfMa...	17.00	mm						Fertigungsbeschränk...
Va.	AchsDicke	2.00	mm						R&D Parameter
Va.	RadSichbarkeit	15.00	mm						
Va.	MAXAbfallW...	5.00	°						R&D Parameter
Va.	BAFront	2.00	mm						Boden Abstand Nase ...
Va.	Heckflügel_...	50.00	mm						
Va.	RadSeite	1.50	mm						
Va.	KL	4.00	mm						Konstruktionslinie
Va.	Heckflügel_L...	15.00	mm						
Va.	Höhe_Front	17.00	mm						
Va.	RadHeck	65.00	mm						R&D Parameter

Assembly

The main task of the assembly is to define the relations between the components and to assemble the components to build a car.



Linked files

Group variables are essential for a parametric assembly. The set of the group variables is the intersection of the set of the variables from the components.

Inter-part relationships

Inter-part relationships bring about a dynamic parametric assembly so that the geometry of components adjust to changes made to one component.

Goal Seek

We utilized the feature 'Goal Seek' to attain the optimal Centre of Mass and our goal mass for components by changing variable parameters like wall thickness.

GLOBAL CONSIDERATIONS 1

General structure of the car:

The rules specify that the car must contain the virtual cargo, the cartridge chamber with chamber safety zone, front and rear wings (hereby specifying that they must encompass a volume of 2mm*15mm*50mm; the front wing being between 13mm and 5mm above the track and in front of the front wheels; the rear wing being 47mm to 63mm above track and rear to the rear wheels) and wheels

This means that the body must join the front and rear wheel suspension systems, the virtual cargo and the volume encompassing the cartridge chamber. To determine the shape of this body we linked our analysis of influencing factors and came up with the following ideas:

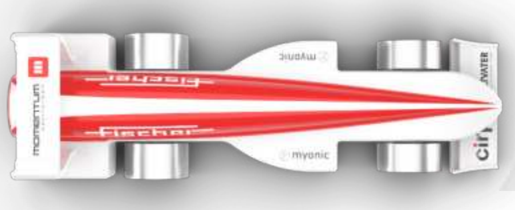
Design concepts:

catamaran principle

- We used the catamaran principle because
- the diverging surface in the back reduces the area with slow-moving air.
- The attack surface is also reduced and the car weighs less!
- The mass distribution is optimal for launch behaviour

Rocket shape

A rocket shape is similar to the optimal teardrop shape and, in contrast to it, is well suited for the construction of our cartridge chamber.



General design concepts:

These are design concepts we used through multiple components due to the great benefits.

Fillets

Simulations have shown that sharp edges lead to unwanted turbulence. That's why we avoided sharp edges and instead used fillets to prevent this turbulence.

Drop Shape

The drop shape is the optimal shape to reduce drag when the wind speed is subsonic. This is why we adapted the drop shape to any airfoil attacked by the air. This way turbulent air and low pressure areas are minized due to perfect consolidation of airstreams.

Light weight structures

We hollowed components like the side pods and the wheel blocks so that centre of mass is shifted upwards and we save mass.

Introduction

Through the analysis of the influencing factors, we can determine many parts of the car such as the whole wheel suspension system and the tether line guides. However, there are a few parameters which cant be determined, because the influencing factors give us contradicting results. Reasonable compromises must be made here based on our global considerations. Since we don't have the time and resources to solve all of these conflicts by our own real test suites, we made a test suite that can solve almost all conflicts at once. Since you can already determine the eyelets and wheels through the isolated considerations and thus exclude them from the test series, we have focused on the following competing approaches:

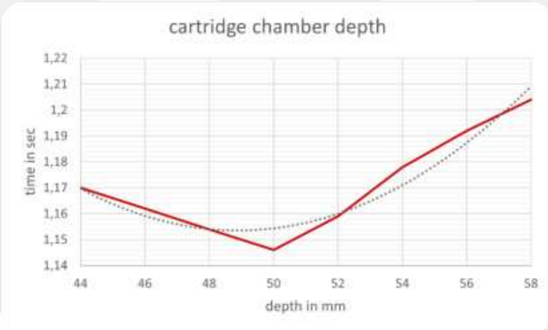
- Aerodynamics
- Aerodynamic stability
- Startup behavior

Before we could start development using CFD simulations, we had to determine two parameters that significantly influence the geometry and thus the airflow of the car. First we did a series of tests on the length and width of the vehicle and a series of tests on the position of the wheels.

There are some parameters which can be determined only by our constraints and the isolated considerations:

Cartridge Chamber Depth: We tested the same car with different cartridge chamber depths. Our results were suprising:

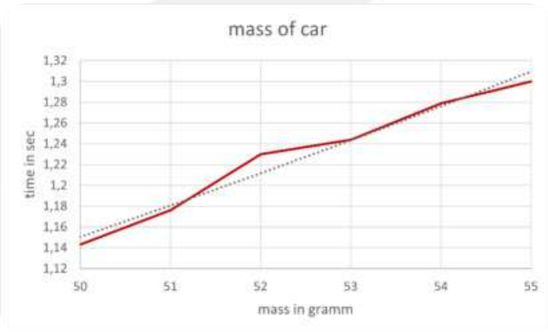
Our track tests showed that 50 mm being the optimal cartridge chamber depth. The results were suprising because they showed us that up to 0.07 seconds of race time is dependent on the depth of the cartridge chamber and the optimal cartridge chamber depth was such a round number.



From past years we knew that minimal car mass was essential for a fast car. This is because of:

=> the velocity of the car is inversely proportional to the car's mass. Track tests validated this theory showing, that only 1 extra gramm corresponds to 0.03-0.04 seconds in race time

$$E_{kin} = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{\frac{2E_{kin}}{m}}$$



1st series of tests: vehicle length

Longer vehicles have better aerodynamics and aerodynamic stability. This is due to the fact that the angles of their surfaces are flatter and the eyelets are further apart. However, they have a poorer starting behavior. This is because shorter cars allow you to distribute mass better than long cars.

Our series of tests with vehicles of different lengths from previous competitions has also shown that longer vehicles are faster overall. For aerodynamics, however, the width should be minimized in order to reduce the attack surface. To save time we didn't repeat this tests for the World Finals.

For our development, this means that from the outset we design a vehicle that is as long as possible while at the same time being as narrow as possible.

2nd series of tests: wheel positions

Since we could only have a limited number of prototypes made, we developed a special clip-on car, which enabled us to test many different axle positions with the same mass and cartridge chamber. In order to get meaningful results, we have already applied the findings from the last test series and used a car that is as long as possible.

When it comes to wheel positions, the competing approaches are:

From an aerodynamic perspective, the wheelbase should be minimized to minimize the angles of the surfaces

from the point of view of aerodynamic stability, the wheelbase should be maximized

From a launch perspective, the front axle should be as far forward as possible and the rear axle as close to the center of mass as possible

It has been found that a wheelbase of 110mm with the second shortest nose (20mm) offers the perfectly balanced compromise between aerodynamics, launch behavior and aerodynamic stability.

GLOBAL CONSIDERATIONS 2

DERIVATION OF THE UNIVERSAL EQUATION

In the following I will derive a equation, that is able to calculate the race-time as accurately, as possible using modern physics. This equation can be used resolve any contradictions that arise from the analysis from earlier pages.

We will assume that we have already calculated the thrust function of time using our calculations earlier and the specifications paper from F1 in Schools.
Basically the idea is to first calculate the angle at which the thrust is applied relative to the track and then subtract the losses from drag. We will ignore the losses by friction and the wheel suspension as we have already fixed the wheel suspension and we want to use the equation for comparative results. For this we first calculate the angle created by lateral pivoting.

By taking the mean of the angle between airflow and car from 100 test runs in which we tried our best to perfectly align the car we got an average alignment error of 1,2°. Then using CFD we compute the horizontal torque acting around the COM: T_1.
Let the distance of the COM to the back of the car be d_R. Then the horizontal angle between race track and car is:

$$1,2 - \arcsin\left(\frac{\tau_1 t^2}{2M[d_R]^2}\right)$$

Then we compute the vertical torque using this and our previous calculations:

$$\tau_{com}(t) = F(t)(H - h(t)) - M(t)gh\mu(t)$$

Then the vertical angle between the track and the car is:

$$\arcsin\left(\frac{\tau_{com}(t)t^2}{2M[d_R]^2}\right)$$

Then we also the constant c = 1/2pC_DA, where A is the cross-sectional area, C_D is the drag coefficient which we can compute from CFD and p the density of air at 20°C.

Then F = v(t)^2c is the drag.

Now we can compute the Net Force:

$$F(t)\sin\left(1,2 - \arcsin\left(\frac{\tau_1 t^2}{2M[d_R]^2}\right)\right)\frac{\tau_{com}(t)t^2}{2M[d_R]^2} - c\left(\int_t \frac{F(t)}{M}\sin\left(1,2 - \arcsin\left(\frac{\tau_1 t^2}{2M[d_R]^2}\right)\right)\frac{\tau_{com}(t)t^2}{2M[d_R]^2}\right)^2$$

With this we can also derive the universal equation:

$$\int\int_t \frac{F(t)\sin\left(1,2 - \arcsin\left(\frac{\tau_1 t^2}{2M[d_R]^2}\right)\right)\frac{\tau_{com}(t)t^2}{2M[d_R]^2} - c\left(\int_t \frac{F(t)}{M}\sin\left(1,2 - \arcsin\left(\frac{\tau_1 t^2}{2M[d_R]^2}\right)\right)\frac{\tau_{com}(t)t^2}{2M[d_R]^2}\right)^2}{M}$$

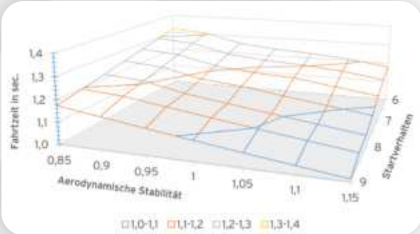
3rd series of tests: Validation of universal equation

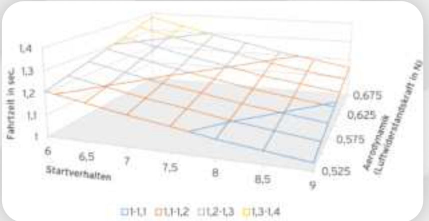
Even if the first two test series restrict the geometry quite severely, there are still many parameters such as e.g. B. the shape of the nose or the position of the rear wing flexible. In order to save time and resources, we have designed a series of tests that look at all conflicts at once. The coefficients, with which the 3 influencing factors can be quantified, play an important role here:

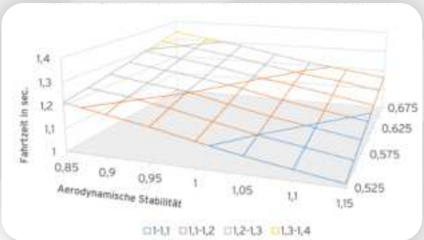
- Starting behavior: the vertical torque around the COM
- aerodynamic stability: the mean of net horizontal torque when simulated at an angle of 1% and 2%
- Aerodynamics: drag force in Newtons

The aim of this 3rd series of tests was to find an optimum for the 3 coefficients.

The clip-on car specially designed for the tests enabled us to
2 different bridges
4 different noses
3 different rear wings
interchangeable and recombinable at will. In this way, we were able to obtain a large number of data points for a meaningful evaluation.







The graphics show the evaluation of our 3rd series of tests.

In all diagrams, the average driving times (in seconds) are shown on the z-axis and the coefficients of the 2 influencing factors on the x and y axes. We have entered our data points and connected and expanded them over an area. All data points were in the orange range, since logically it is not possible to optimize all influencing factors at the same time. The first area shows that launch behavior is a bit more important than aerodynamic stability. You can see that the 2 bottom surfaces are similar to each other, showing that aerodynamics are much less important than the other influencing factors.

We also computed the difference in race times of different cars (so that the error of not including the energy losses from the wheel suspension cancel out) with the universal equation and with the track tests. We came to the conclusion that the univeral equation had a error tolerance of only 1%

Both: the universal equation and this series of tests quantified the importance of the individual influencing factors and came to the same result: If you are in the given ranges of the coefficients which appear in cars permitted by the rules, the launch behavior is most important, the aerodynamic stability is just behind and the aerodynamics is almost irrelevant. This surprised us quite a bit as most teams only focus on aerodynamics in their development. It can be explained by the big difference in the magnitude of the thrust force as time goes on. Therfore it is very important to direct the thrust in the right direction and only secondary to optimize aerodynamics. Also we could validate our universal equation. It has a maximum error of 1% which is very impressive.

DESIGN PROCESS EVALUATION

	Time	Resources	Value
Using Physics to analyze influencing factors	Medium do research, derive equations, (use Matlab to find solutions)	Low requires low computing power	High basis for development for many influencing factors and global considerati ons
FEM simulation	Low setup the simulation, simulate (only needs computing time)	Medium requires medium computing power	Low together with Physics ensure that nothing breaks
Surface, Volume and Mass calculation with Solid Edge	Low simply read the values from computer	Low requires low computing power	High Ensures that mass of car is optimal
CFD simulations	Medium Setting up the simulation requires significant time and effort	High requires high computing power	Low results only give isolated view
Track Tests	High Planning of the tests, Manufactur ing parts. testing	Super High requires a lot of resources for sponsors	Super High are indespensa ble because they can be directly compared to the race

ENGINEERING OF THE FINAL CAR

Introduction

Till now we have described how we came up with the method which we used to develop our car. The development itself is now straightforward (we determine the geometry of the car, step by step, by using our conclusions from the analysis of the influencing factors and if conflicts arise we solve them with our universal equation) and the results will be described on this page.

Nose cone development

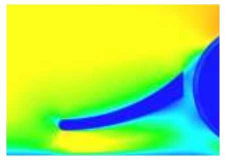
Identification of constraints:

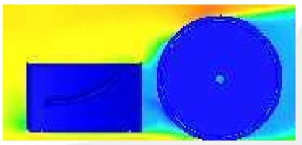
- able to be manufactured by SLS: mimnum wall thickness: 1mm
- rules impose a lot of contraints on the front wing such as minimum dimensions, location and visibility

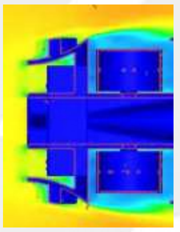
Influencing Factors

Aerodynamics:
nose cone should direct the air over the wheels and to create as little turbulence as possible.
Launch Behaviour:
nose cone should be light and the COM should be as high as possible
Directional Stability:
nose cone shouldn't have big vertical structures
Global consideration:
We have to find the best aerodynamic solution for a short front to guarantee the best possible launch behavior. Because of the contraints given by rules, it makes sense to integrate the front wing in a vortex generator.
A Vortex generator creates targeted turbulence of the air to reduce air resistance. The edges of the wheels and the disconnected front wing severely disrupt airflow on the side of the car. This way the airflow becomes more laminar and the drag reduces by more than 5%.

This is the best possible areodynamic solution, which has a high front wing and a light nose which gurantees the best starting behaviour but compromises the directional stability because of the vertical surfaces. The universal equation says that the areodynamic benefits outweigh the worsening of directional stability. This is probably because the nose cone has the greatest aerodynamic potential and the vertical surfaces are not only very small, but they are curved to that the airfoil wich is created the car tilts is almost nonexistent.







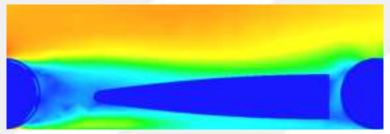
Side pods development

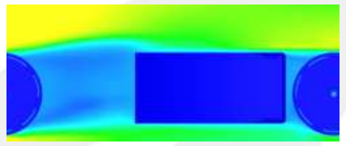
Identification of constraints:

- able to be manufactured by Milling: mimnum wall thickness: 2.5 mm
- rules define exclusion zones
- needs place for official F1 in Schools decal

Influencing Factors

Aerodynamics:
The task of our sidepods is to minimize areas with turbulence (concept of virtual mass of air), caused by the exclusion zones, without creating new turbulence.
Launch Behaviour:
side pod should be light and the COM should be as high as possible
Directional Stability:
side pod should minimize vertical surfaces.
Global consideration:
We can fill out the area between the exclusion zones to minimize the area with turbulence with material and hollow the side pod to raise the COM (concept of lightweight structures). Furthermore the universal equation tells us that deleting the vertical surface in the catamaran tunnel will increase the drag, but the benefits of the directional stability outweigh the drag increase and we can save 0.03 seconds by doing so.





Hubcaps finetuning

We eliminated the inner hubcaps to improve starting performance. The aerodynamics have only deteriorated marginally as a result. We also made the outer hubcaps thinner and hollowed the aluminium structure and sticked sheets to still fulfill the function, which had a positive effect on the center of mass and thus improved starting behavior.

Rear wing development

Identification of constraints:

- able to be manufactured
- rules define mimimum dimensions and location

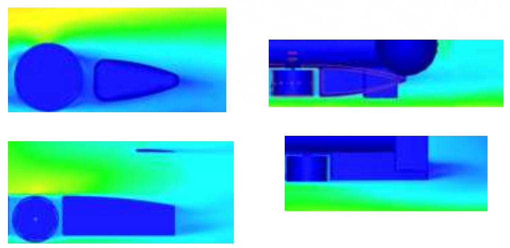
Influencing Factors
Aerodynamics:
Task of the rear wing is to not create any turbulences (concept of drop shape)
Launch Behaviour:
rear wing should be as heavy and high as permitted.
Directional Stability:
maximize surface area of vertical rear wing support structures
Global consideration:
This was one of the rare cases in which there were no conflicts and we didn't have to use the universal equation. We used the drop shape to minimize drag and placed the rear wing as high as allowed by rules for optimal lauch behaviour. We manufactured the rear wing out of titanal to raise the COM and improve launch behaviour. We used massive support structures to immensely improve directional stability.

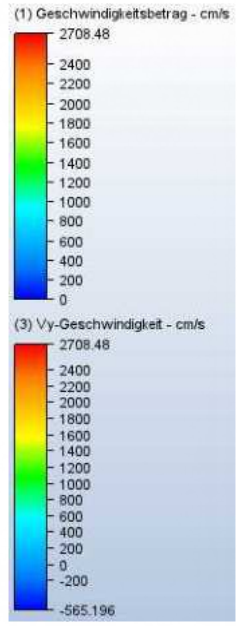
Wheel Block development

Identification of constraints:

- able to be manufactured by Milling: mimnum wall thickness: 2.5 mm
- rules define exclusion zones

Influencing Factors:
Aerodynamics:
The task of our wheel blocks is to minimize areas with turbulence (concept of virtual mass of air), caused by the exclusion zones, without creating new turbulence and decrease the turbulence behind the car.
Launch Behaviour:
wheel blocks should be light and the COM should be as high as possible
Directional Stability:
wheel block should maximize vertical surfaces.
Global consideration:
We can fill out the area behind the car to minimize the area with turbulence with material and hollow the wheel block to raise the COM (concept of lightweight structures). Furthermore the universal equation tells us that converging toward the end will decrease the drag, but the drawbacks of the directional stability outweigh the drag increase and thus straight surfaces decrease the race time by 0.04 seconds.





Manufactoring Process

For the manufacturing of our cars several points had to be considered and some decisions had to be made:

- Selection of materials and manufacturing processes
- Decision between self and third party manufacturing
- Selection and acquisition of suitable manufacturing sponsors

In addition, we made sure to always keep an eye on the weight of the cars in order to be able to take countermeasures in time in case of emergency, if the self-imposed limits were exceeded due to tolerances in the individual production steps.

After completing the design and selecting the processes, we worked with our sponsors to manufacture the various components. Close coordination was important here, e.g. to take manufacturing tolerances into account so that all parts would fit together perfectly in the end. But good schedule coordination was also very important, because despite a tight schedule we had planned an extensive series of tests with various prototypes, for which we needed extra prototype parts.

Selective Laser Sintering vs. Fused Deposition Modeling:

For our components such as the nose and our rear wing structure, there were two processes to choose from: selective laser sintering (SLS) and fused deposition modeling (FDM). Both are so-called "3D printing processes" in which a plastic is applied layer by layer. We were able to test both materials and decided in favor of the SLS process, as finer structures are possible here due to the thinner layer structure. This means that the manufacturing tolerances are very low and optimum fitting accuracy is guaranteed. In addition, the surface is easier to machine.

Assembly & Coating

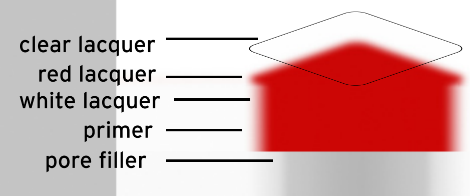
Precise pre-assembly

During pre-assembly, we mounted the chassis and the components that had to be painted, or could not be installed after painting. It was important that the assembly was as accurate as possible to avoid rework such as filling as far as possible. Of course, gaps and unevenness have to be evened out before priming. All parts must also be thoroughly prepared for painting by sanding and cleaning.

Coating process

Since a good surface quality was one of our main goals, we spent a lot of time testing different pore fillers, primers and paint options to find the optimal combination. Two factors were important to us: A perfect surface with the lowest possible weight at the same time. Our decision to carry out the painting entirely ourselves enabled us to keep the timing of the process under control at all times.

In addition, we were able to check the weight after each step and touch up areas that were not yet perfectly finished. By working in many thin coating steps, the weight could be monitored very precisely while maintaining a high surface quality.



Accurate final assembly

After painting the cartridge chamber, the sponsor stickers were accurately applied and additionally fixed with an extra layer of clear lacquer to prevent them from peeling off during scrutineering or racing. Then the wheels were equipped with excellent ball bearings provided by our long-time sponsor Myonic. Wheels and hubcaps were mounted and the threads were fixed with Loctite to prevent them from accidentally untwisting or overtightening during racing. Finally, thin foils were put on the hubcaps to improve the aerodynamics. To save weight, we decided to use finely milled out hubcaps, which we sealed with transparent foil to keep the structures visible.

The last step was to insert sleeves int the tetherline guides to improve their sliding properties. For this we used slide bearings provided by igus. Then the cars were weighed and inspected one last time to determine the two cars for the competition and to mark them with the stickers for Car A and Car B.

CAM & CNC

What is CAM?

Computer Aided Manufacturing (CAM) is the use of software and computer controlled CNC machines to automate a manufacturing process.

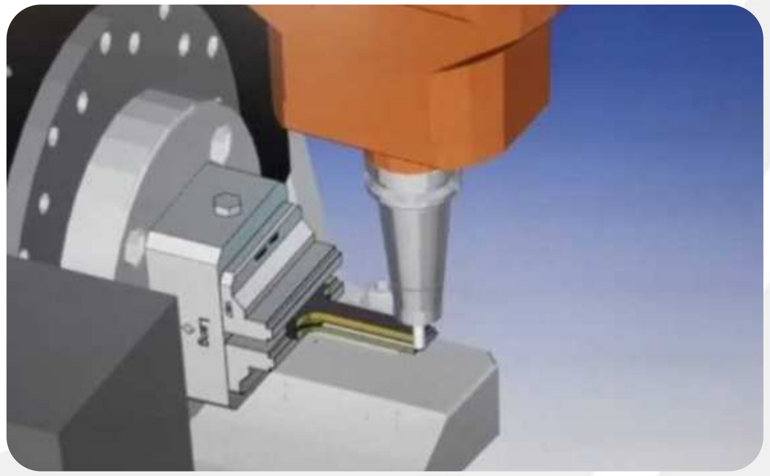
The CAM file was created in collaboration with our manufacturing sponsor Fischer. To do this we utilized the software hyperMILL which is ideal for complex geometries.

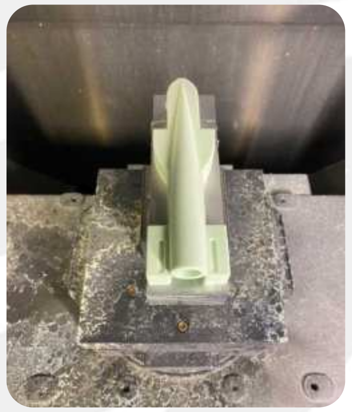
Each of the 36 tasks in our milling process was assigned to one of two milling processes. Every time, the workpiece was roughed out first and then finished.

To minimize our important sponsor Fischer's effort to a reasonable level, we needed to create an efficient CAM file. As a result, finding the best tool and milling process combination was essential.

Steps in creating the Heidhain Codes of Milling:

1. Import the parasolid file into hyperMILL.
2. Adjust the relative position of the car to the mill by matching coordinate systems and zero-points
3. Generate list of tasks, defining the milling process for the car as well as choosing operations for the tasks such as contour milling and playback milling.
4. hyperMILL calculated the tool routes and we simulated each task to check for potential tool collisions.
5. Convert the CAM file into Heidenhain Codes, so that the CNC milling machine can execute the tasks, using a post-processor.





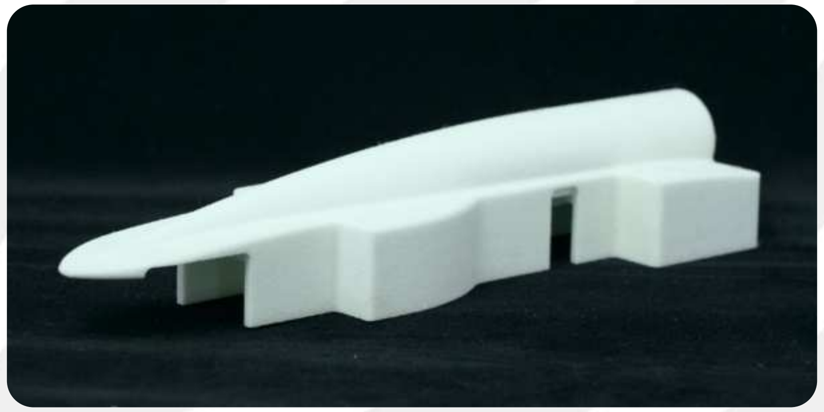
Milling of the car:

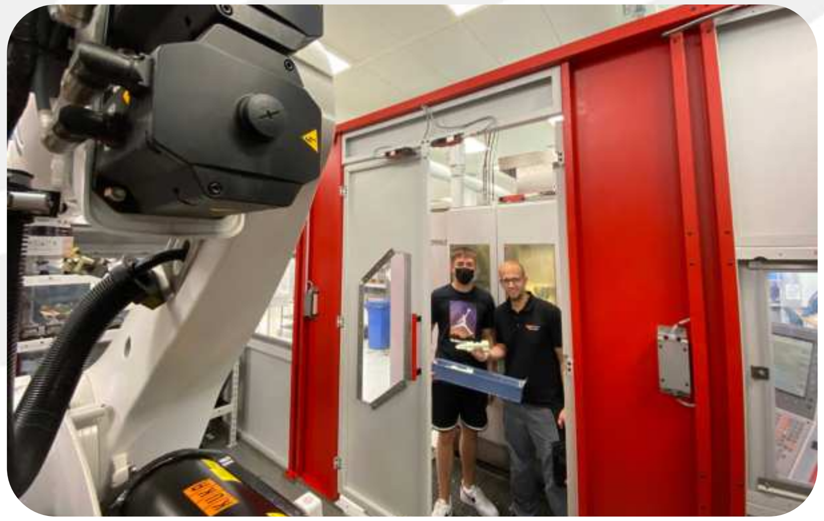
Safety Precautions:

- The machine was kept closed while we were in the vicinity
- safety briefing

Procedure:

1. glue the F1 in schools model block to the machine
2. roughing the bottom surface with a 1.2 face mill cutter at a feed rate of 6-7 m / min and a rotational speed of 17,000 rpm.
3. finishing with a ball nose cutter (diameter 3mm), feed rate 5-13m/min, rotational speed 10,000-22,000 rpm
4. finishing plane surfaces and side pods with a ball nose cutter (diameter 1mm), feed rate 2.5-5m/min, rotational speed 10,000-22,000 rpm
5. For the milling of the pockets (diameter of 1.6mm), we used an additional ball nose cutter with a feed rate of 2.5 - 5m/min and a rotational speed of 10,000 - 22,000 rpm.
6. remounting the workpiece
7. roughing the upper side using a 1.2 face mill cutter at a feed rate of 6-7 meters per minute and a rotational speed of 19,000 revolutions per minute
8. finishing with a ball nose cutter (diameter 3mm), feed rate 5-13m/min, rotational speed 10,000-24,000 rpm.
9. finishing with a 1mm diameter ball nose cutter (feed rate: 2-5m/min, rotating speed: 25,000 rpm)





Turning of Metal Parts

Safety precautions:

- maintaining distance from machine
- wearing earplugs and glasses to protect hearing and eyes
- safety briefing by employees

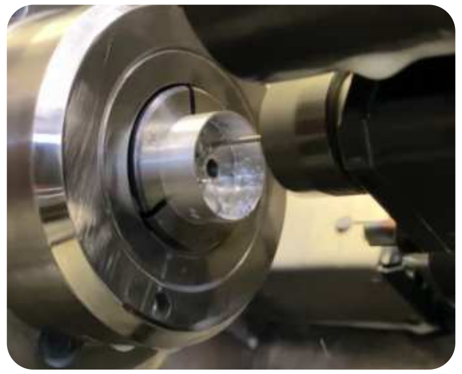
We turned our wheels on a Spinner SB-CNC.
To stabilize the rolling surface of our car, we had to create our own mounting device. We used an average feed rate of 0.15m/min and a rotational speed of 3,000rpm throughout the process.

We rough-turned the outside first, then finished the inside, and finally finished the outside. We used an average rotational speed of 2,000-4,000rpm during this process.

To produce our wheels we turned the rolling surface and milled inner contour.
We used the following process:

1. raw part is turned from the solid material.
2. the spokes are milled into the cylinder.
3. the cylinder is screwed onto a fixture (consisting of two parts) which supports the tread from the inside.
4. the rolling surface is turned to a thickness of 0.1 mm
5. the wheel is unscrewed from the fixture and cleaned.

Step 1



Step 2

Step 3

Step 4