Instructor:
Prof. Ighor Uzhinsky

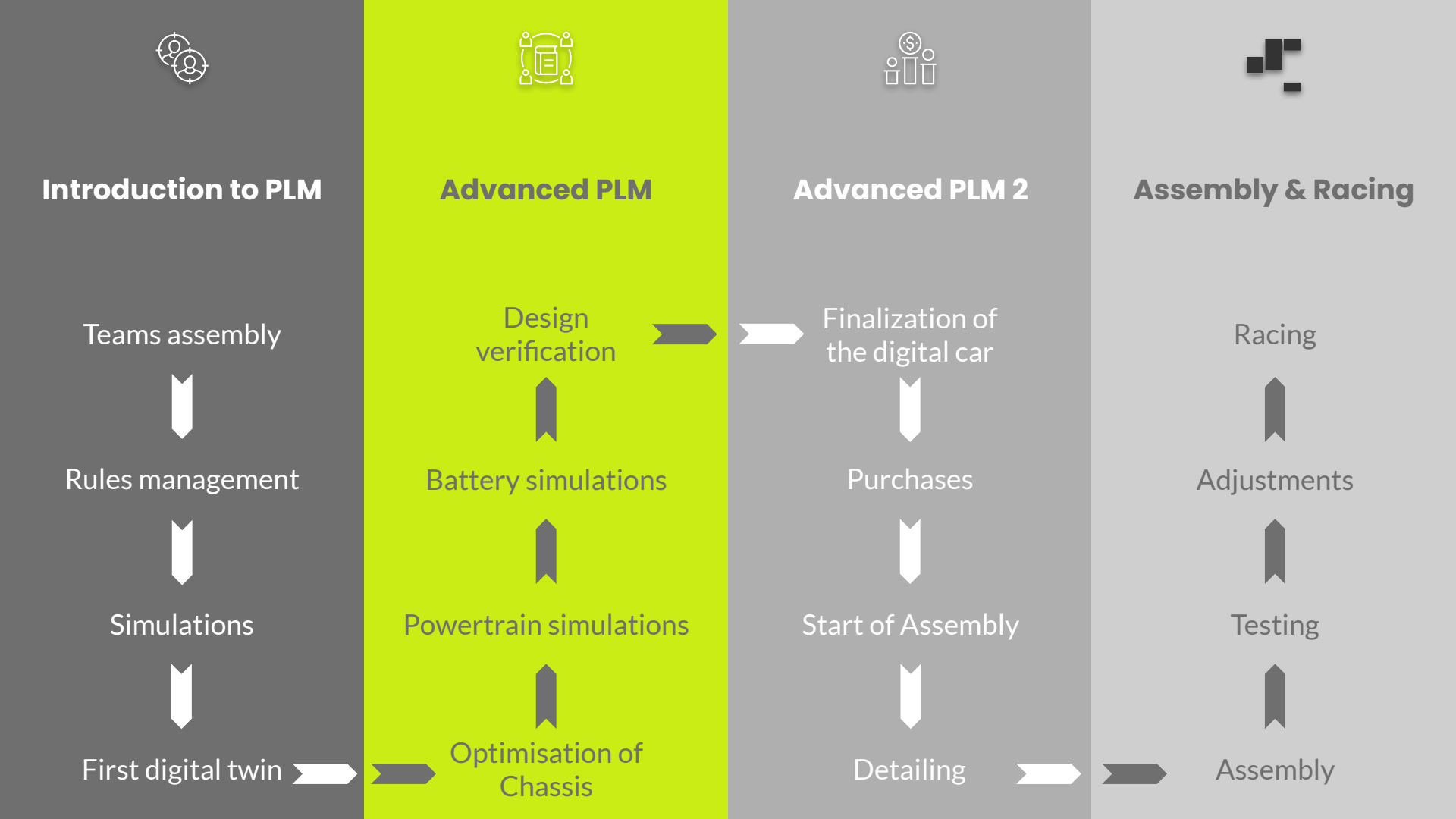
Formula Student

Advanced PLM course
CDMM, 2020

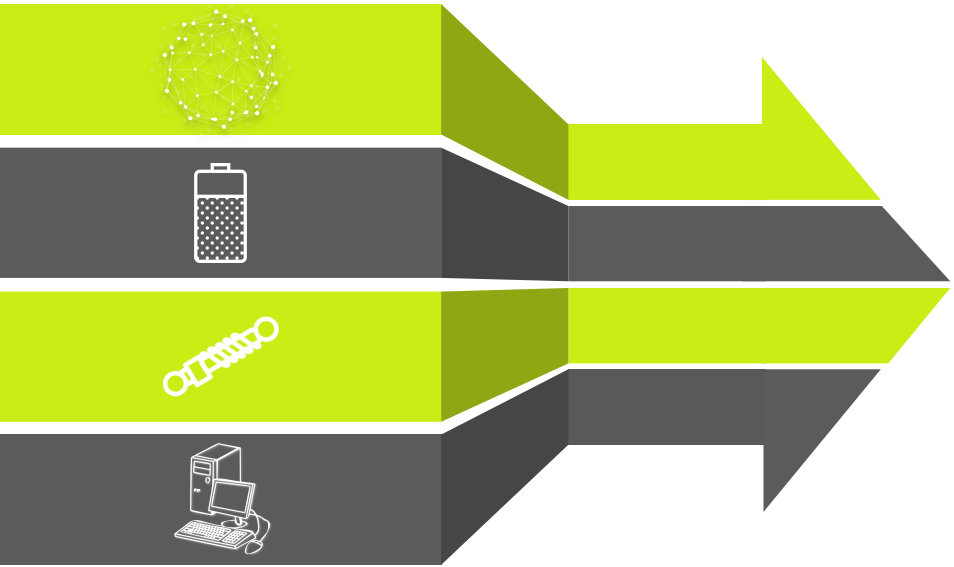
30
Countries

600
Universities

1500
Sponsors


Introduction to PLM
Advanced PLM
Advanced PLM 2
Assembly & Racing
Teams assembly
Rules management
Simulations
First digital twin
Optimisation of Chassis
Powertrain simulations
Battery simulations
Design verification
Finalization of the digital car
Purchases
Start of Assembly
Detailing
Assembly
Testing
Adjustments
Racing

Teams Assembly



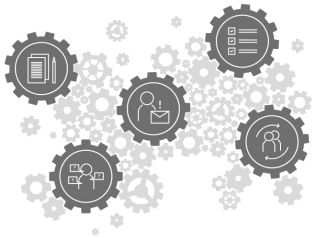
Systems Engineering

Powertrain

Suspension

Chassis

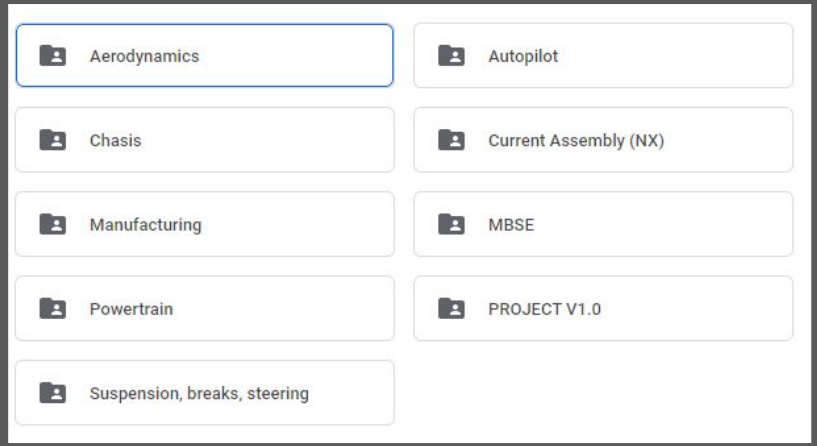
Systems Engineering



Powertrain
Suspension
Chassis

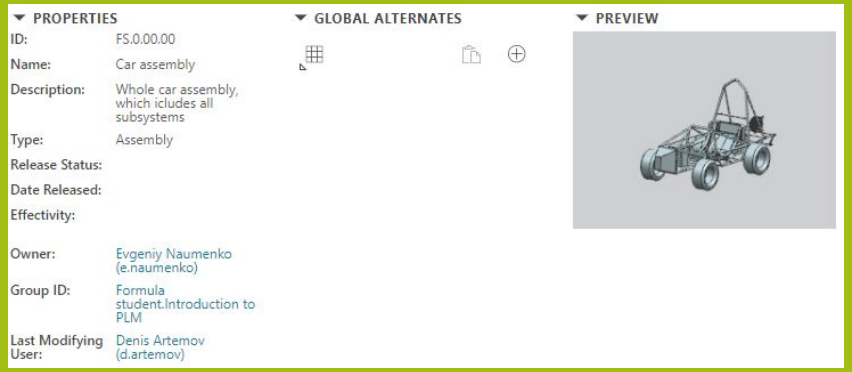
Project organization

How it was



Folder type organization

How it is now



PLM type organization

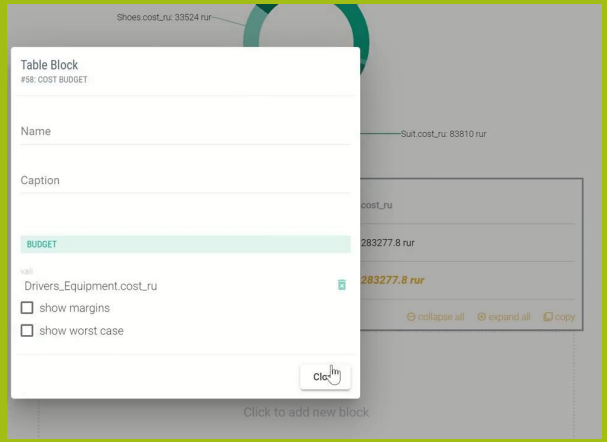
Cost report generation

Current approach

System	Part	ight / / Ma	Cost	Quantity	Exchange rate Multiplier	Total
Drivers' Equipment	Helmet	Bought	€500.00	2	73	73,000.00 ₽
	Underhelmet	Bought	€20.00	2	73	2,920.00 ₽
	Suit	Bought	€500.00	2	73	73,000.00 ₽
	Gloves	Bought	€100.00	2	73	14,600.00 ₽
	Undersuit	Bought	€50.00	2	73	7,300.00 ₽
	Underpants	Bought	€50.00	2	73	7,300.00 ₽
	Socks	Bought	€20.00	2	73	2,920.00 ₽
	Shoes	Bought	€200.00	2	73	29,200.00 ₽
	Seatbelts	Bought	€400.00	1	73	29,200.00 ₽
	Arm restraints	Bought	€50.00	2	73	7,300.00 ₽
					Total system cost:	246,740.00 ₽

Excel, google sheets, etc.

Future approach



ValiSpace

Completed plans

Requirements implementation

All project in Teamcenter

Smart car assembly

Systems Engineering

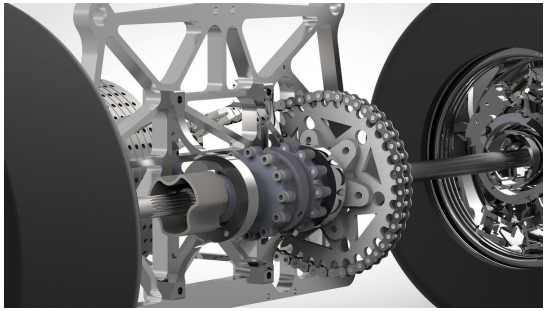
Powertrain

Peter Savchenko
Aleksandr Esin
Denis Artemov

TA: Tikhon Uglov

Suspension
Chassis

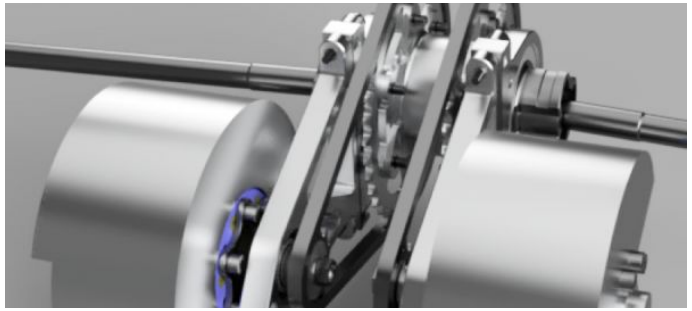
Configurations



One motor

Good for the first experience;
Simplest control system;
Requires less self manufactured parts: mounting parts, flanges for sprockets and motor shaft.

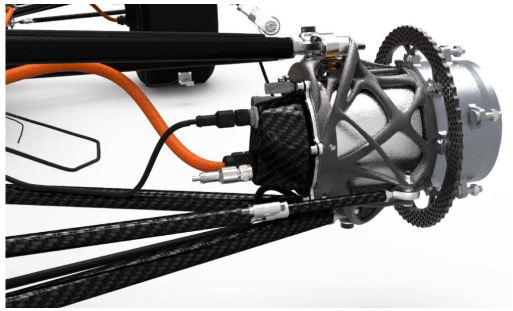
Loses in performance compared to multi-motors cars



Two motors

Better performance than 1 motor config;
Does not need differential

More complex control system;
Higher price;
Reduction gear design and manufacturing required.

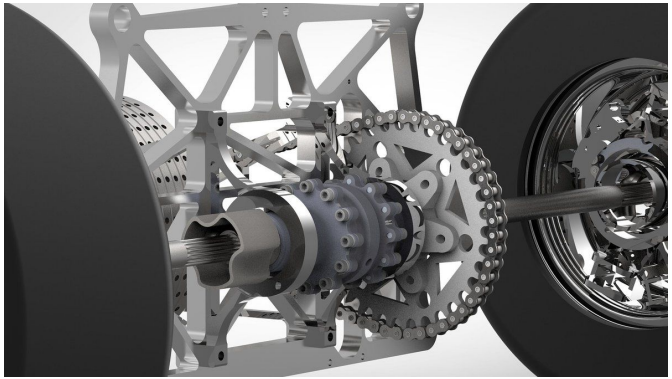


Four motors

Best performance and high acceleration;
Turning can be achieved by motors (tank like) - used in autopilot FS.

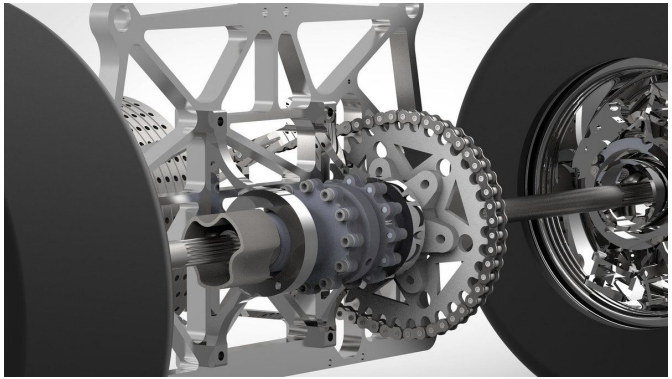
Complicated control system
The highest price;
Planetary reduction gear manufacturing required.

One, two or four electric motors?



	Single motor config.	Two motors config.	Four motors config.
Pros	Good for the first experience; Simplest control system; Requires less self manufactured parts: mounting parts, flanges for sprockets and motor shaft.	Better performance than 1 motor config*.; Does not need differential	Best performance and high acceleration; Turning can be achieved by motors (tank like) - used in autopilot FS.
Cons	Loses in performance compared to multi-motors cars	More complex control system Higher price; Reduction gear design and manufacturing required.	Complicated control system The highest price; Planetary reduction gear design and manufacturing required.

One, two or four electric motors?



	One motor config.	Two motors config.	Four motors config.
Pros	Good for the first experience; Simplest control system; Requires less self manufactured parts: mounting parts, flanges for sprockets and motor shaft.	Better performance than 1 motor config*.; Does not need differential	Best performance and high acceleration; Turning can be achieved by motors (tank like) - used in autopilot FS.
Cons	Loses in performance compared to multi-motors cars	More complex control system Higher price; Reduction gear design and manufacturing required.	Complicated control system The highest price; Planetary reduction gear design and manufacturing required.

Electric motor - Emrax 228

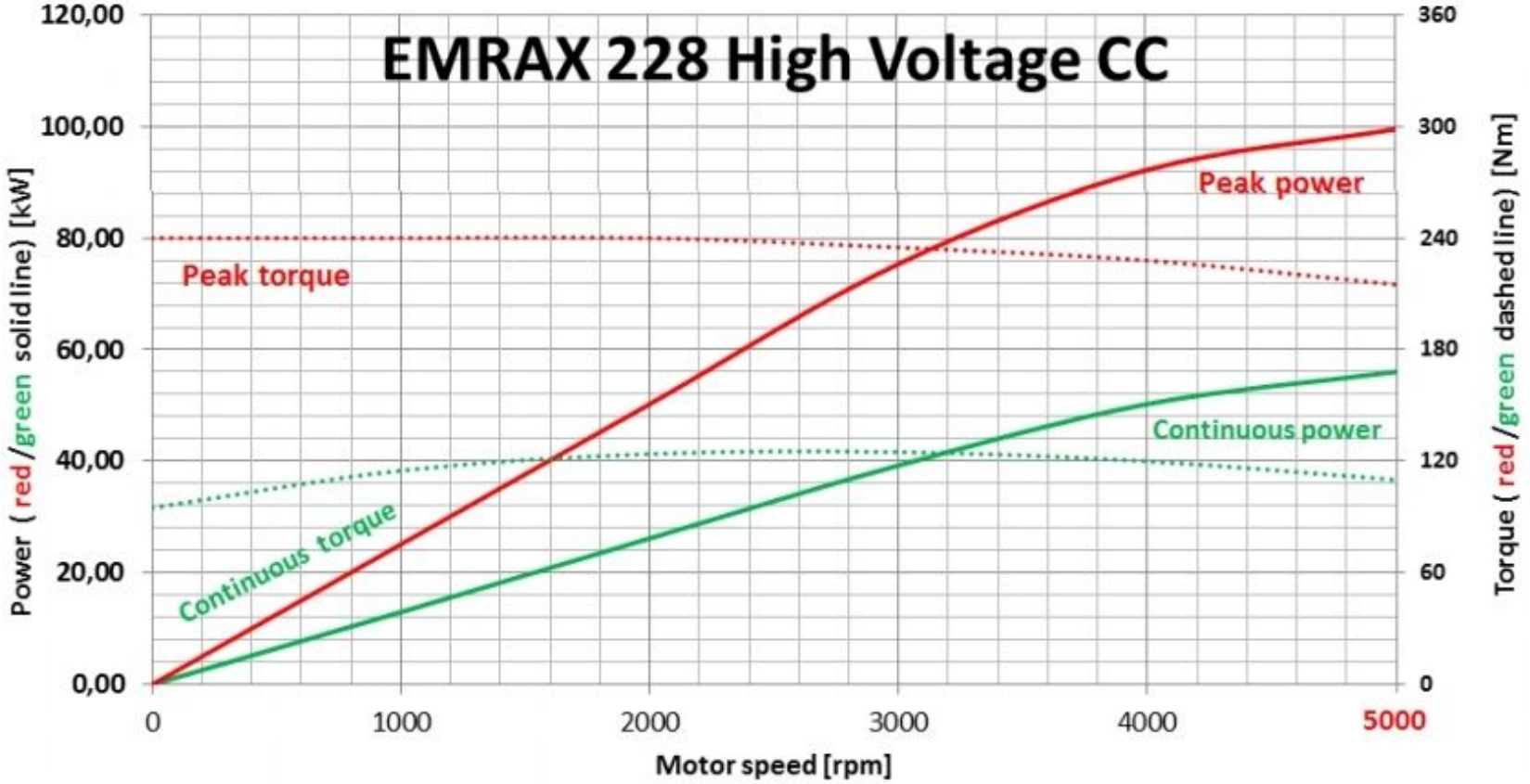
continuous power ~62 kW
continuous torque ~ 120 Nm

Peak power 109 kW
Peak torque 230 Nm

Water cooling
(mean heat ~1 kW)

Great High voltage
performance (600 VDC)

Power curve


EMRAX 228 High Voltage CC
Power (red /green solid line) [kW]
Torque (red /green dashed line) [Nm]
Motor speed [rpm]
120,00
100,00
80,00
60,00
40,00
20,00
0,00
360
300
240
180
120
60
0
0
1000
2000
3000
4000
5000
Peak power
Peak torque
Continuous power
Continuous torque

Electric motor - Emrax 208

Two motor setup

Peak power 68 kW
Peak torque 140 Nm

Water cooling (mean heat ~630 W per one)

continuous power ~41 kW
continuous torque ~ 80 Nm

Emrax 228 vs 208 (x2)

Motor	Emrax 228	Emrax 208 x2
Continuous power (80 kW limit)	~68 kW	~ 82 kW
Heat	1025 W	1266 W
State of charge after 24 km (same pack capacity)	19%	10%
Suitable pack configuration (x4)	41 cells in series, 4 in parallel (150V, 80A)	80 cells in series, 2 in parallel (288V, 55A)
Pack heat	195 W	375 W

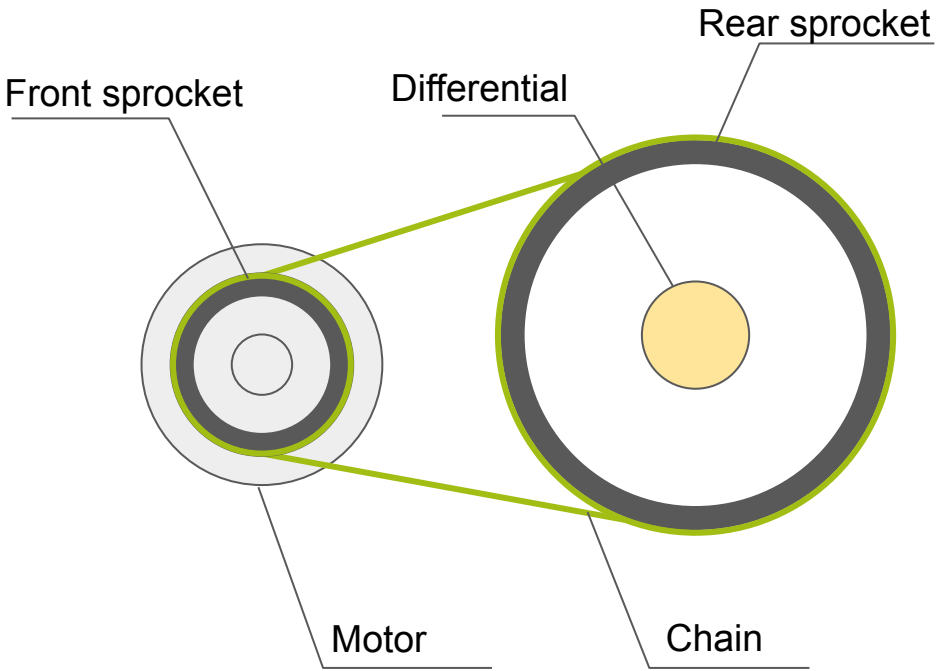
Motor controller – Bamocar d3

Recommended by Emrax

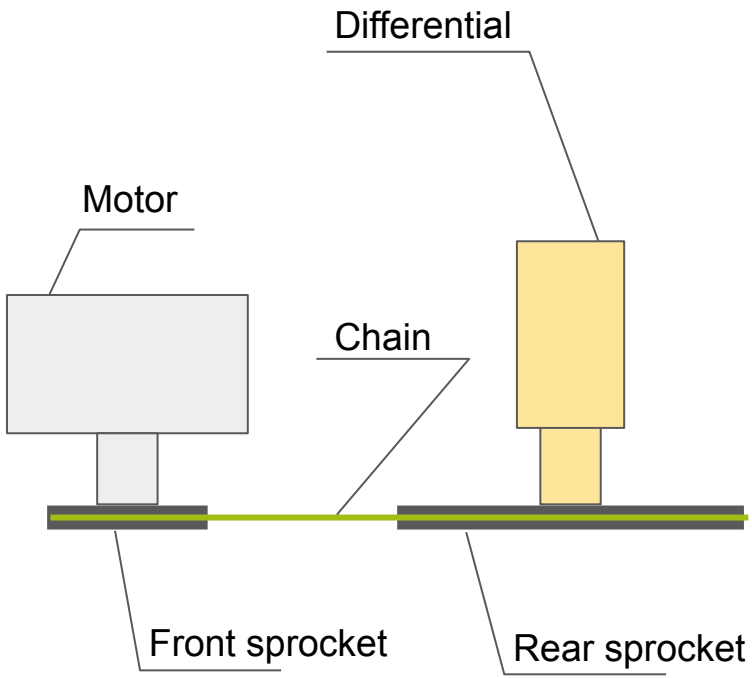
Programmable operation

Water cooling

Transmission Scheme



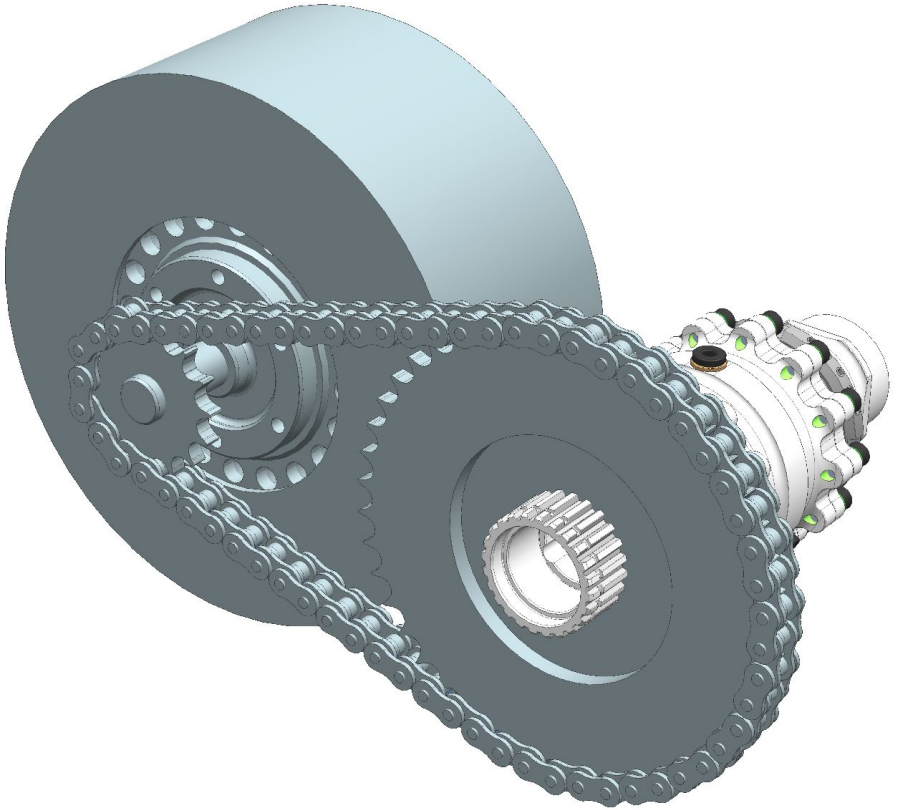
Side View



Top View

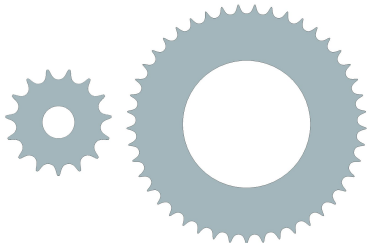
Power transmission

1. Emrax 228 max. Moment = 230 N*m
2. Moment req. on wheels to launch = 600 N*m
3. Gear Ratio = 3
4. Acceleration = 11 m/s^2
5. Max. approximate speed = ~140 km/h
6. Chain load = ~800 kg



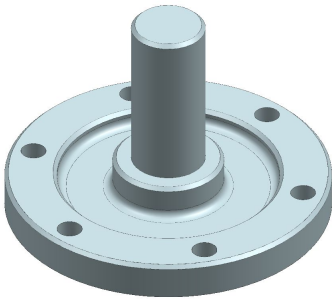
Transmission system equipment

Chain: DID 428-VX
X-ring oil seals
Elements needed: 65
Tensile Strength:3365.655 kg
Price: ~75 $



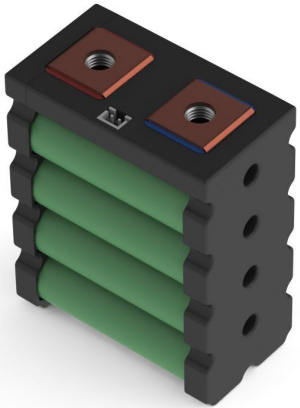
Self Made Sprockets
Z_1=15, Z_2=45
Ratio: 3

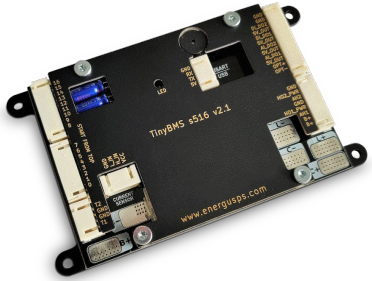
Drexler Adjustable Limited Slip Differential V2
It enables to adjust the preload with a hook wrench.
Six modes:
85,272% (Torque Bias Ratio)
58,672%
49,231%
41,310%
28,424%
Max. torque: 1200 Nm
Weight: 2,3 kg
Price: 2043 $



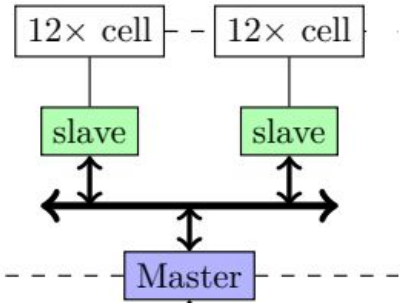
Self Made Motor Shaft
6 attachment points

Battery pack





ENERGUS
POWER SOLUTIONS

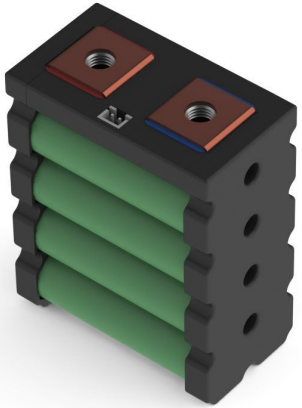


6 kWh pack discharges from 80% to 19% during 24 km run (650 cells)

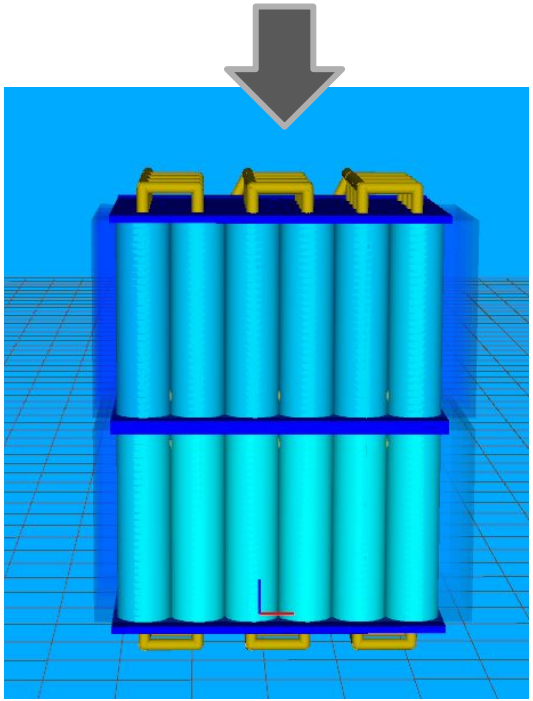
BMS Master-slave system

Continuous measurement of all cell voltages, total current and temperature of >30% of cells

Battery pack



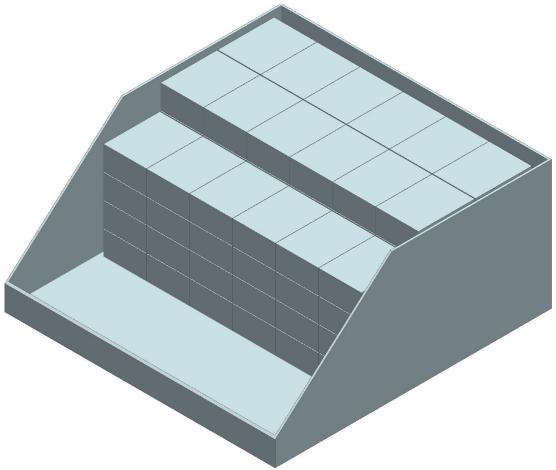
Cold Air



1 individual cell generates ~2 W of heat
Temperatures are 5% higher in the second row of cells

Can operate with air cooling

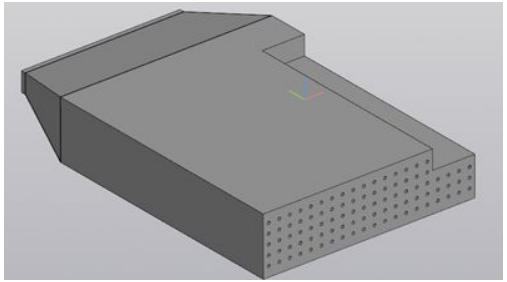
Battery layout



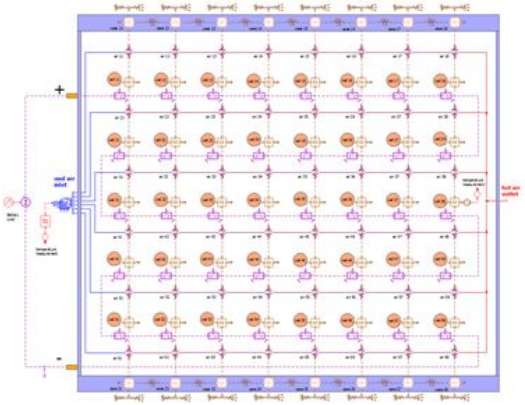
Air - Cooling system

Amount of holes	92
Length of holes	0,42 m
Diameter of holes	0,006 m
Air inlet velocity	20 m/s
Air velocity inside battery	0,5 m/s
Pressure drop, Pa	$\Delta P = \Delta P_{fr} + \Delta P_{loc} = 218{,}78\ Pa$

Simplified battery pack model

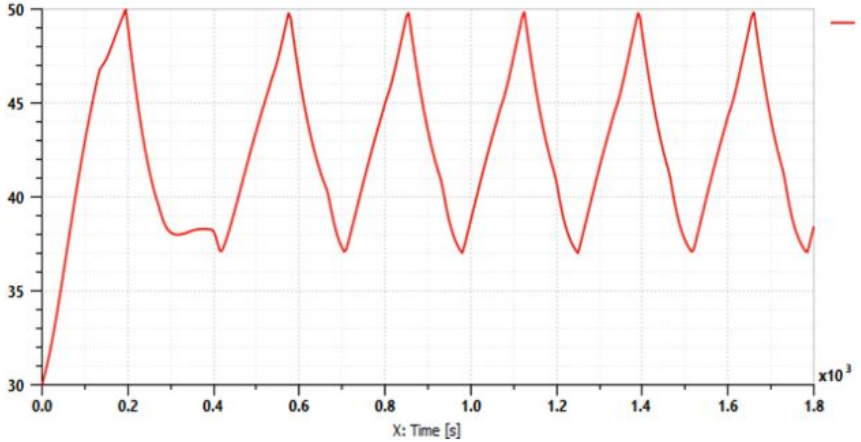


Battery pack Amesim model

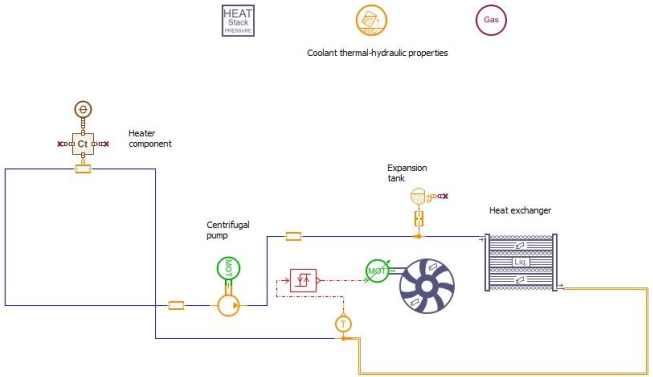


Water - Cooling system

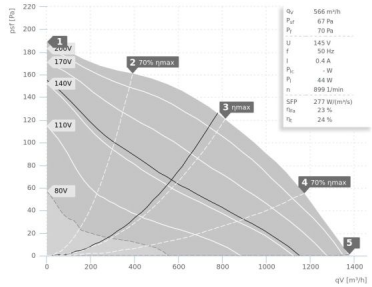
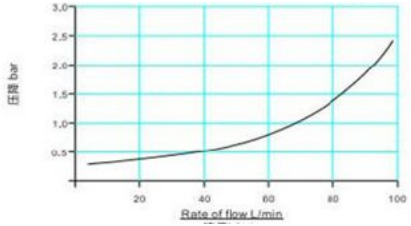
Ventilator operating process



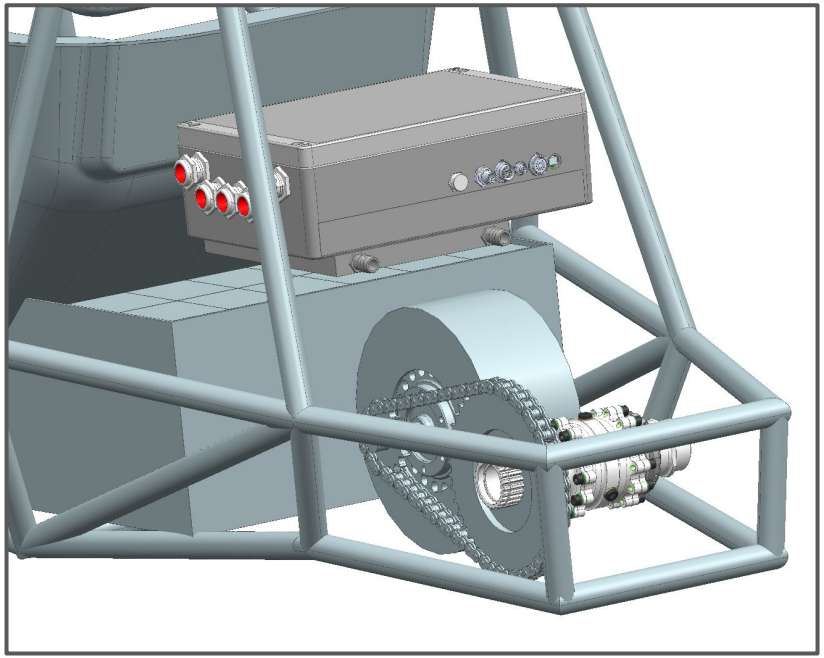
Water-cooling process



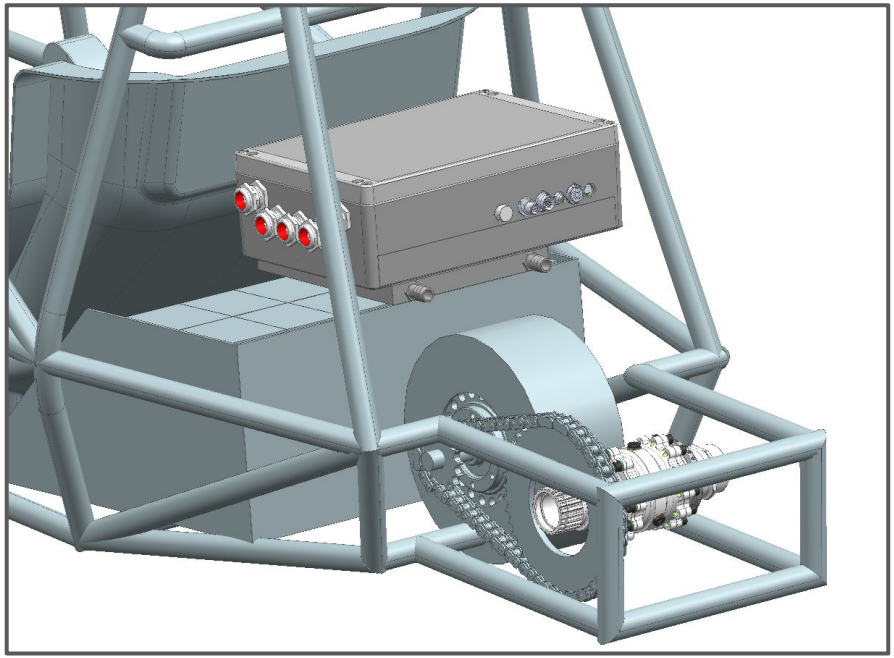
Cooling system equipment

	Pump Type: Pmsm Pump Voltage: 12V DC Allowable Voltage: 10V-15V Maximum flow rate: 1100 Lph Head: 3.8 m Connectors: 4Pin + PWM Rotation speed: 5000 rpm Operating temperature: 45 ° after 4000 rpm Price: 60-70 $	
	Type of fan: backward curved centrifugal fan Volume flow: 566 m3/h : Pressure drop: 67 Pa Rotation speed: 899 1/min Voltage: 230V Maximum current 0,4 A Weight: 2,9 kg	
	Heat-exchanger type: ECO-04 Pressure drop: 150 Pa Working pressure: up to 20 bar Thermostat: operating temperature 50 ±3 C Fan Power: 100W Cooling Power: 3.5 kW Weight: 7 kg Price: 80-100 $	

Possible components layout and frame



7th iteration frame variant



8th iteration frame variant

Future plans

To design:

- Drivetrain mounting parts;
- Flanges for driving sprockets;
- Detailed Battery System;
- Cooling system parts.

To buy:

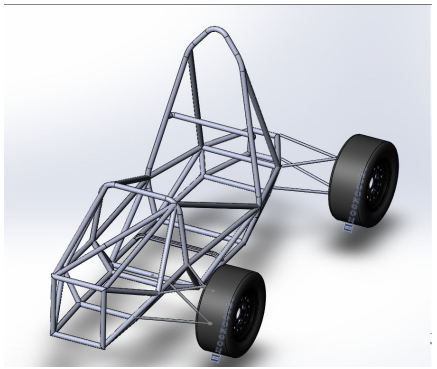
- Battery parts;
- Electric motor and supplements;
- Cooling system parts;
- Sprockets and chain;
- Differential, driveshaft-assy.

Systems Engineering
Powertrain

Suspension

Lida Silkina
Anastasija Cumika

TA: Tihon Uglov

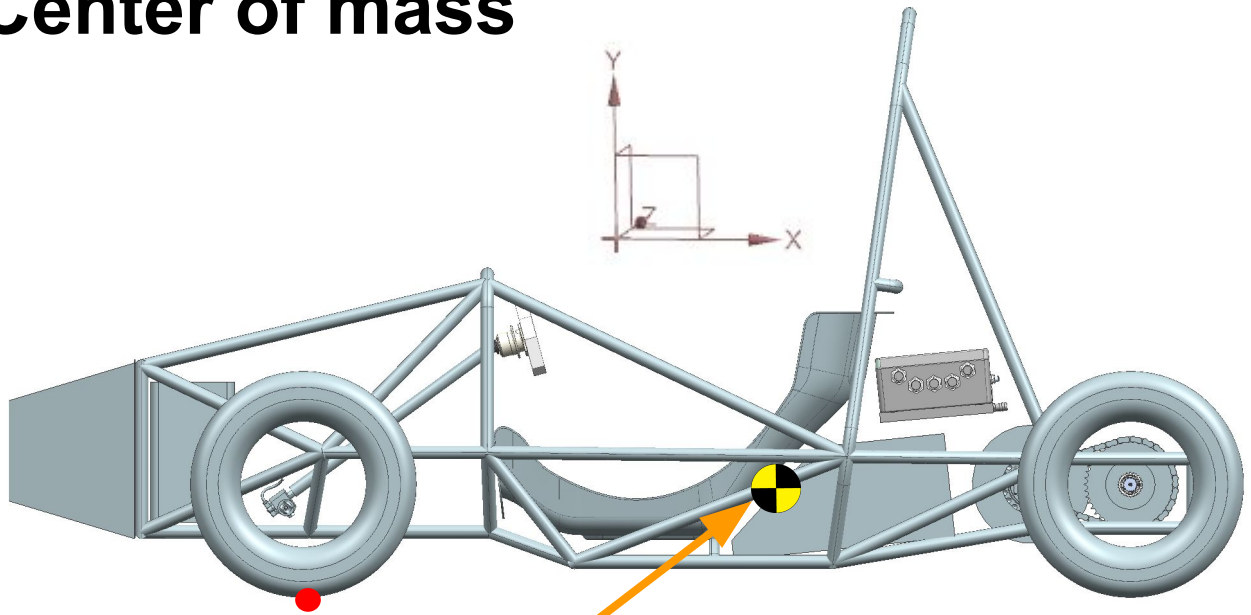


Chassis

Center of mass

Ratio F/R = 49.5:50.5
Goal F/R ~ 45:55

Wheelbase = 1675 mm

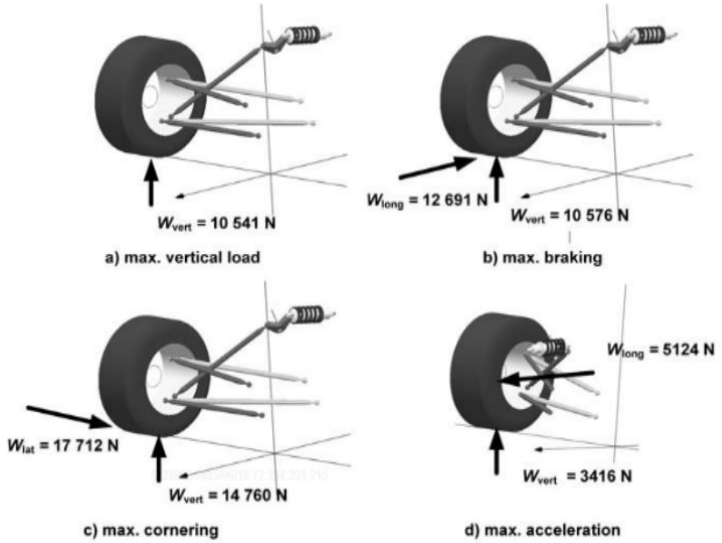


Center of gravity
Y = 274 mm
X = 890 mm
Z = 0

Limiting cases

Acceleration:

- Longitudinal weight transfer 442 N
- Max acceleration from start 9.82 m/s^2



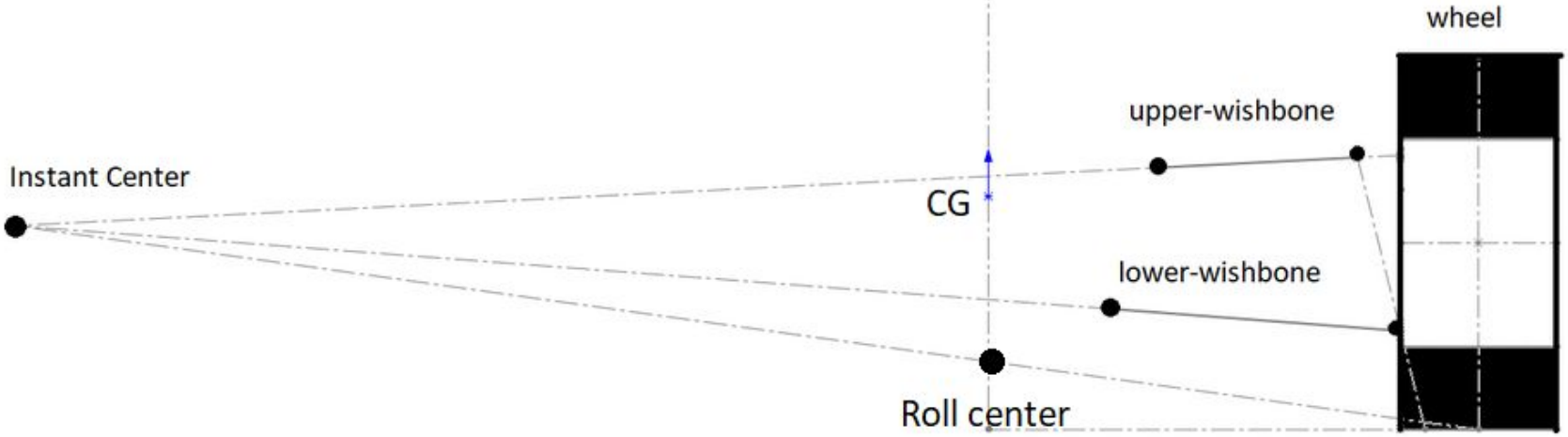
Breaking:

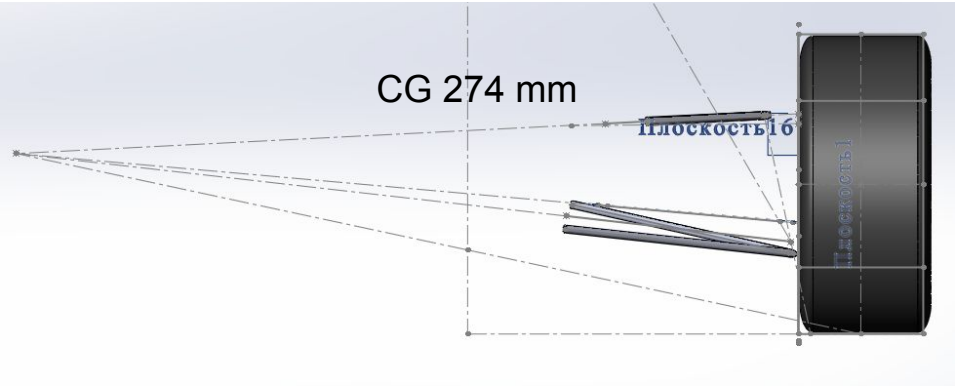
- Longitudinal weight transfer 662 N (from rear to front axle)
- Max deceleration 14.7 m/s^2

Cornering:

- Lateral weight transfer 934 N
- For 3.5 m radius max velocity 7.17 m/s

Wishbones geometry. Front view.

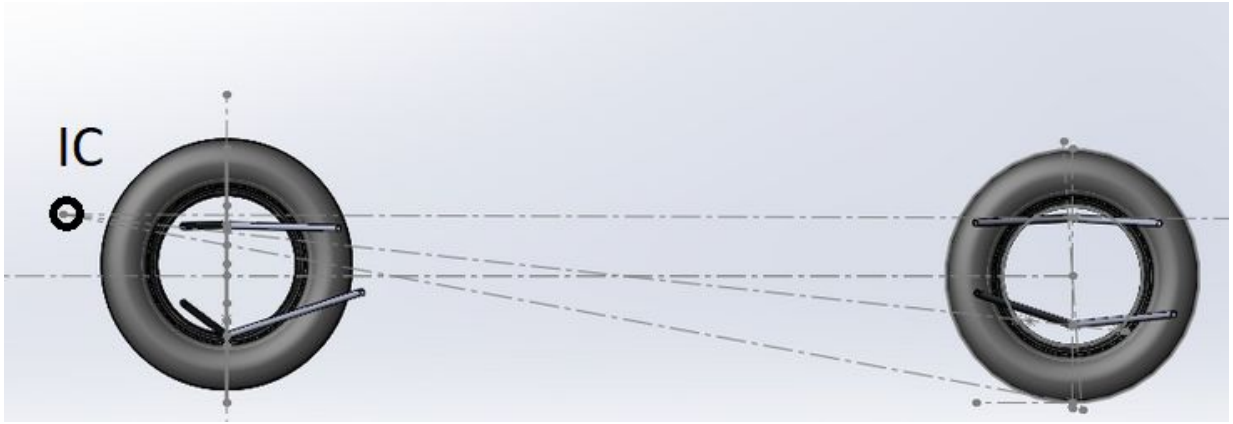




Rear RC - (0; 0.152)m

Front RC (0; 0.128)m

Wishbones geometry. Side view.

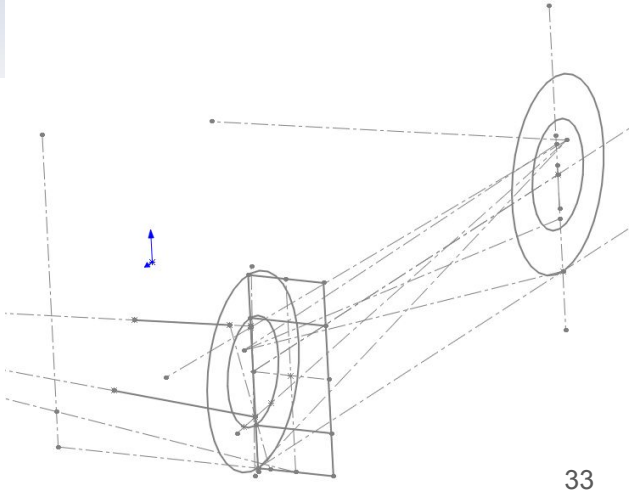


- %anti-dive = 84.53%
- %anti-lift = 29.46%
- %anti-squad = 77.56%

Side-view IC location

Rear (1.613; 0.293)m

Front (1.838; 0.343) m



Brake system

Master Cylinder diameter

Front = 15.88 mm
Rear = 19.05 mm

Pedal ratio = 5

Break torque

Front = 483 (332) N
Rear = 209 (116) N

RacingPedalBoxes RPB

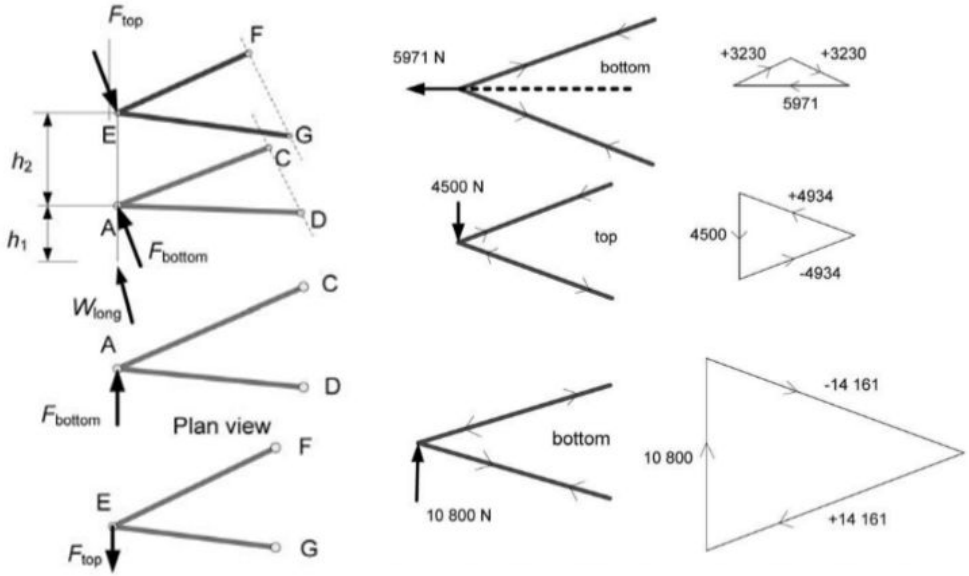
AP RACING

Piston area = 10.1 cm^2

Forces on wishbones

4 max cases studies:

Vertical, breaking, accelerating, cornering.



Max forces front:

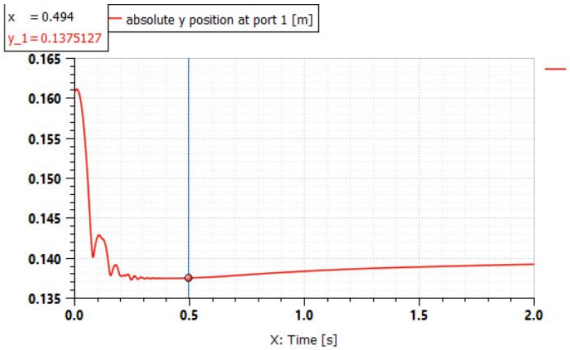
Pushrod front = 2316 N (Vertical)
AC = 2121 N (Cornering)
AD = 3062 N (Breaking)
EF = 1079 N (Cornering)
EG = 1015 N (Cornering)

Max forces rear:

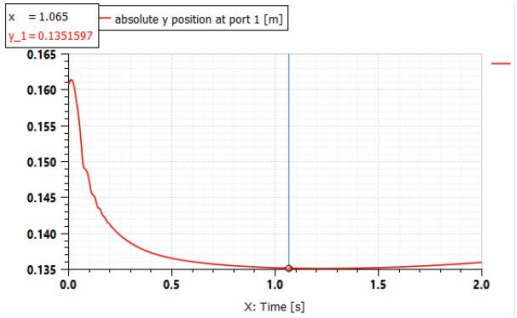
Pushrod front = 3553 N (Vertical)
AC = 2327 N (Accelerating)
AD = 760 N (Vertical)
EF = 911 N (Accelerating)
EG = 1217 N (Cornering)

Springs: pushrod design

Spring stiffness 350 lb/in
Shrinkage: 24 mm (not enough)

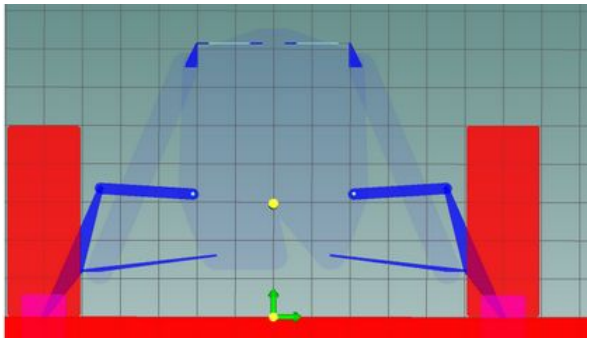


Spring stiffness 175 lb/in
Shrinkage: 26 mm



Minimum compliance (according to FSAE rules): **+-25mm**

Functional model in Amesim



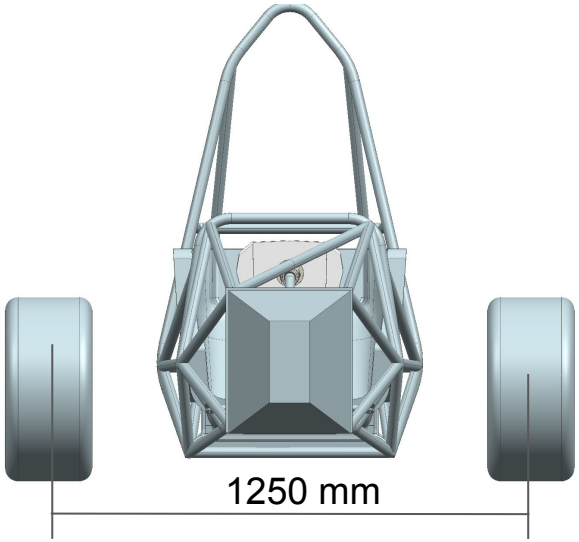
Öhlins ttx25 175 lb/in

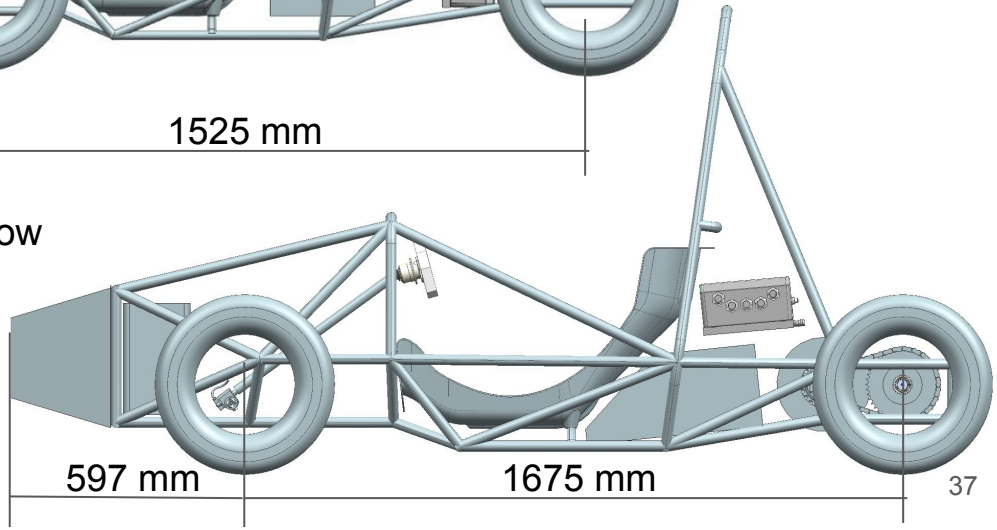
- Overall length: 257 mm (center to center of spherical bearings, fully extended)
- Stroke: 57 mm
- Weight: 394 g (without spring)

Comparison

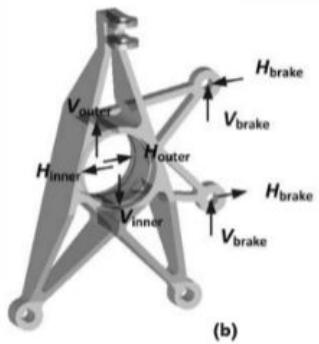
How it was

How it’s now

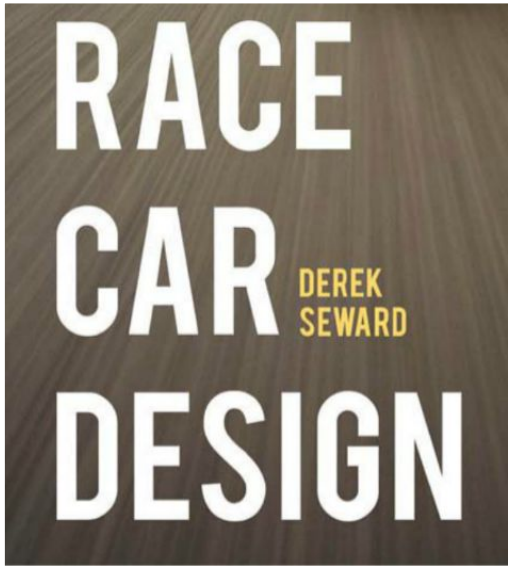




Future plans



- Car Balancing (in progress)
- Knuckle 3D model
- Front and rear wheel assemblies
- pSeven optimization



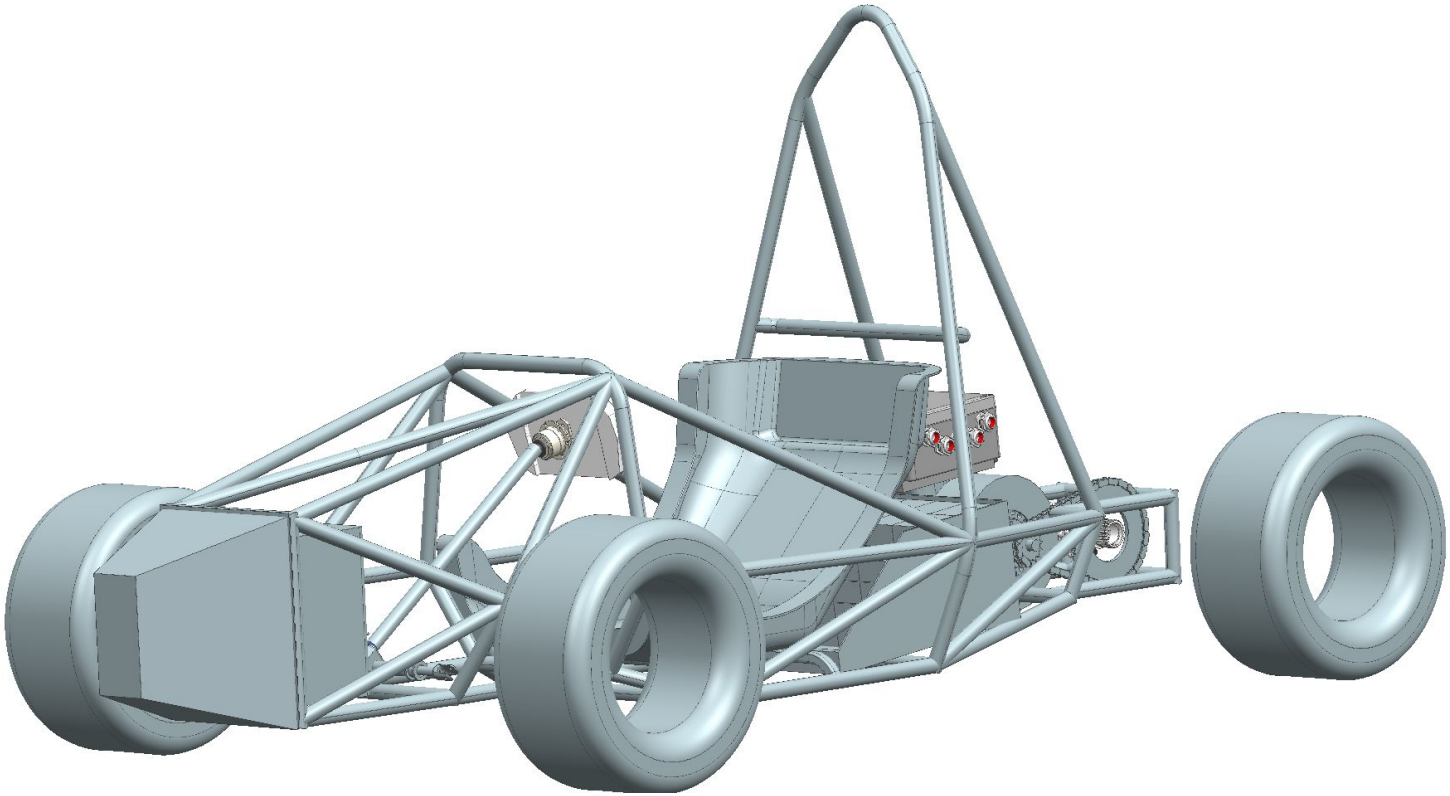
Systems Engineering
Powertrain
Suspension

Chassis

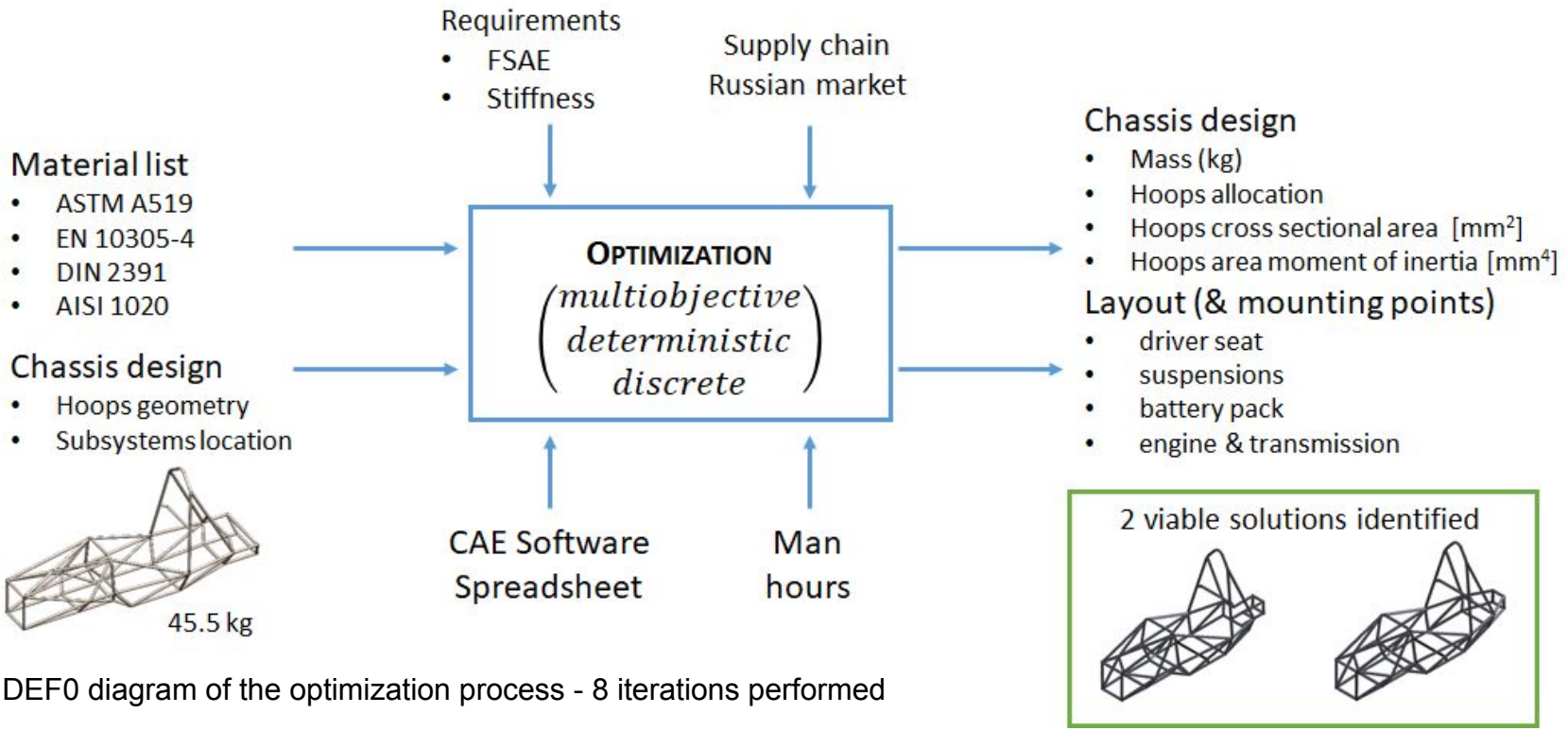
Nicola Garzaniti
Semen Chetverin
Muhammad Umair

TA: Tihon Uglov

Chassis

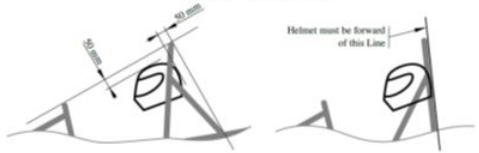
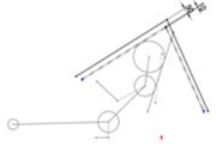
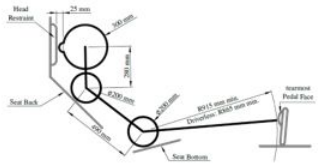
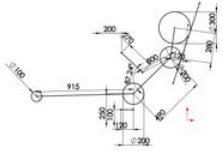


Chassis optimization

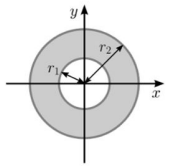


IDEF0 diagram of the optimization process - 8 iterations performed

Chassis optimization

	Requirements				Verification method	Design decision	Pass/Fail
T2.7.1	The vehicle must have a wheelbase of at least 1525 mm.				RoD	1525 mm	✓
T3.2.1		Minimum wall thickness [mm]	Minimum cross sectional area [mm²]	Minimum area moment of inertia [mm⁴]			
	Main and front hoops, shoulder harness mounting bar	2	175	11320	RoD	ISO pipe 26.9 x 2.3	✓
	Side impact structure, front bulkhead, roll hoop bracing, driver's restraint harness attachment	1.2	119	8509	RoD	ISO pipe 21.3 x 1.6	✓
T3.2.2	Steel tubing has to be made from unalloyed carbon steel with a maximum content of 0.3% carbon, 1.7% manganese and 0.6% of any other element. All other steel grades are considered alternative materials and require additional testing and documentation				RoD	AISI 1020	✓
T3.2.4	Non-welded strength for continuous material calculations						
	Young's Modulus (E)	200 GPa			RoD	200 GPa	✓
	Yield Strength (Sy)	305 MPa				370 MPa	✓
	Ultimate Strength (Su)	365 Mpa				550 Mpa	✓
	Welded strength for discontinuous material such as joint calculations:						
	Yield Strength (Sy)	180 Mpa			RoD	200 Mpa	✓
	Ultimate Strength (Su)	300 Mpa				550 MPa	✓
T4.3.1	Percy (95th percentile male) 				RoD		✓
T4.3.2	The 95th percentile male is represented by a two dimensional figure consisting of two circles of 200mm diameter (one representing the hips and buttocks and one representing the shoulder region) and one circle of 300mm (representing the head with helmet).				RoD	see below	✓
T4.3.3	The two 200mm circles are connected by a straight line measuring 490mm. The 300mm circle is connected by a straight line measuring 280mm with the upper 200mm circle.				RoD	see below	✓
T4.3.4	Percy placement 				RoD		✓

		Minimum wall thickness [mm]	Minimum cross sectional area [mm²]	Minimum area moment of inertia [mm⁴]	Verification method	Design decision	Pass/Fail
T3.2.1	Main and front hoops, shoulder harness mounting bar	2	175	11320	RoD		✓
	Side impact structure, front bulkhead, roll hoop bracing, driver's restraint harness attachment	1.2	119	8509	RoD		✓



$$I_x = \frac{\pi}{4}\left(r_2{}^4 - r_1{}^4\right)$$

$$I_y = \frac{\pi}{4}\left(r_2{}^4 - r_1{}^4\right)$$

$$I_z = \frac{\pi}{2}\left(r_2{}^4 - r_1{}^4\right)$$

size	mm
D	26.9
d	22.3
wt	2.3

cross sectional area [mm²]	
A_{cs} [mm²]	177.7513

area moment of inertia	
Ix [mm⁴]	13563.54
Iy [mm⁴]	13563.54
Iz [mm⁴]	27127.07

size	mm
D	26.9
d	23.7
wt	1.6

cross sectional area [mm²]	
A_{cs} [mm²]	127.1717

area moment of inertia	
Ix [mm⁴]	10215.86
Iy [mm⁴]	10215.86
Iz [mm⁴]	20431.72

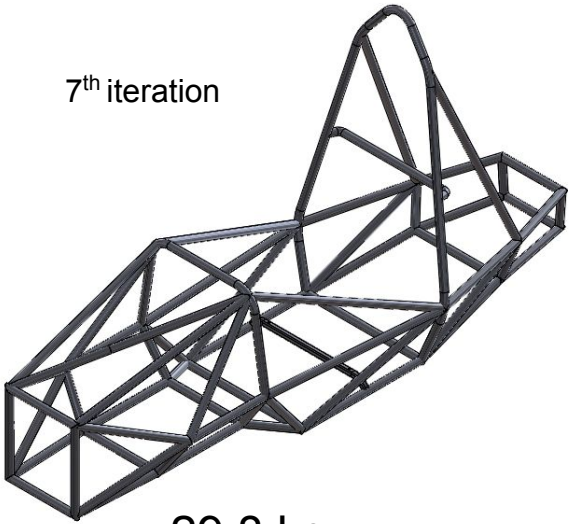
Requirement verification & traceability matrix

Hoop size optimization & verification process

Chassis optimization results

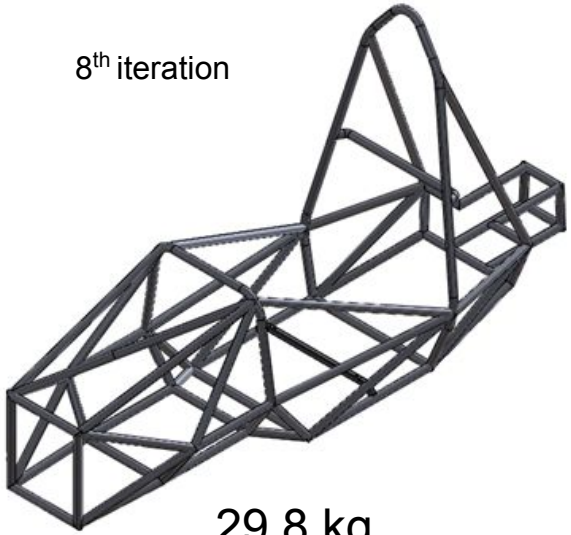
Mass reduction ~30%
Length shorten ~ 14%

7th iteration

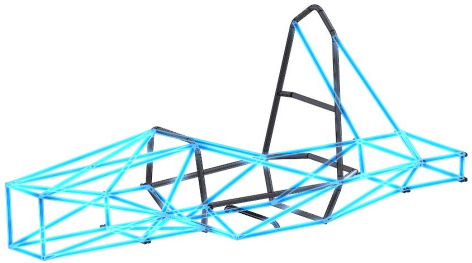


29.8 kg

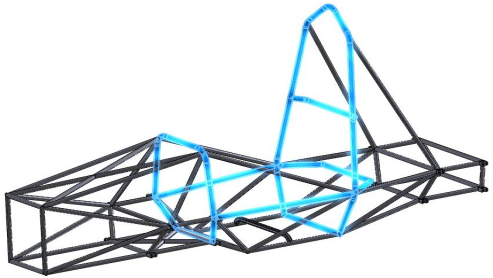
8th iteration



29.8 kg



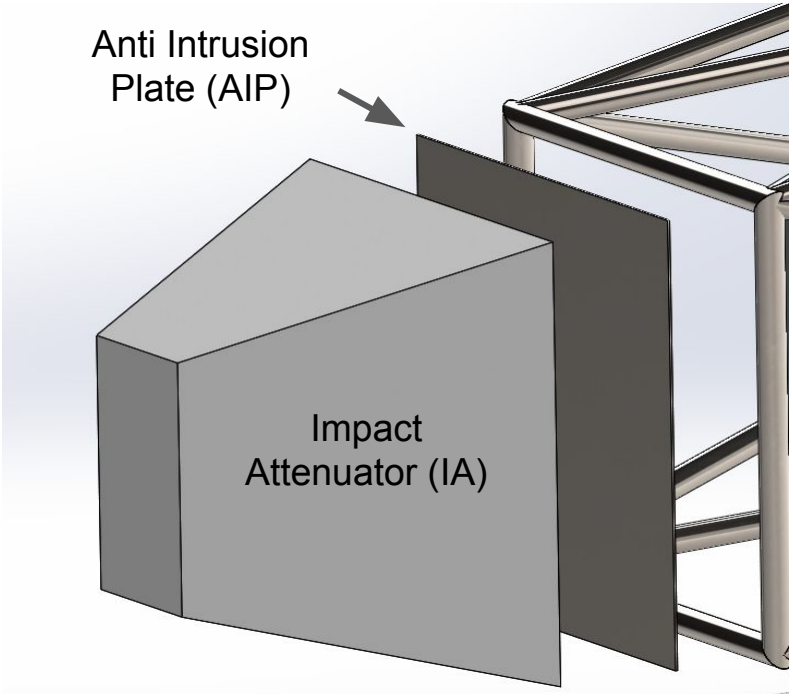
ISO pipe 26.9 x 2.3

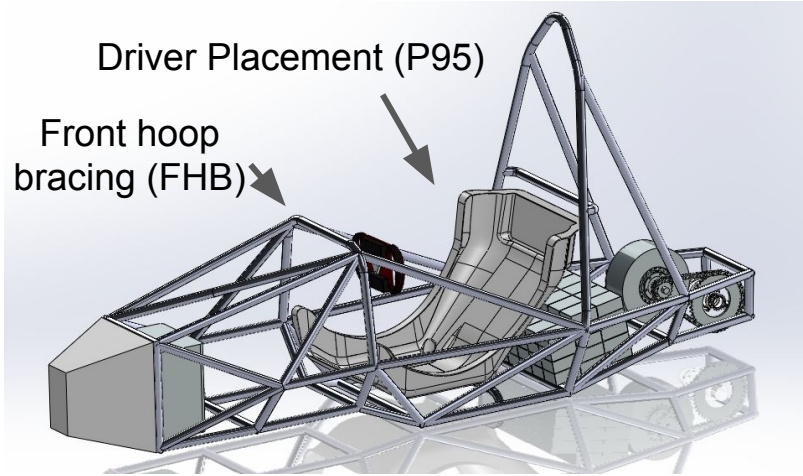


ISO pipe 26.9 x 1.6

Material
AISI 1020 - Russia Equivalent: Марка стали 20

Chassis subassemblies layout verification

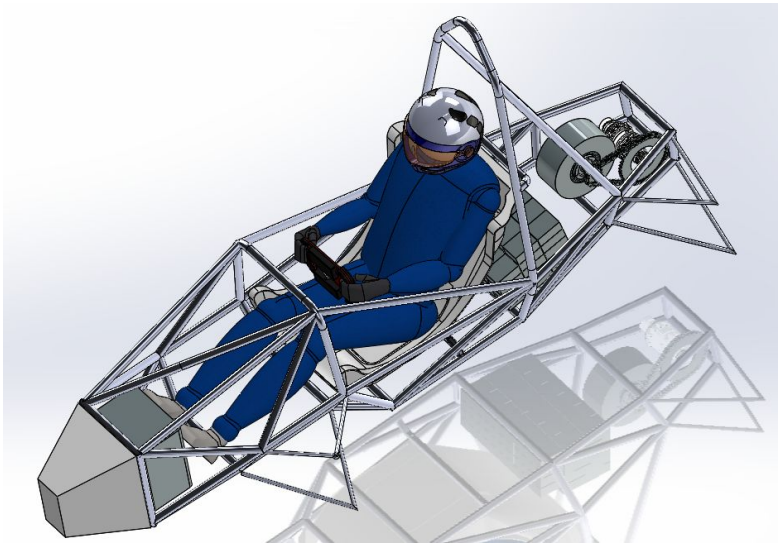


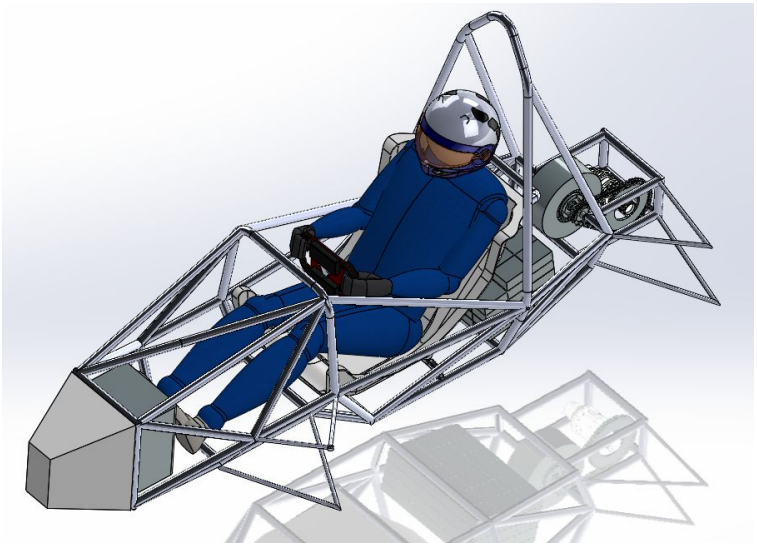


FHB	T3.11.1	Assembly position	✓
IA	T3.17.2	size, position & material	✓
AIP	T3.17.3	size, position & material	✓
P95	T4.3	Percy dimensions	✓

Chassis optimization results

Subassembly definition and verification



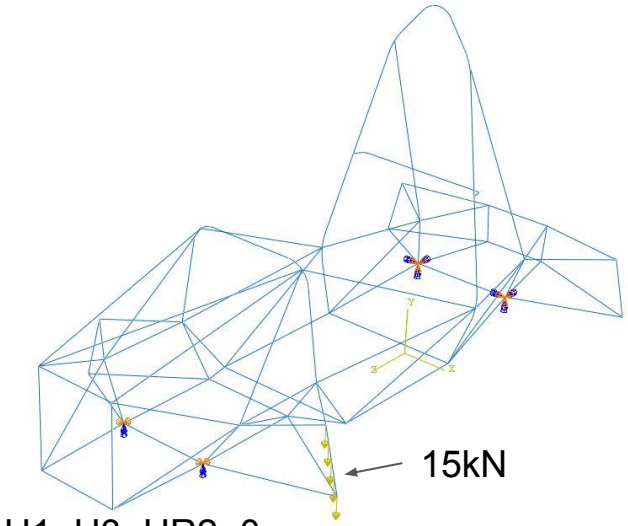


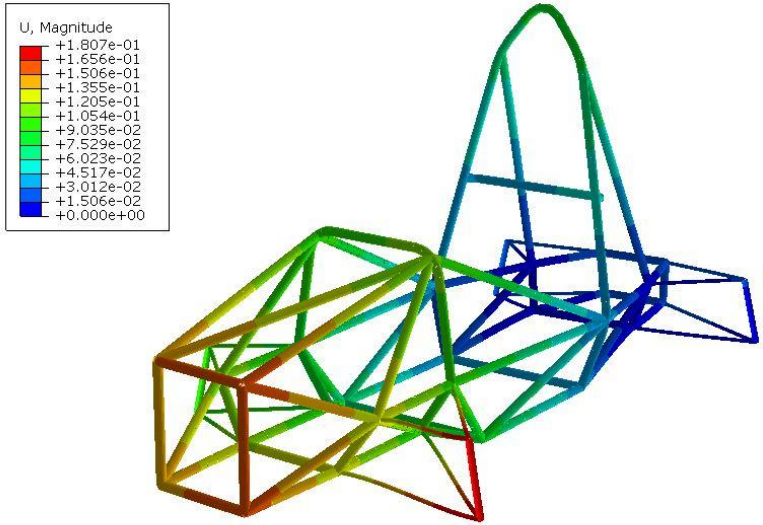
Layout definition

Suspension mounting points
Driver seat

Battery pack
Engine & differential

Chassis Torsional stiffness analysis





Converted bodies model in curve model (IGES format) → FEM analysis on Abaqus

$$C_T = \frac{T}{\theta}\left[\frac{Nm}{deg}\right] = 239\left[\frac{Nm}{deg}\right]$$

Chassis

Torsional Testing of Chassis.

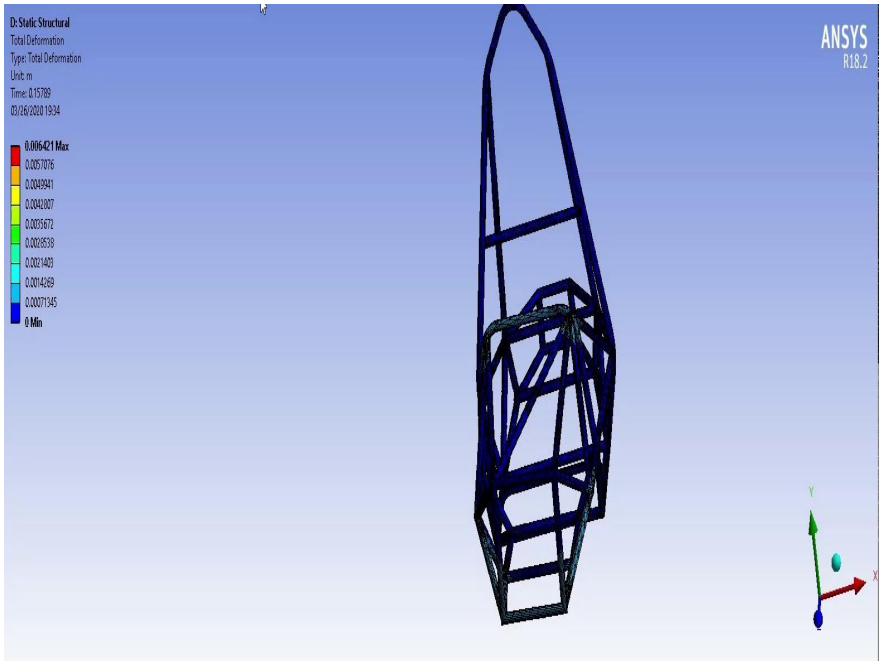
Technical Detail:

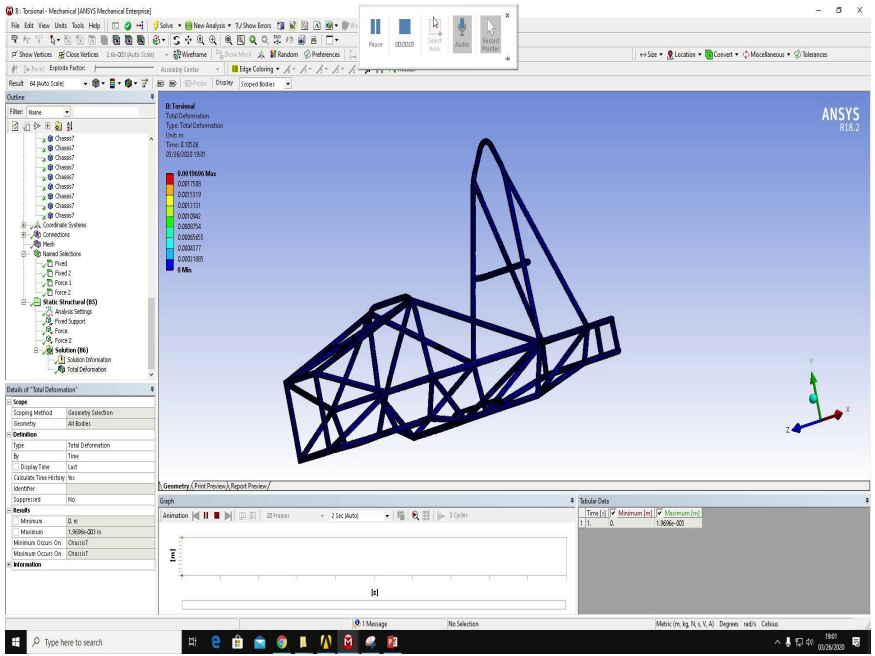
1. Material AISI 1020.
2. 15KN Force is applied on the opposite side of the frame.
3. Displacement along Y-axis is 4-6mm.

Results:

Structure can hold the load by distributing stresses along the beam. We can evaluate the critical points.

Chassis (Torsional Analysis)





Costs report

System	Part	Bought / / Made	Cost	Quantity	Exchange rate Multiplier	Total
Drivers' Equipment	Helmet	Bought	€500.00	2	73	73,000.00 ₽
	Underhelmet	Bought	€20.00	2	73	2,920.00 ₽
	Suit	Bought	€500.00	2	73	73,000.00 ₽
	Gloves	Bought	€100.00	2	73	14,600.00 ₽
	Undersuit	Bought	€50.00	2	73	7,300.00 ₽
	Underpants	Bought	€50.00	2	73	7,300.00 ₽
	Socks	Bought	€20.00	2	73	2,920.00 ₽
	Shoes	Bought	€200.00	2	73	29,200.00 ₽
	Seatbelts	Bought	€400.00	1	73	29,200.00 ₽
	Arm restraints	Bought	€50.00	2	73	7,300.00 ₽
					Total system cost:	**246,740.00 ₽**
Aerodynamics & Body	Seat	Bought	€460.00	1	73	33,580.00 ₽
	Headrest	Bought	€125.00	1	73	9,125.00 ₽
	Padding	Bought	€100.00	1	73	7,300.00 ₽
	Leg pads	Bought	€50.00	2	73	7,300.00 ₽
	Frame	Made	183,000.00 ₽	1	1	183,000.00 ₽
	Aerodynamics	Made	365,000.00 ₽	1	1	365,000.00 ₽
					Total system cost:	**605,305.00 ₽**
Steering System & Pedal Assembly	Steering wheel	Bought	€265.00	1	73	19,345.00 ₽
	Quick Release	Bought	€250.00	1	73	18,250.00 ₽
	Rack	Bought	€1,265.00	1	73	92,345.00 ₽
	Rotary sensor	Bought	€200.00	1	73	14,600.00 ₽
	Spline coupler	Bought	€65.00	1	73	4,745.00 ₽
	Bevel gears	Bought	€930.00	1	73	67,890.00 ₽
	Steering coloumn	Bought	€130.00	1	73	9,490.00 ₽
	Suspension bushings	Bought	€6.50	4	73	1,898.00 ₽
	Suspension arms	Bought	€130.00	1	73	9,490.00 ₽
	Rod-ends	Bought	€15.00	4	73	4,380.00 ₽
	Pedal assembly	Bought	€2,000.00	1	73	146,000.00 ₽
					Total system cost:	**388,433.00 ₽**
Brake System	Brake lines	Bought	€30.00	5	73	10,950.00 ₽
	Banjo bolts	Bought	€10.00	10	73	7,300.00 ₽
	Tee	Bought	€50.00	4	73	14,600.00 ₽
	Olives	Bought	€1.50	17	73	1,861.50 ₽
	Fittings	Bought	€15.00	17	73	18,615.00 ₽
	Pressure sensors	Bought	€30.00	2	73	4,380.00 ₽
	Brake light	Bought	€40.00	1	73	2,920.00 ₽
	Pressure regulator	Bought	€250.00	1	73	18,250.00 ₽
	Brake calipers	Bought	$150.00	4	64	38,400.00 ₽
	Brake disks	Made	1,000.00 ₽	5	1	5,000.00 ₽
	Bobbins	Bought	$4.00	20	64	5,120.00 ₽
					Total system cost:	**127,396.50 ₽**
Suspension	Shock absorbers	Bought	15,000.00 ₽	4	1	60,000.00 ₽
	Springs	Bought	5,000.00 ₽	4	1	20,000.00 ₽
	Bell cranks	Made	5,000.00 ₽	4	1	20,000.00 ₽
	Bell bearings	Bought	350.00 ₽	4	1	1,400.00 ₽
	Pushrods	Made	5,000.00 ₽	4	1	20,000.00 ₽
	Rod-ends	Bought	€15.00	36	73	39,420.00 ₽
	Upper A-arm	Made	5,000.00 ₽	4	1	20,000.00 ₽
	Lower A-Arm	Made	5,000.00 ₽	4	1	20,000.00 ₽
	Rear steering link	Made	1,000.00 ₽	4	1	4,000.00 ₽
	Spacers	Made	30.00 ₽	96	1	2,880.00 ₽
	Upright	Made	50,000.00 ₽	4	1	200,000.00 ₽
	Bearings	Bought	3,500.00 ₽	8	1	28,000.00 ₽
	Hub	Made	50,000.00 ₽	4	1	200,000.00 ₽
	Wheel disks	Bought	$250.00	8	64	128,000.00 ₽
	Dry tires	Bought	$183.00	4	64	46,848.00 ₽
	Wet tires	Bought	$172.00	4	64	44,032.00 ₽
	Camber regulator plates	Made	300.00 ₽	10	1	3,000.00 ₽
					Total system cost:	**857,580.00 ₽**

Costs report

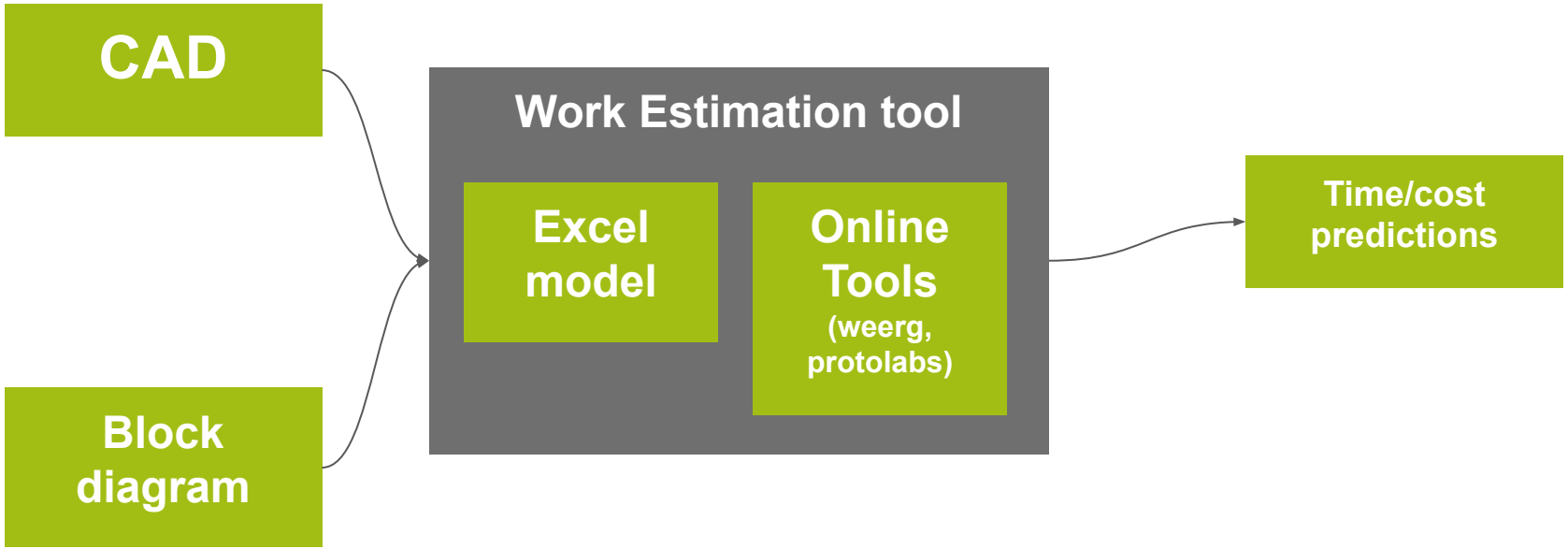
Powertrain	Electrical Motor	Bought	€7,500.00	1	73	547,500.00 ₽
	Battery pack	Bought	500,000.00 ₽	1	1	500,000.00 ₽
	Differential	Bought	€1,700.00	1	73	124,100.00 ₽
	Controller	Bought	$6,000.00	1	64	384,000.00 ₽
	Chain	Bought	€100.00	1	73	7,300.00 ₽
	Sprocket	Made	€30.00	1	73	2,190.00 ₽
	Chain protection	Made	500.00 ₽	1	1	500.00 ₽
	Halfshafts aasy	Bought	€3,530.00	1	73	257,690.00 ₽
					Total system cost:	**1,823,280.00 ₽**
Electrical System	Electrical components	Bought	500,000.00 ₽	1	1	500,000.00 ₽
					Total system cost:	500,000.00 ₽
					Additional contingencies:	25.0%
					Total system cost (considering additional contingencies)**:**	**666,666.67 ₽**
Fasteners & Miscellanious	Fasteners	Bought	10.00 ₽	3000	1	30,000.00 ₽
	Fasteners	Made	50.00 ₽	30	1	1,500.00 ₽
	Glues	Bought	5,000.00 ₽	8	1	40,000.00 ₽
	Liquids	Bought	3,000.00 ₽	15	1	45,000.00 ₽
	Paints	Bought	2,000.00 ₽	5	1	10,000.00 ₽
	Others	Bought	30,000.00 ₽	1	1	30,000.00 ₽
					Total system cost:	**156,500.00 ₽**
					Total Cost:	4,871,901.17 ₽
					Contingencies:	25.0%
					Total Cost (considering contingencies)**:**	**6,495,868.22 ₽**

Still mostly estimates

Next steps:

- Refine estimates
- Start the definition of the final report

Time and cost estimations

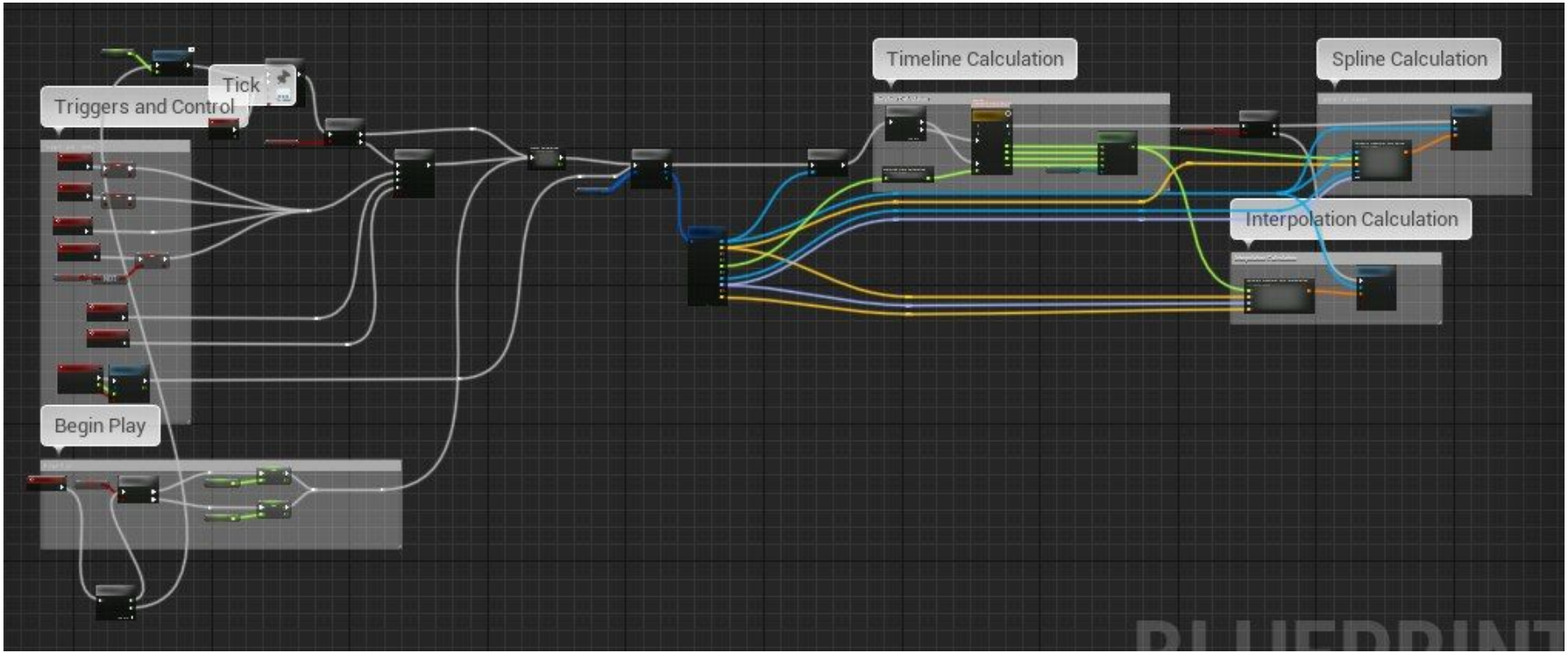


Car visualisation

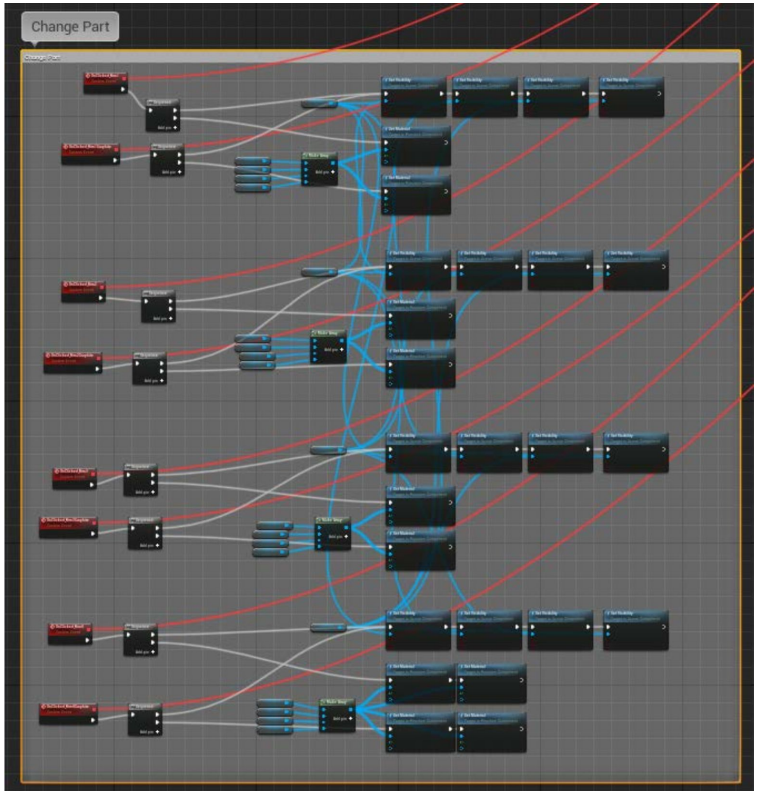
Pipeline / Progress

- Modeling / Added new location 
- Texturing / Added texture for new locations 
- Lighting / Optimized lightning 
- Layout / Changed scene composition
- Visual Programming / Created several new functions
- Optimization / New version is more stable

Real time exploded view visualisation



Toggle part variations in real time



Demonstration

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Coming

Thank You!
Keep Safe!