MEC-E1060 - Machine Design

Detailed Design Report

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1. INTRODUCTION

Connecting the wheels and tires to the car is a simple concept, but doing it in a manner which obtains good performance is a different matter altogether. In traveling around the circuit, the car experiences bumps from the track surface, and weight transfers from braking, accelerating, and cornering, and the design of the suspension geometry (relative angles and lengths) determines how the vehicle reacts to these forces. It has been a topic of interest to control vehicles and allow the wheels to move, adjust, and adapt to quickly changing road and driving conditions.

In this project, the aim was to design the front wheel suspension kinematics and components for a Formula Student race car with two different mechanisms (Double wishbone and McPherson suspension systems). The objective from the point view of kinematics is to design the linkage that fully determines the wheel path in specified manner when the wheel is having a vertical motion relative to the frame of car.

2. SELECTION OF CONCEPT BASED ON MBS, FEM AND REQUIREMENTS

The double wishbone suspension system was selected for suspension type. There are many reasons why to use that one instead of McPherson suspension system. The most important is the space and mounting requirements of the suspension system. The frame of the Formula Student car should be as narrow as practically possible. This requirement allows all the suspension and spring mounting points to be mounted in a sensible way if double wishbone system is used. With McPherson system one of the mounting points (strut mounting point) should be brought quite near to the wheel because the strut has to be at nearly vertical position. This becomes from the fact that in McPherson system the strut itself actually rotates when the wheel is steered.

Another important reason for selecting double wishbone system is the large number of possible adjustments for the suspension. In real built suspension there will be several mounting points for each pivot joint in the frame.

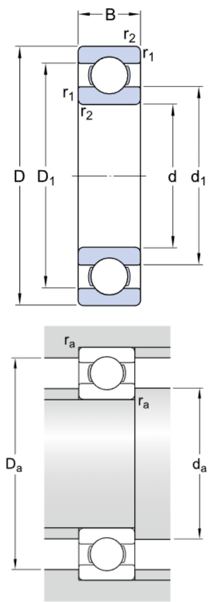
Also, the double wishbone system can be constructed of tubular members in wishbones. In addition, they can be made triangular such a way that the structure acts like a truss (only tension or compression in wishbones). This leads to lightweight design of the overall suspension.

3. MACHINE COMPONENTS AND MATERIALS

The machine components were selected upon requirements and suitable materials were chosen as listed below. The wheel hub forces were estimate by correlating it with the mass of the car (350 kg), weight distribution, vertical wheel load (1.7 kN), dynamic radius of the wheel, tire friction and finally obtaining the longitudinal and lateral wheel loads (1.8 kN). Although most of the parts are built by manufacturers with single materials, the durability of the materials were checked by taking into account the yield and ultimate strength to handle the stresses on the components.

Components:

- Deep groove ball bearing for wheel (16010)
  The selection of this bearing from SKF [1] was to achieve the required level of equipment performance and it is suitable for high and very high speeds, accommodate radial and axial loads in both directions and require little maintenance. According to our calculations in the last report, the average rotational speed that can be achieved is 530 rpm for the selected tire with a dynamic radius of 0.25 m. By taking into account the lubricant used with this bearing, we were able to estimate the equivalent dynamic bearing load (4.71 kN) as well as the equivalent static load (5.37 kN) which fits the requirement.



d		50	mm
D		80	mm
B		10	mm
d_1	≈	60	mm
D_1	≈	70	mm
$r_{1,2}$	min.	0.6	mm
d_a	min.	53.2	mm
D_a	max.	76.8	mm
r_a	max.	0.6	mm

Calculation data

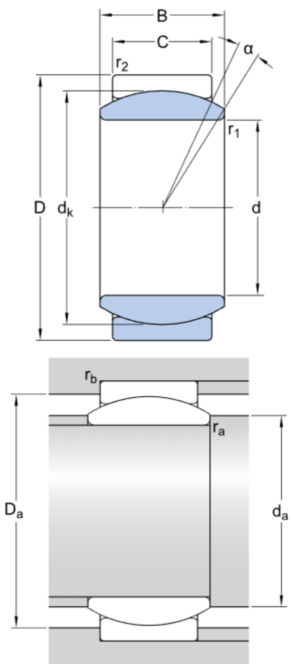
Basic dynamic load rating	C	16.8	kN
Basic static load rating	C_0	11.4	kN
Fatigue load limit	P_u	0.56	kN
Reference speed		18000	r/min
Limiting speed		11000	r/min
Calculation factor	k_r	0.02	
Calculation factor	f_0	14.1	

Mass

Mass bearing	0.18	kg

Figure 1. Deep groove ball bearing for wheel

- Radial spherical plain bearing (GE 10 E)
  The selection of this bearing from SKF [2] was for a design that is particularly suitable for bearing arrangements where alignment movements between shaft and housing have to be accommodated, or where oscillating or recurrent tilting or slewing movements must be possible at relatively slow sliding speeds, often accompanied with heavy loads. Radial spherical plain bearings have an inner ring with a sphered convex outside diameter and an outer ring with a correspondingly sphered but concave inside surface. This bearing well fits the mechanism and the requirement as shown in the validation part previously.



d		10	mm
D		19	mm
B		9	mm
C		6	mm
α		12	°
d_k		16	mm
r_1	min.	0.3	mm
r_2	min.	0.3	mm
d_a	min.	11.7	mm
d_a	max.	13.2	mm
D_a	min.	15.2	mm
D_a	max.	17.5	mm
r_a	max.	0.3	mm
r_b	max.	0.3	mm

Calculation data

Basic dynamic load rating	C	8.15	kN
Basic static load rating	C_0	40.5	kN
Specific dynamic load factor	K	100	N/mm²
Specific static load factor	K_0	500	N/mm²
Material constant	K_M	330	

Mass

Mass plain bearing	0.012	kg

Lubricant	Regular relubrication – grease
Design (sliding contact surface combination)	Steel/steel
Sealing solution	-

Figure 2. Radial spherical plain bearing (GE 10 E)

- M8 rod end with a male thread, self-lubricated
  Rod ends consist of an eye-shaped head with integral shank that forms a housing for a spherical plain bearing. SKF supplies rod ends with a threaded shank with a right-hand thread as standard [6]. This rod end was used in upper and lower wishbone component as can be seen in the detailed CAD model.
- Wheel Hub
  The selection of the wheel hub was done after knowing different car parameters such as the mass, loads, friction, distance from wheel footprint center to outer bearing, distance between the bearing centerline while taking into account the required cross-section of 443 mm^2. The lifecycle of the wheel hub was important and hence fatigue calculations were performed. The safety factor with respect to fatigue was calculated to be 9.4.
- Upright
  Upright must provide the mounting for brake caliper (Wilwood Dynalite 3a) with mount spacing of 95.3 mm and hence it was modeled in a way to be connected to the wheel where the wheel is centered to transfer the vertical load to upright. With this component, we were able to adjust the static camber angle of the wheel by 10 degrees as well as provide the mounting for control arms and tierod.
- Frame
- Lower and Upper Wishbone
  The feasibility, durability and dimensions were checked. The thread stripping while inserting the whishbone in the rod end connection were checked and the optimum size was selected with respect to the shear yield load.
-

Materials:

- Ruber and Aluminum for front wheel
- Aluminum 7075-T6

This material has a very high strength used for highly stressed structural parts [4]. T6 temper 7075 has an ultimate tensile strength of 530 MPa and yield strength of at least 460 MPa with failure elongation of 5–11% which makes it an adequate selection for our components in many ways as discussed previously.

- Steel S355J2

  S355 structural steel plate is a high-strength low-alloy European standard structural steel which offers high yield and tensile strength with a minimum yield strength of 355 N/mm² [5]. Some of our mechanism components uses this grade of steel such as bearing, frame, lower wishbone and upper wishbone.

Lubricant:

- SKF LGMT3, Lithium Soap thickened grease NLGI 3 / Grease NGML2

  It is a mineral oil based, lithium soap thickened grease [3]. This premium quality, general purpose grease is suitable for a wide range of industrial and automotive applications requiring stiff grease. The kinematic viscosity (125 mm^2s^{-1}) of base oil of the grease was an important input for our selection as we were able to calculate the minimum required radial load (0.138 kN). This value was further used to know the maximum axial and radial force in inner and outer bearing and obtain an equivalent static load (5.37 kN) that fits the requirement.

4. LIFETIME CALCULATION

The lifetime calculation was carried out on the wheel hub and the results were presented by doing fatigue calculation. Since the wheel hub is acting like an axle, it's under reversing bending moment all the time when car is moving.

Fatigue calculation of wheel hub

$W_{max} := \frac{W}{4} = 858.375$	Maximum load on wheel (N)
$W_{min} := -\frac{W}{4} = -858.375$	Minimum load on wheel (N)
$\sigma_{max} := \frac{W_{max} \cdot a}{W_t} = 6.028$	Maximum normal stress at shoulder (N/mm^2)
$\sigma_{min} := \frac{W_{min} \cdot a}{W_t} = -6.028$	Minimum normal stress at shoulder (N/mm^2)
$\sigma_m := \frac{\sigma_{max} + \sigma_{min}}{2} = 0$	Mean stress (N/mm^2)
$\sigma_a := \frac{\sigma_{max} - \sigma_{min}}{2} = 6.028$	Stress amplitude (N/mm^2)
$\sigma_{D0} := 159$	Fatigue strength of Al-7075-T6, test bar (N/mm^2)

Surface roughness Ra=1.6

$k_1 := 0.85$	Fatigue strength influence factor due to surface roughness
$k_2 := 0.82$	Fatigue strength influence factor due to size
$k_3 := 0.897$	Confident factor
$k_4 := 1$	Temperature factor

Notch sensitivity according to Neuber

$\rho := 0.4$ Notch radius (mm)

$a_1 := 0.5$ Material constant for aluminium alloys (mm)

$$q := \frac{1}{1 + \frac{a_1}{\rho}} = 0.444$$ Notch sensitivity

$K_f := q \cdot (K_t - 1) + 1 = 1.756$ Fatigue stress concentration factor

$k_5 := \frac{1}{K_f} = 0.57$ Fatigue strength influence factor due to stress concentration

$\sigma_D := \sigma_{D0} \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 = 56.625$ Reduced fatigue strength (N/mm^2)

$n := \frac{\sigma_D}{\sigma_a} = 9.393$ **Safety factor respect to fatigue**

The bearing lifetime calculation result is presented below. It is done with help of SKF calculation software.

Result

L_{10mh} SKF rating life	739800 hour
a_{SKF} SKF life modification factor a_{SKF}	50
κ Viscosity ratio	4.94
P Equivalent dynamic bearing load	2.16 kN
η_c Factor for contamination level	0.83
ν_1 Required kinematic viscosity for κ=1	25.3 mm^2/s
L_{10h} Basic rating life	14800 hour
C/P Load ratio	7.8

For the rest of the components, according to FEM-results, the static stress peaks are below the fatigue strength of the materials, which are 235MPa for S355 steel and 159MPa for Aluminum 7075-T6. (Half of the ultimate strength of steel and quarter of ultimate strength of Aluminum).

5. GEOMETRICAL RENDERING

To illustrate final product of this machine design project rendered images and videos have been created. In figure 3, the product is further shown from all angles according to first angle projection rule. In addition, Mechanism also visualized at factory environment. This is shown in Figure 4 and similar AVI-format animation will be submitted separately for the recipients of this report.

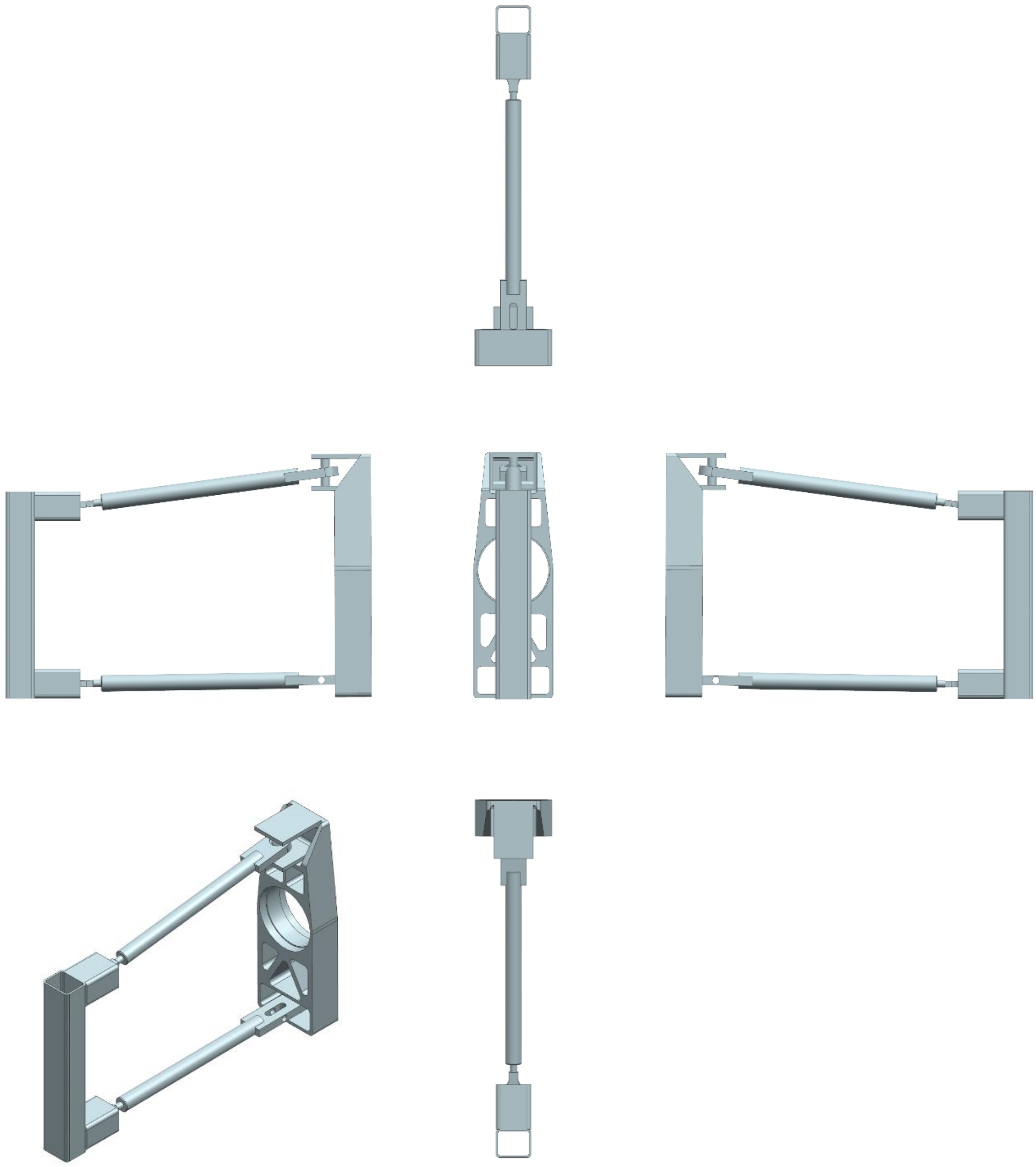


Figure 3. Double Whishbone mechanism, First angle projection rule.

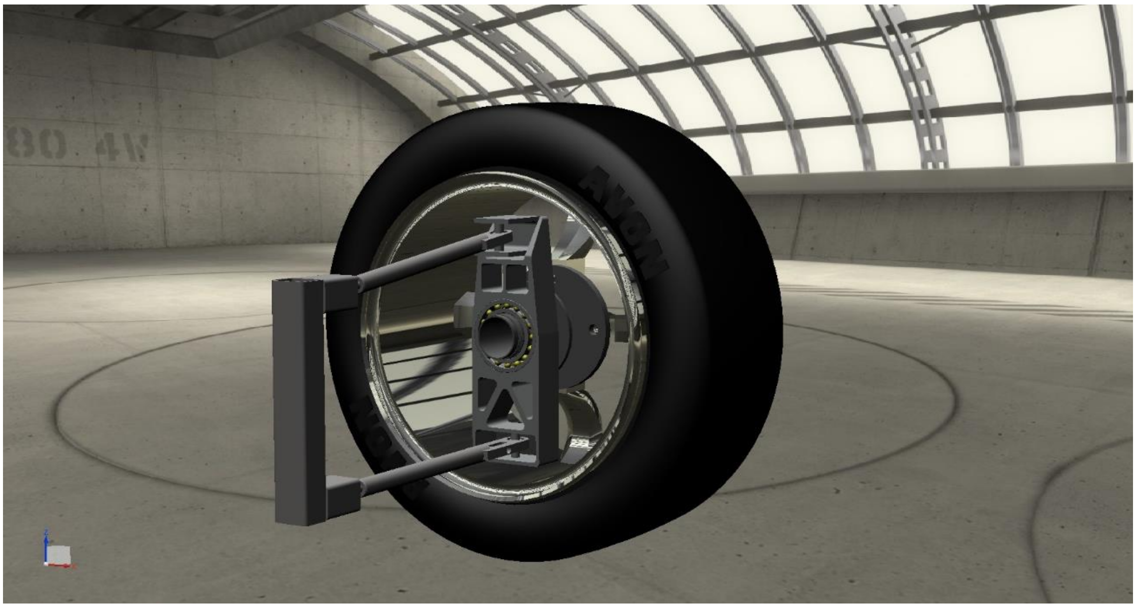


Figure 4. Illustration of final mechanism.

6. EVALUATING THE REQUIREMENTS

Most of the requirements set at the beginning were structural, meaning that the mechanisms must withstand the certain amount of load. All of these requirements were achieved but the safety factor respect to wishbone buckling was little bit lower than given in requirements (4.92 vs 5.0) but considered to be adequate. Moreover, the deflection of the assembly was within 5mm. The bearing lifetime was adequate.

Of course the practical requirement that the assembly must be able to be installed inside the 13’’ wheel was achieved as can be visualized from the pictures. Also, the joints for the wishbones were provided. But when it comes to the upright and wheel hub design, the mounting of the brakes (caliper and disc) and tie rod was not finished.

The kinematic requirements were actually changed a little bit during the design. The final roll center height at the front became to 45mm above the ground. We changed the plan because we wanted more percentage of the lateral load transfer through the springs so that more of the weight transfer distribution could be controlled by adjusting the roll stiffness’s. The camber-curve became as wanted.

The total weight of the assembly was 2.2 kg so the mass requirement was not fulfilled.

7. DESCRIPTION OF THE DESIGN PROCESS

Initially, the case of study was describes by showing the operation principle of two different mechanism for a front wheel suspension kinematics and components for a Formula Student race car, namely Double wishbone and McPherson suspension systems, as well as a preliminary sketches of the selected mechanisms. A set of detailed requirements were created according to personal needs. An elaborative free body diagram were drawn to show all the forces applied on the movable mechanism.

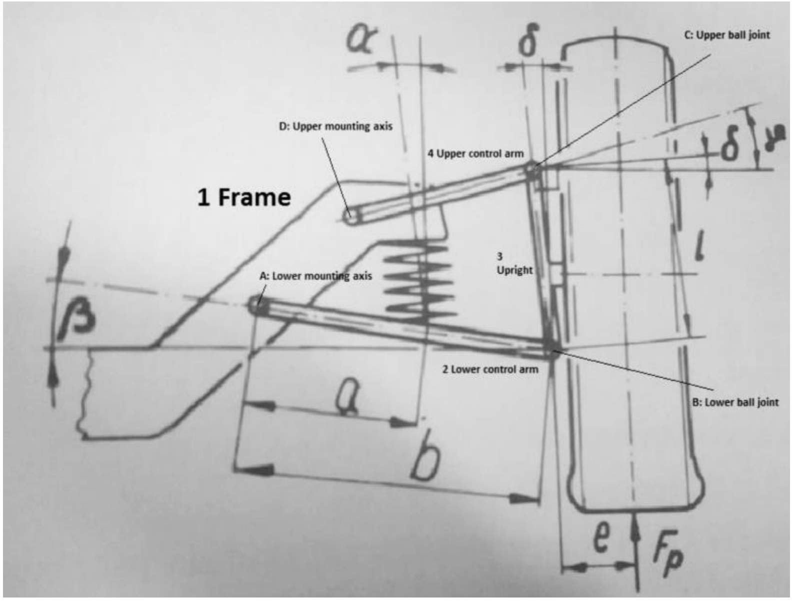


Figure 5. Double wishbone system sketch

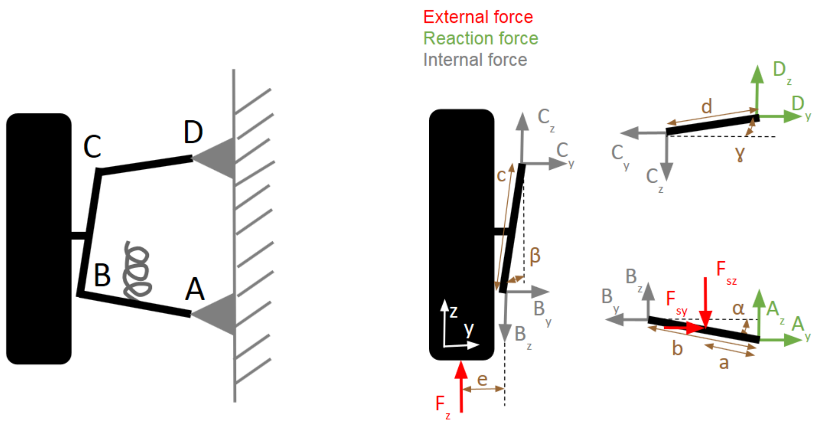


Figure 6. Free body diagram for links of double wishbone system

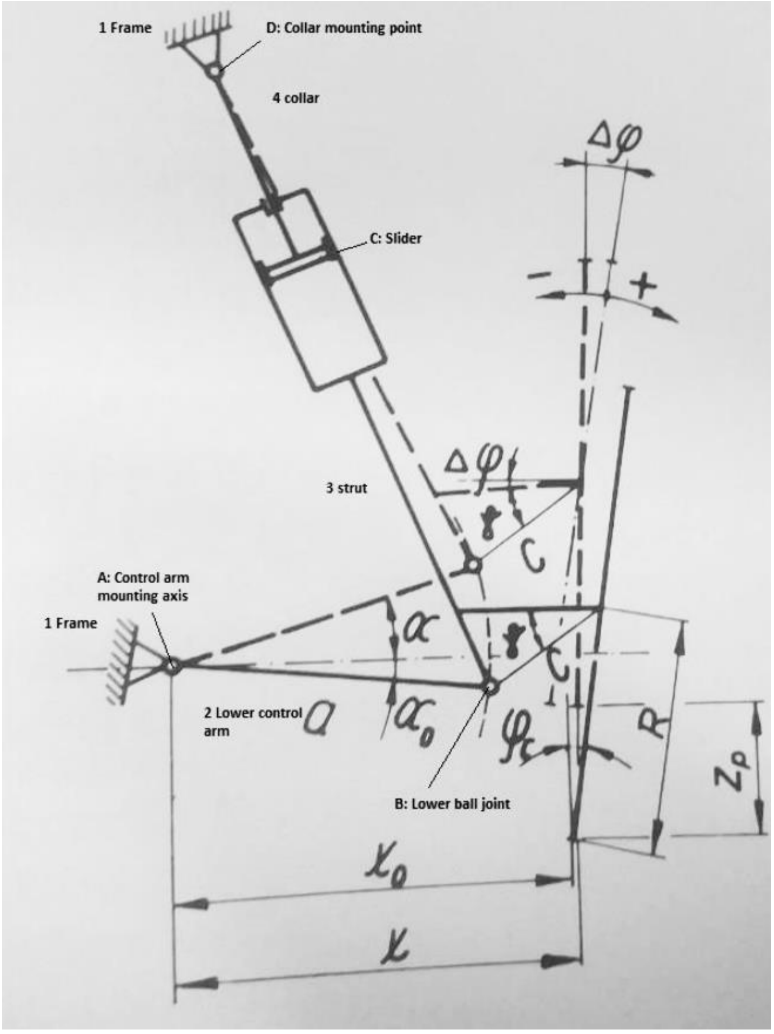


Figure 7. McPherson linkage sketch

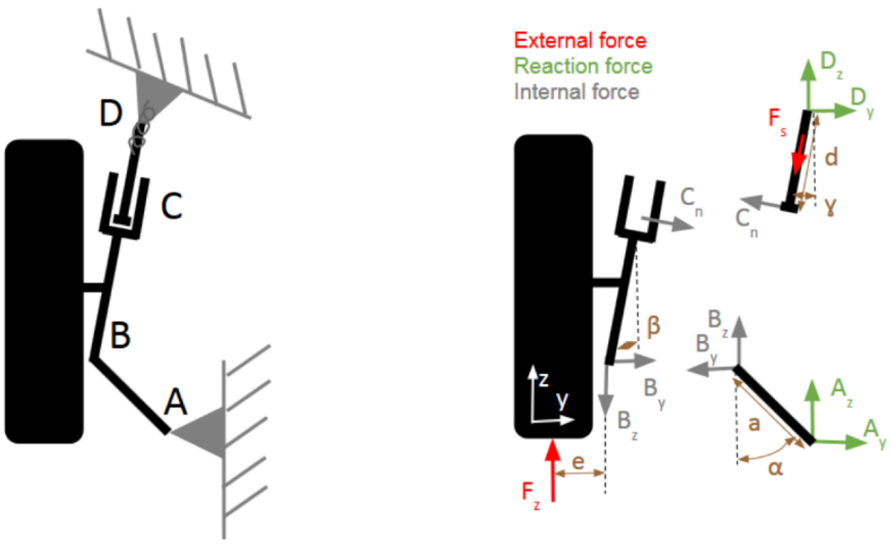
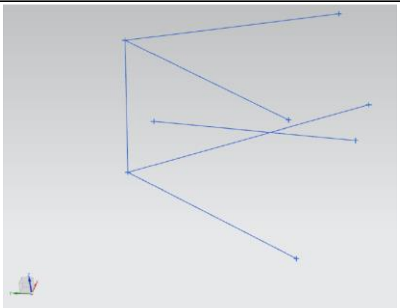
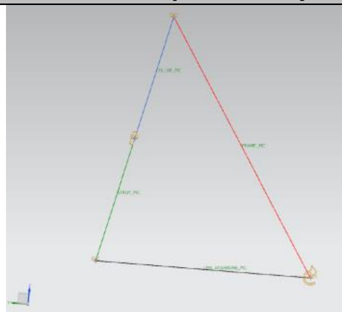
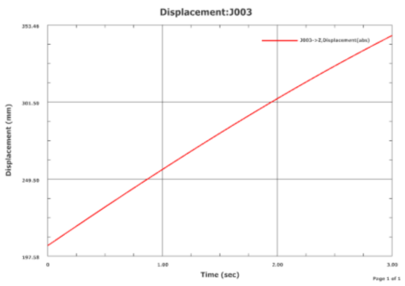
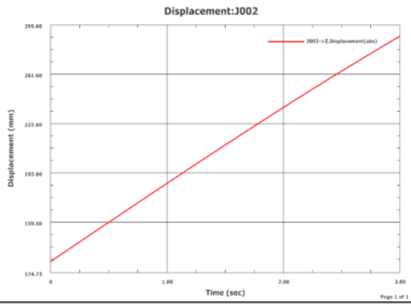
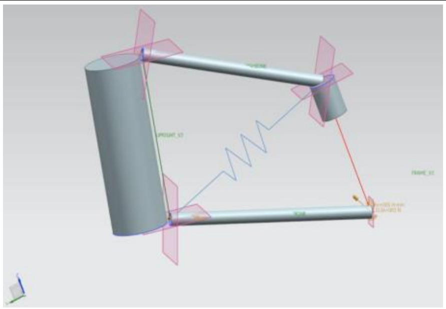
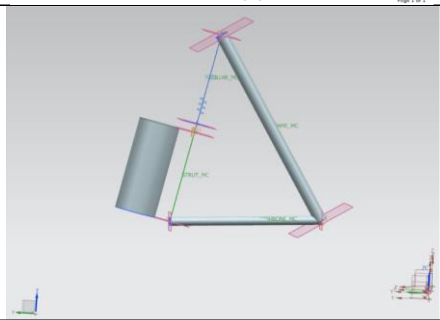


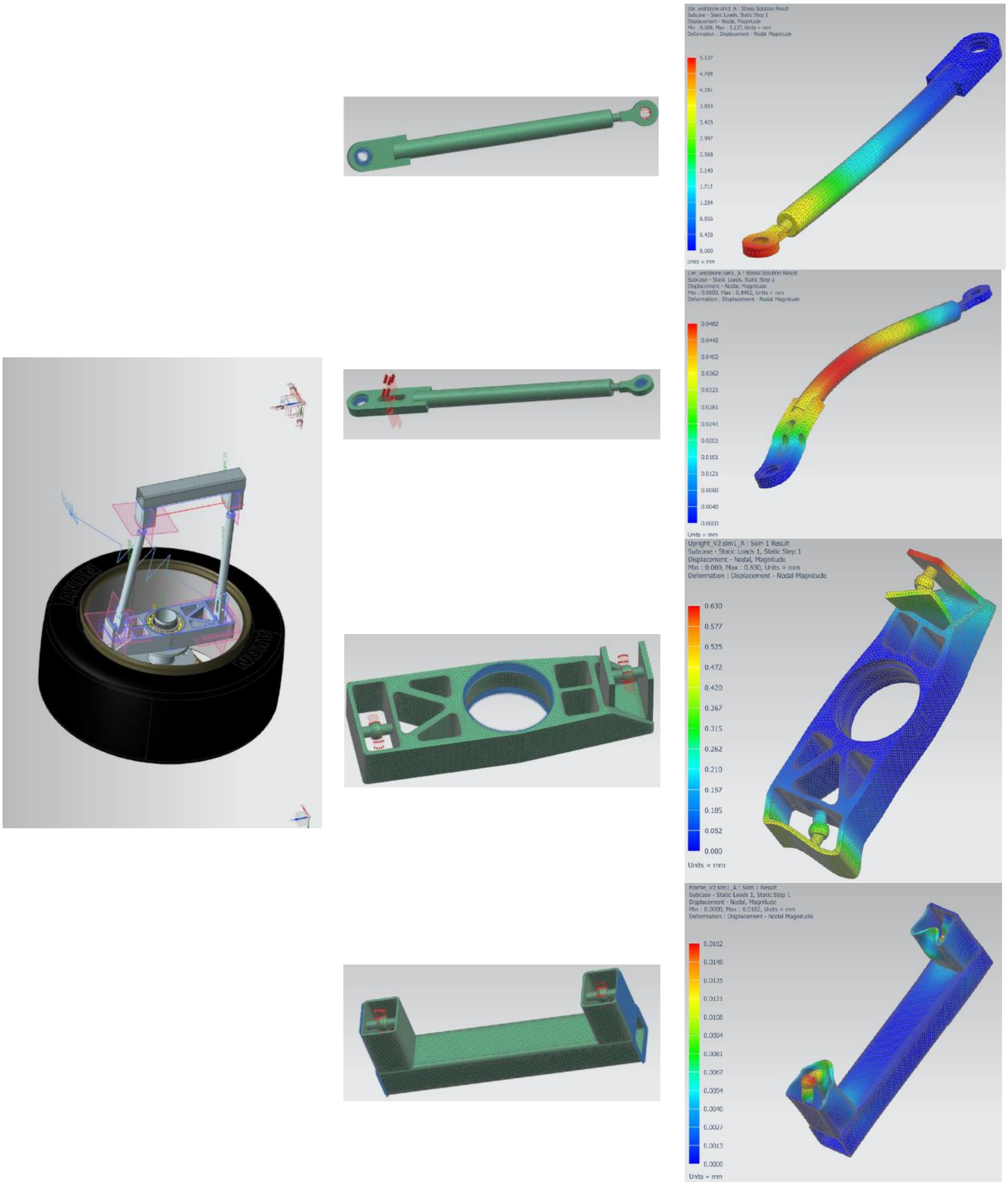
Figure 8. Free body diagrams for links of McPherson linkage

Skeleton model, kinematic simulations and dynamic simulations were carried out for both proposed mechanisms.

Double wishbone system	McPherson suspension system
	
	
	

The mechanisms were analyzed as a group of bars with reactions, pointed the equations that define the mechanical equilibrium in all the pieces and updated the skeleton model to something that has volume and is closer to real product. This was done by simulating the velocities in the joints of the machine and the forces in the component using both MathCad Solve Block procedure and NX movement simulation.

The CAD models of the mechanism were updated for MBS, while taking into account no overlapping geometry. FEM models from all the main parts were made by defining all the needed parameters and trying to get reasonable results by the means of meshing.



The results obtained from FEM were studied using hooks law on elastic materials. Estimating deflections and stresses by means of the principle of structural mechanics proved FEM results were reasonable. The main way of defining the validity of our result was to compare the results with the expected behavior for each part according to literature and experience.

To finalize the final detailed mechanism, there was a need to check other aspects than the mechanic and structural problems. By defining all the components and having all the results obtained by MBS and FEM, we started selecting the materials, lubricant and the components from manufacture's website. Checking the list of requirements at this stage was crucial to evaluate the final mechanism by comparing the result obtained with the results we aimed for at the early stage of the project to analyze if the product meets the requirement.

Lifetime calculation and cost estimation were carried out. For the former, one component was selected and then using Mathcad with a set of equations, the fatigue of that part was calculated which gave a good indication for the life cycle of the part. As for the later, a detailed table was made to show all the expected costs from component parts and machining, all the way to the production phase. BoM was made to represent the final mechanism in an illustrative way.

The geometrical design was rendered using NX and an animation was made to show the product in a time lapse.

8. COST ESTIMATE

Following are a list of costs of the final product which includes the unit price (hr,pc and kg), total number (hr,pcs and kg) and total cost taken from SKF website.

Name	Unit price hr/pc/kg	Total hr/pcs/kg	Total Cost (€)
Machining	120 €/hr	80 hr	9600
Welding	45 €/hr	15 hr	675
Rod ends	50 €/pc	25 pcs	1250
Bearings	100 €/pc	4 pcs	400
Ball joints	50 €/pc	12 pcs	600
Aluminum	20 €/kg	10 kg	200
Laser cutting	80 €/hr	2 hr	160
Steel tube	10 €/kg	1.5 kg	15
Total Cost			**12900**

9. Conclusion

The suspension system is one of the most important components of a race car because it not only connects the sprung mass to the chassis, but is important for maintaining maximum tire contact patch at all times. This report shows the detailed model as well as discussing all aspects in developing the mechanism from sketches, MBS, FEM to selecting components and performing life cycle analysis as well as estimating the cost of the final product.

Based on the lessons learned, created models and outcome of our documentation our estimate for the grade is 5. We succeeded to make a machine out of a preliminary sketch, identify all aspects in developing the mechanism, perform studies and validation, combine different components to create a moving machine with defined function, redesign and improve the model, present and discuss the obtained results and learn to use NX in the process. The collaboration between the 3 members in the group were adequate and helped in improving a skillset of all as a result. The choice of topic and complexity in it shows eager to learn and calls for extra enthusiasm. These results will also be used in Formula Student project and are thought carefully.

10. References

[1] http://www.skf.com/group/products/bearings-units-housings/ball-bearings/deep-groove-ball-bearings/deep-groove-ball-bearings/index.html?designation=16010

[2] http://www.skf.com/group/products/bearings-units-housings/plain-bearings/general/radial-spherical-plain/index.html?designation=GE%2010%20E

[3] http://www.skf.com/group/products/lubrication-solutions/lubricants/general-purpose-industrial-and-automotive-NLGI-3-grease/index.html

[4] http://www.matweb.com/search/DataSheet.aspx?MatGUID=4f19a42be94546b686bbf43f79c51b7d&ckck=1

[5] http://www.beverlysteel.com/products/steel-plate/s355j2-s355j2-n-steel-plate.html

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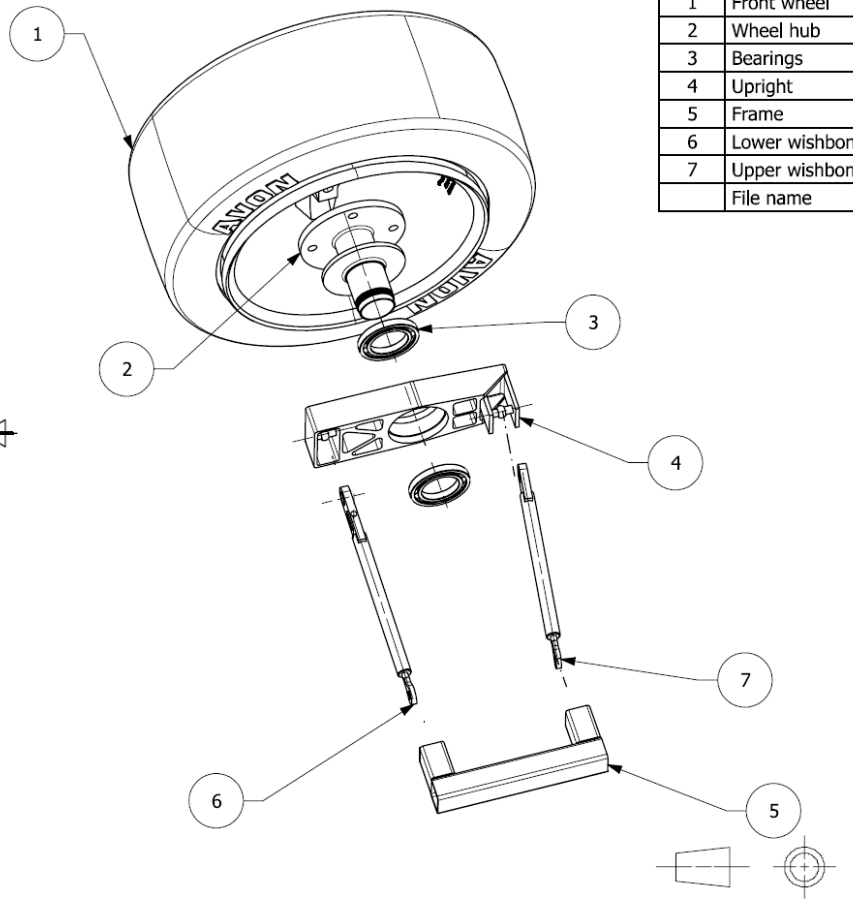
[8] Olavi Laine, Autotekniikka, 2. Osa, Jousitus ja pyörän tuenta, Kustannusyhtymä (1970), p.174.

[9] David H. Myszka, Machines and Mechanisms, Pearson Prentice Hall (1998).

Appendix A. Bill of Materials (BOM)



1	Front wheel	Ruber/Aluminium	-	1
2	Wheel hub	Aluminium 7075-T6	Grease NGML2	1
3	Bearings	Steel	Grease NGML2	2
4	Upright	Aluminium 7075-T6	Grease NGML2	1
5	Frame	Steel S355J2	Grease NGML2	1
6	Lower wishbone	Steel S355J2	Grease NGML2	1
7	Upper wishbone	Steel S355J2	Grease NGML2	1
	File name	Material	Lubricant	QTY

SIEMENS

THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE

FIRST ISSUED	18.10.2018	TITLE: Double Whishbone
DRAWN BY	G16	
CHECKED BY	G16	
APPROVED BY	Kaur Jaakma	SIZE: A3 · DWG NO.: Assembly_V3/C;1-A · SHEET REV: A
		SCALE 1:5 · SHEET 1 OF 1