UNIVERSITY OF TRENTO

INDUSTRIAL ENGINEERING

Academic Year 2021/2022

PROTO CHALLENGE 2022 | TEAM 2

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Team 2 - CMV

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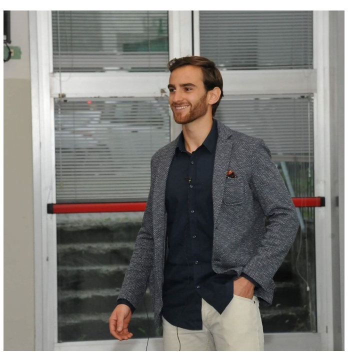

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Company

The challenge has been carried on with the collaboration of CMV Costruzioni Meccaniche Valentini, a company based in Roncone, which designs and manufactures machines and automatic mechanisms for handling steelwork turnkey products. CMV S.p.a. manufacturing lines are designed to meet specific customer needs and are based on hydraulic power packs, hydraulic and/or pneumatic valves, electrical cabinets, PLCs and SUPERVISION systems. The design and construction follows the standards for the production of continuous billet, blooms or slabs and for meeting to specific metallurgical characteristics. CMV S.p.a. is also providing the service for revamping iron and steel manufacturing equipment by improving the structural and functional changes in order to improve the efficiency and to be compliant with the new safety standards. CMV was founded in 1968 as an artisan mechanical workshop, a one-man firm of entrepreneur Fausto Valentini. The geographical location in a heavily timbered area initially directs towards the design and construction of wood handling equipment. In the following years CMV acquired the position of national leader and extended its activities abroad. From 1980, following the strategic vision to invest in competences of steel working and steel industry, CMV started to design, manufacture and install lines for automatic handling of small and large pipes for OIL GAS and other mechanical applications. Thanks to the local customer satisfaction, the company quickly became supplier of international manufacturers. The experience in the OIL GAS markethas growth at intercontinental level reaching installation in Algoma (Canada), Bay City (USA), Tamsa (Mexico), TuboCaribe Colombia), Siderca (Argentina). The collaboration with the RIVA GROUP marked the company's experience and orientation also in the other products sector (billets, rounds, angles, plates, coils); Italy, France, Spain and Germany are the major market destinations. The demand for increasingly larger lines lead to the expansion in 2016 of the production unit reaching about 12,000 square meters.


cmv

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Product

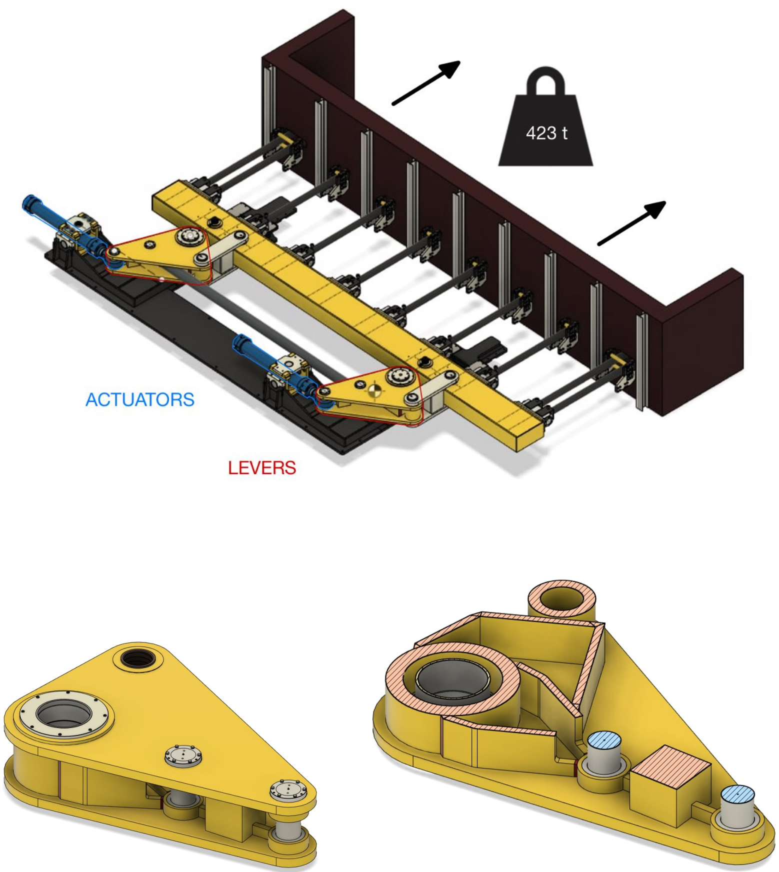

Figure 3.0.1: (a) Pushing mechanism (b) Lever 3D model (c) Lever section view

The challenge proposed by *CMV* has the objective to optimize a particularly stressed component, used in a pushing mechanism in the steel-industry. The component is the mechanical lever highlighted in figure 3.0.1(a); it amplifies the force produced by the 2 hydraulic actuators that push a set of steel billets into an oven. The pusher is able to move up to 423 tonnes of steel.

Due to past failures of similar mechanisms, the actual version of the lever has been extensively over-sized mainly for avoiding any possibility of failure since steel production plants commonly works with continuous casting methods and rarely stops. This situation allows a wide margins for the optimization design.

Challenge

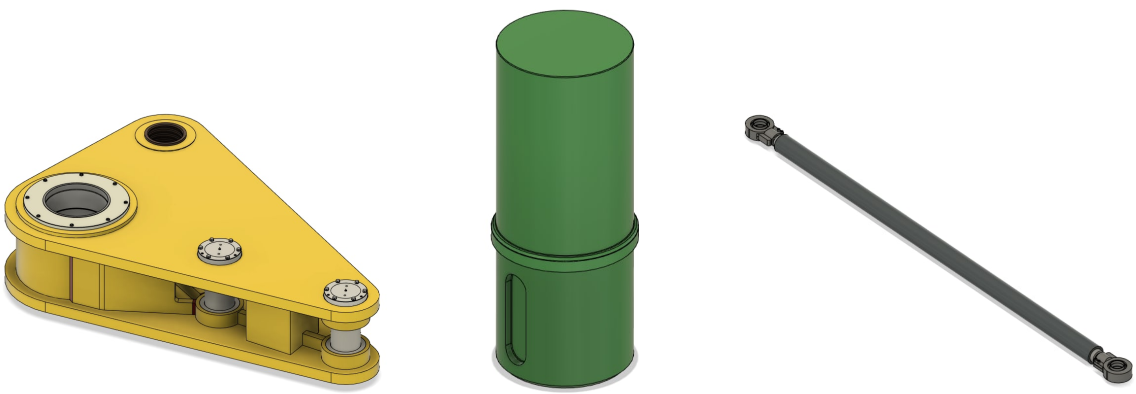

Figure 4.0.1: CAD models of: (a) the original lever (b) Grounded pin (c) Tie-beam

The task assigned to the team was to reduce the mass of the linkage (figure 4.0.1 (a)), to reduce the number of the component assembly and to lower the production cost while maintaining the same performance. Hence we have redesigned the component with the strategy to remove the material which does not provide structural support while respecting the boundary condition of the complex geometries and the space constraints.
The linkage has a dimension of 3m. This forced the team to develop solutions considering mainly the manufacturing technologies used by CMV that rely on plasma cutting, welding and CNC milling of steel plates and cylinders. Following this perimeter, the initial discussion converged on the redesign of the internal stiffening ribs starting from scratch and adjust the thickness of the plates.

Before optimizing the linkage, the team performed a kinematic analysis of the entire leverage system in order to find the boundary condition in terms of components position and related load. The result permitted to sharpen the CMV's analysis and become familiar with the operation of the system.

The team verified also the compliance of the pin with the highest load (figure 4.0.1 (b)) and the tie-beam as well (figure 4.0.1 (c)). Additional effort was used for the optimization of the tie-beam dimensioning which connects the two linkages.

Process

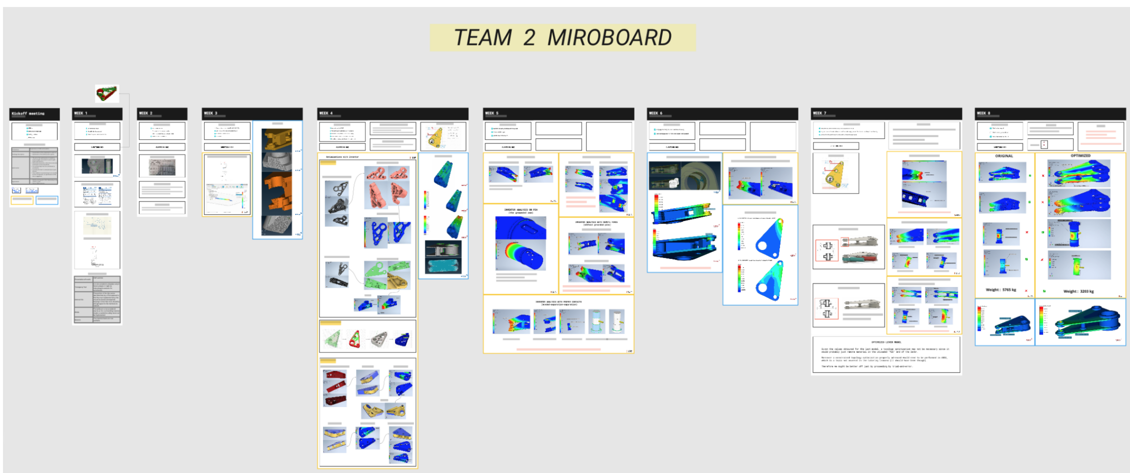

Figure 5.0.1: Work-flow chart on *Miro Board*
https://miro.com/app/board/uXjVOHLl-LA=/?invite_link_id=803767634518

In order to schedule our tasks we planned weekly meeting with the company engineers, Ing. Fabrizio Rossi and Ing. Riccardo Filisetti and the mentor Ing. Silvio Antonioni from HIT. During these meetings we presented our work progression and set the next week's goals. We used the *Miro Board* online platform to gather all the ideas and to presents the results in a work-flow chart (figure 5.0.1), which also helped us during the ice-breaking phase. During the second week we had the meeting at the *CMV* headquarters and visited the plant.
The team has organized into subgroups in order to address more effectively the different tasks, mainly related with different design strategies; we frequently compared results and shared opinions also with our HIT mentor.

We used several software to compute all the needed analysis, also to overcome the timings of *BetaCae* training sessions and avoid non-operational days; namely *BetaCAE ANSA-META-EPYLISIS*, *Autodesk Inventor*, *Autodesk Fusion-360* and *Wolfram Mathematica*.

During the 10 weeks we had 6 main development phases:

1. **Kick-off:** this was the first phase in which we acknowledged the tasks and the initial conditions of

the challenge.

2. **Kinematic and load analysis:** firstly the team performed a kinematic analysis of the original mechanism and we computed the nominal loads applied on the various components. In this phase we refined the data provided by the company.

3. **As-it-is components analysis:** the team performed a static stress analysis on each component in order to understand their behavior and to estimate the margins of optimization. An optimization on the diameters of the tie-beam has been performed at this stage.

4. **Mass-Stiffness optimization:** the team performed several optimizations with mass reduction objective, based on the linkage CAD model provided by CMV, using different configurations in order to highlight the most stressed parts. The first optimization was run without manufacturing constrains in order to verify the "line forces". This process helped us to find the most effective path to follow. After comparing different models we settled on the best compromise in terms of lightening and cost of production.

5. **Final optimization:** we performed many different load analysis with several software, which permitted the team to assess the variation among the different solvers. Once we achieved a satisfying mass reduction, we verified the stresses on the component considering a sufficiently large safety factor (it is not possible to disclose the details).

6. **Report:** the last phase was devoted to wrap up and to draft the report and the presentation of the optimized component.

Initial Conditions

6.1 Load condition

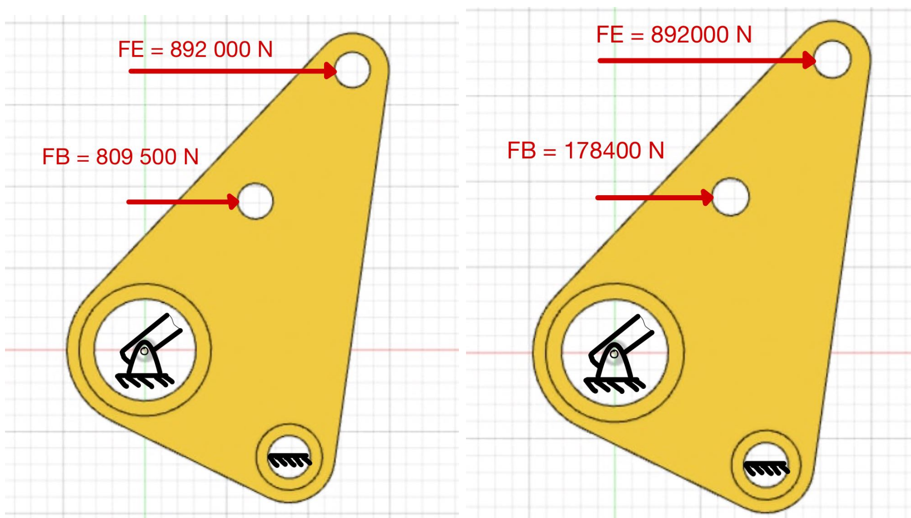

Figure 6.1.1: (a) Initial load condition (b) Final load condition

The first goal of the team was to estimate the loads acting on the linkage, in order to be able to perform a correct optimization. To get started, the company provided us with a very detailed *Microsoft Excel* document that included the pistons applied loads along the entire piston stroke.

The static analysis as been performed considering the maximum load provided by the piston: 140 bar (maximum operating pressure) that generates a force of 892'000 N.

Under typical conditions both pistons work at the same pressure and both linkages move simultaneously in the same manner. In the event of a malfunction there is a safety tie-beam that connects both levers and guarantees a correct operation of the system. The contribution of this element must also be taken into consideration since it exchanges loads with the linkage. The worst condition has been chosen for this load and it refers to the case for which one of the pistons is completely out of service and the tie-beam starts moving stationary linkage (figure 6.1.1 (a)). This situation, despite being the worst, is also unrealistic: in fact there are safety device that stop the system in the event of a pressure drop in one of the two pistons. Therefore, CMV considered the tie-beam load at 20% to be a safe condition to be applied (figure 6.1.1 (b)).

In order to complete the static analysis it was necessary to set the constraints: the housing of the major pin has been modelled as a a revolute joint; considering the friction load induced by the nominal force acting on the billets, the pin connected to the push rod (lowest one in figure 6.1.1) was considered to be fixed.

6.2 Boundary conditions

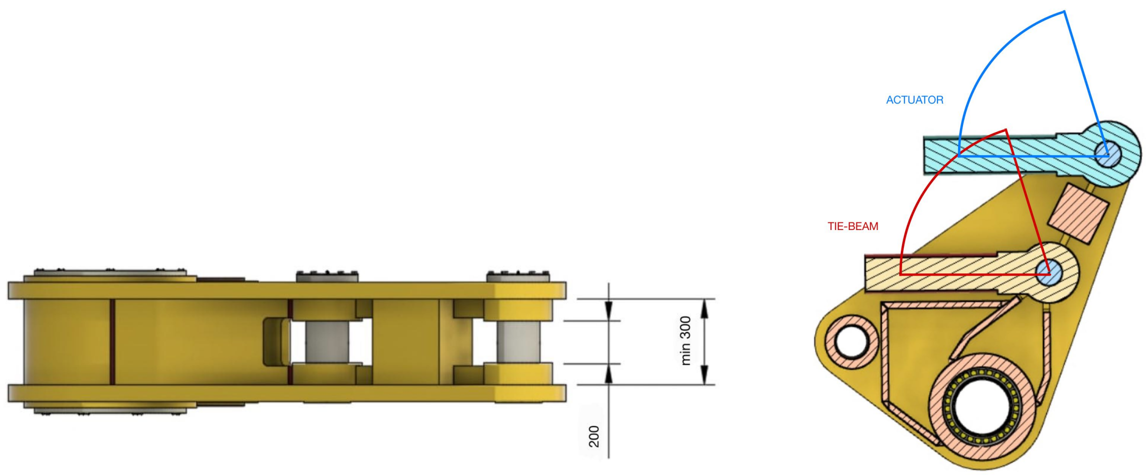

Figure 6.2.1: (a) Boundaries on height (b) Movement range of the piston and tie-beam

The objective is to lighten the linkage as much as possible, while keeping some dimensions unchanged such as the dimension of the pins and the ball bearing housings which depend on standard components supplied by external companies.

The materials have been imposed by the company and are based on their weldability, mechanical characteristics and costs. Particularly, the S275JR steel was used for the linkage and the 42CrMo4 steel for the major pin while the other pins are made of hardened and tempered C45 steel.

The allowable stress are 50 MPa max for the lever and 80 MPa for the pins without considering peaks related to geometrical discontinuities.

Finally, a rather complicated condition has been considered in order to allow at least 200 mm between the two pin shoulders of the piston and the tie-beam bushings. For the same reason the distance between the upper and lower plates must not be smaller than 300 mm (figure 6.2.1 (a)). Furthermore, the movement area of the linked components must not be hindered by the designed structure, figure 6.2.1 (b).

FEA on the initial version of the product

7.1 Mesh

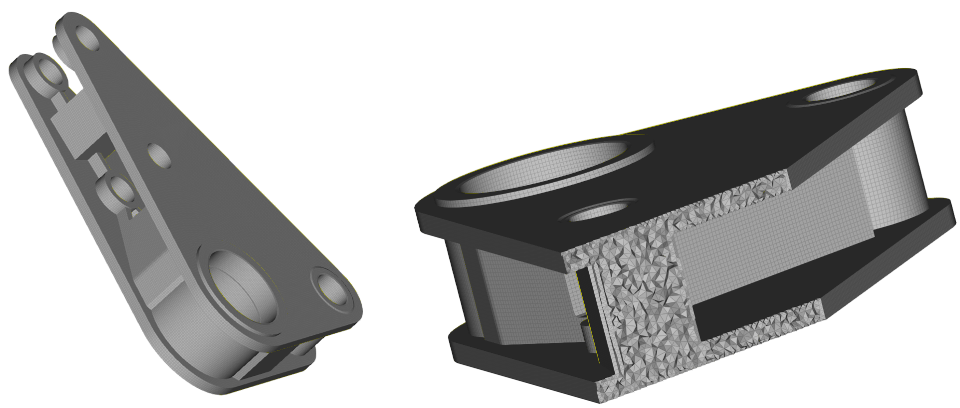

Figure 7.1.1: 2D and 3D mesh of the lever in *ANSA*

In order to understand which areas were the most stressed, we performed a static analysis with a *Finite Element Analysis* (FEA) solver using the CAD model provided by the company.

It was decided to use *ANSA v22.1.0* for the FEA analisys. The team started by defining a mixed 2D mesh with a reference dimension of 15 mm (figure 7.1.1), which turned out to be the most balanced value to obtain a good precision without overloading the hardware resources.
For the same reasons, the 3D mesh was created applying tetrahedral elements of 15mm and a growth factor of 1.2 (figure 7.1.1).

7.2 Static Analysis

The solver *META v22.1.0* was used to perform the static analysis on the ANSA-generated 3D mesh. As a first approximation it was decided to apply a single point load of 892 000 N and an additional load of 20% of the tie-beam load (figure 6.1.1 (b)). Subsequently the bearing load applied was reproduced applying the nominal load through RBE3 elements. The RBE3 element is a powerful tool that provides a distributed connection, which does not influence the local or global stiffness of the model.

The housing of the major pin has been modelled as a a revolute joint. The pin connected to the push rod was considered to be fixed.

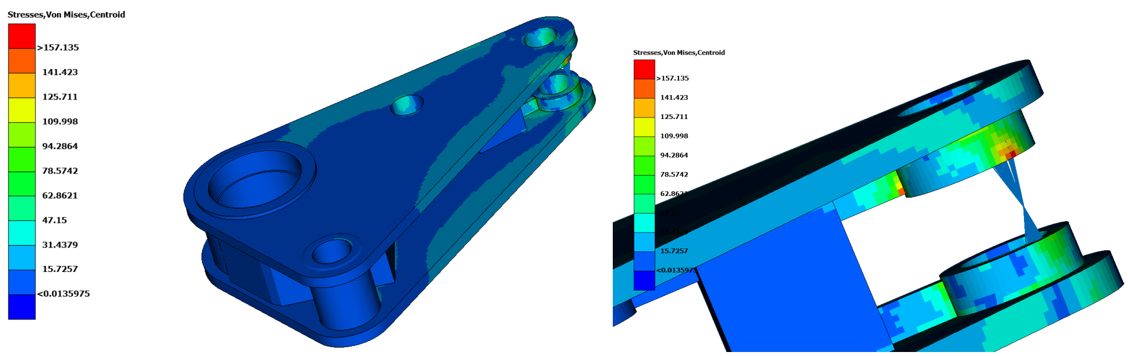

Figure 7.2.1: Static Analysis

The results shows a maximum stress (red points) in a geometric discontinuity while in non-discontinuous areas lower values between 100 and 110 MPa are present. From this first static analysis it was possible to identify the most promising area of improvement in terms of material removal, such as the reduction of the thickness of the two plates.

Topology optimization and other FEA

8.1 Preliminary mass optimization

In order to reduce the mass of the linkage, in accordance with our HIT Mentor, the team decided to start exploring different strategies of optimization with the aim to better understand the different possible solutions. At this stage we worked on three different constraints conditions, exploring the results even if they did not comply with the manufacturing process preferred by CMV and with all the boundary conditions already reported in section 6.2. The aim is to have greater initial design freedom and to let aware CMV about additive manufacturing design potentialities. Starting from the initial conditions in terms of design area and boundary conditions (section 6.1) the team split up into three sub-teams as follows.

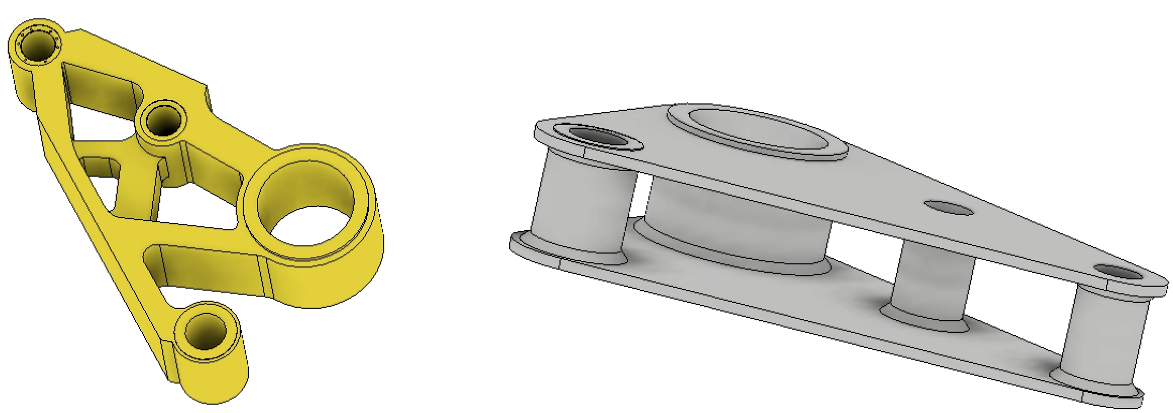

Figure 8.1.1: (a) Discarded optimization (b) Most significant result from the preliminary mass optimization

- 1: First sub-team worked on the more free mass optimization, with the only constraints on the material to be preserved on the 4 pin seats, using the diameters of the original lever. This optimization was very promising in terms of mass reduction (lightest solution) and stiffness optimization but was considered too complex to produce and was discarded (figure 8.1.1 (a)).

- 2: Second sub-team worked on a similar optimization with the additional constraint on the geometry to be preserved on an outer perimeter wall, in addition to the ones of the first sub-team.

- 3: Third sub-team worked on a similar optimization, with the additional constraint on the geometry to be preserved on the two plates, in addition to the ones of the first sub-team.

The most promising solution shown in figure 8.1.1 (b), resulted from the third sub-team, for which only the geometry of the 4 pin seats and of the 2 plates are preserved. This solution shows the best lightening including also an easy manufacturing process limiting material and labor cost.
A static load analysis has been performed for each explored solution. The third solution was considered by CMV to be particularly significant from a construction point of view due to the simplicity of its design. From this point on, we focused on a more detailed optimization of this configuration, with the aim to work on the stress distribution and to the reduction of the maximum displacement.

8.2 Design improvement

In order to reduce the stress on the linkage the team worked jointly with *Inventor*, *ANSA* and *META*, setting the plates thickness to 50 mm. In agreement with CMV , the team designed a slender coupling between the lever and the tie-beam: instead of having a separate pin mounted inside the tie-beam head the team proposed a detachable tie-beam head to be mounted around a fixed cylinder. This solution allows to introduce a structural element, also useful to avoid the separation between the two plates.
In order to reduce the stresses on the linkage, the team decided to bring closer the two plates keeping the height of the 3 pins seats unchanged. The idea was to reduce the load applied by the piston trough the pin and so to reduce the stress due to bending. Considering the minimum distance to be respected between the upper and lower plates, equal to 300 mm (section 6.2), thes span has been set to 320 mm. All these consideration has been included in a new CAD release developed by the team.

8.3 Tie-beam optimization

The tie-beam (4.0.1(c)) has been verified under the most critical conditions (figure 6.1.1(a)). This component has been optimized both for static load and for instability using St.Venant principles and the Euler formulas respectively. In this particular case the instability critical load is higher than the yielding one, so we verifyed to be in a safety area. Moreover we have been assigned a static safety factor $\Phi_Y = 4$ and an instability one $\Phi_i = 3$.
Below a table summing up the optimized dimensions and parameters is plotted.

Parameter	Unit	Original		Optimized
Max. stress (*Von Mieses*)	[MPa]	59	>	50
Yielding stress	[MPa]	200		200
External diameter	[mm]	300	>	273
Internal diameter	[mm]	213	>	170

8.4 Major pin verification

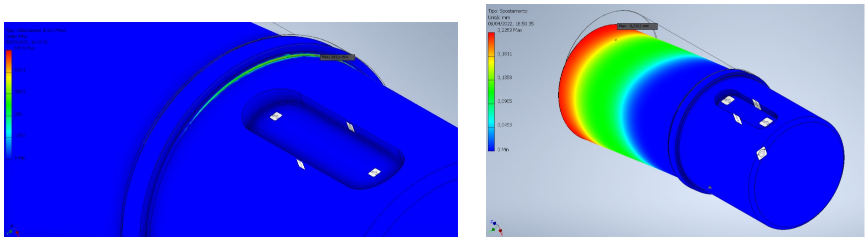

Figure 8.4.1: (a) Stress concentration in the major pin (b) overall displacement

Since we were tasked to verify the compliance of the major pin, we produced a static FE analysis and applied the loads found in the kinematic evolution of the system. In this case the load condition is the one represented in figure 6.1.1(a). The pin resulted to be over-dimensioned, in fact the FEA shows that the load and the displacement are within the allowable limits and hence the pin behavior has been verified (figure 8.4.1(a)(b).

Optimized component

The team worked to design of the final optimal solution based on the previous result analyzed. The CAD picture is shown in Figure 9.0.1.

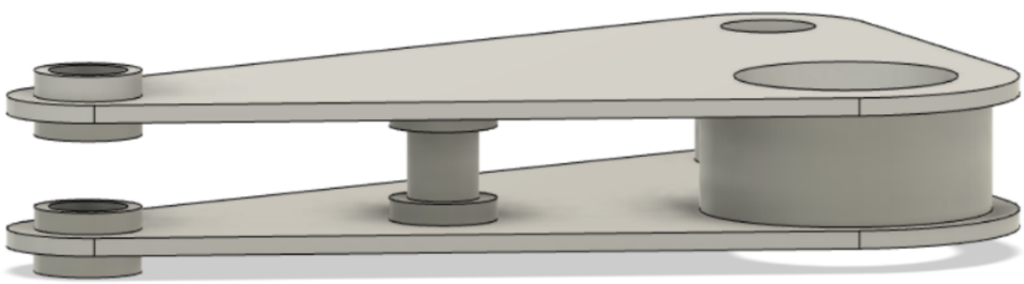

Figure 9.0.1: Final solution CAD.

As a result, the total mass of the lever has been reduced to 3203 kg. Comparing it with the initial linkage proposed by the company (of 5765 kg), the team has **reduced the total mass by 44,5**%. It is a satisfying result, considering that lately the price of the raw material has grown.
Below it's plotted a table which sums up the most important parameters taken into consideration for the optimization, highlighting the difference between the original and final models.

Parameter	Unit	Original		Optimized
Max. body stress (*Von Mieses*)	[MPa]	30	$<$	47
Max. discontinuity stress	[MPa]	61	$>$	53
Max. displacement	[mm]	0.6	$<$	0.9
Mass	[kg]	5 765	»	3 203
N. of components	[-]	18	»	8

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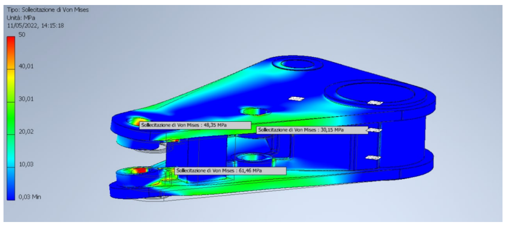
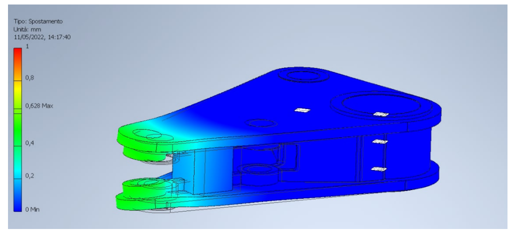
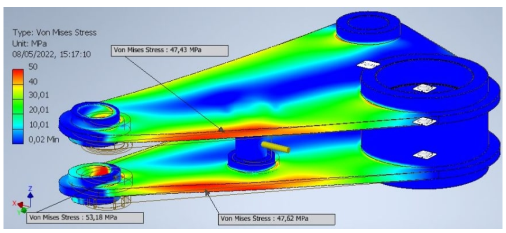
As already stated, the original lever was over-dimensioned, so the stresses computed on the optimized component are slightly higher but within the 50MPa maximum allowable stress and far from discontinuities aand within 1mm displacement as requested by CMV. In figure **??** are plotted the FEA analysis for the original and optimized models



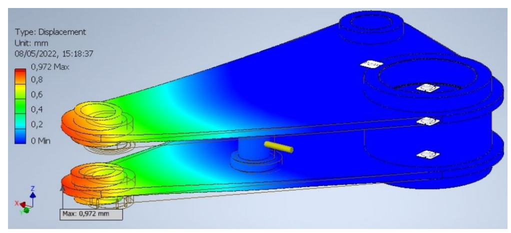
(a) *Original Von Mises stresse*



(b) *Original Displacement*



(c) *Optimized Von Mises stress*



(d) *Optimized Displacement*

Figure 9.0.2: (a) (b) Stress and displacement FEA analysis of the original lever (c) (d) Stress and displacement FEA analysis of the optimized lever

Moreover the team was able to compute the loads and displacements acting on the pin that connects the actuator to the lever. In this case the maximum allowable stress is 80 MPa given the higher performances of the used material.
In this case was able to reduce slightly the stress on the pin (which has the same design as the original one) by reducing the distance between the two plates which induced the reduction of the bending effects. Also in this case a table which highlights the difference between the original and final models is plotted below.

Parameter	Unit	Original		Optimized
Max. body stress (*Von Mieses*)	[MPa]	80	$>$	73
Max. displacement	[mm]	0.6	$<$	0.9

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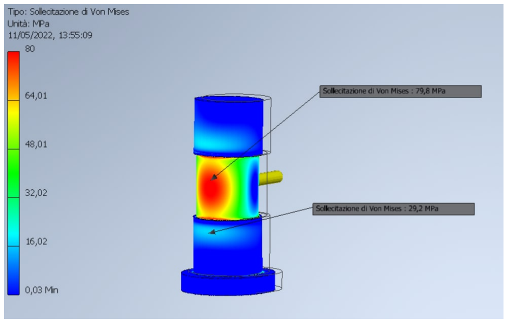
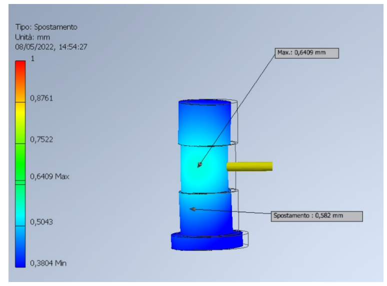
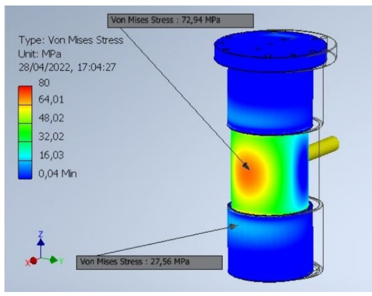
In figure 9.0.3 the FEA analysis produced have been reported.



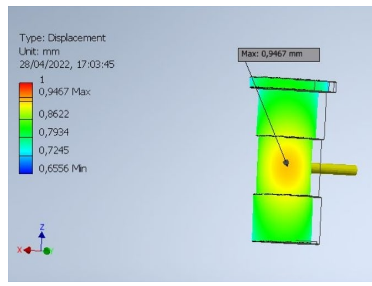
(a) *Original Von Mises stresse*



(b) *Original Displacement*



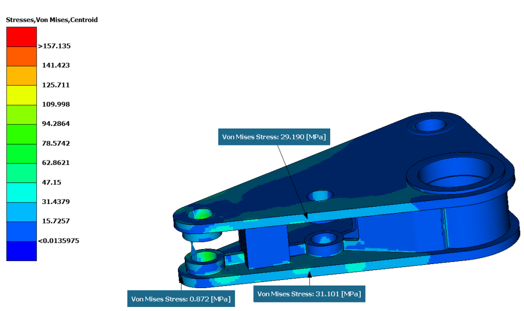
(c) *Optimized Von Mises stress*



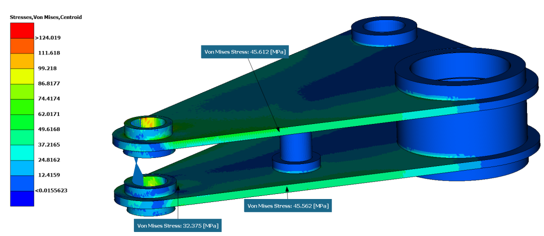
(d) *Optimized Displacement*

Figure 9.0.3: (a) (b) Stress and displacement FEA analysis of the original pin (c) (d) Stress and displacement FEA analysis of the optimized pin

By reaching the goal of 45% mass reduction, the company will be able to obtain significant cost saving due to the high cost of the material used (e.g. steel sheets 2/2.2 €/kg). Another great benefits is given by the total absence of internal ribs, this not only avoids the use of additional material, but also avoids the manufacturing costs related to welding the ribs and bending the metal sheets. In addition to these major benefits it should be noticed that weight saving makes the customer save on sizing the foundations of civil works and the system is easy to handle during manufacturing and transport phases. Finally the stress computation has been verified also in *ANSA* as as shown in figure 9.0.4.



(a) *Original Von Mises stresse*



(b) *Original Displacement*

Figure 9.0.4: (a) Stress FEA of the original lever in ANSA (c) Stress FEA of the optimized lever in ANSA

Encountered difficoulties

One of the major difficulties encountered during the challenge was to work with many constraints at the same time. In fact, from the beginning of the PROTOchallenge various components of the linkage have already been dimensioned and ordered from the suppliers (e.g. piston pin, bearings). Furthermore, since the lever is used in a context where breakdowns are almost not allowed and maintenance is done only once a year, very high safety margins have been required. This strongly affected the optimization of the mass, for which reason some prototypes of the linkage that would have guaranteed greater weight savings were not taken into consideration; an example is shown here below.

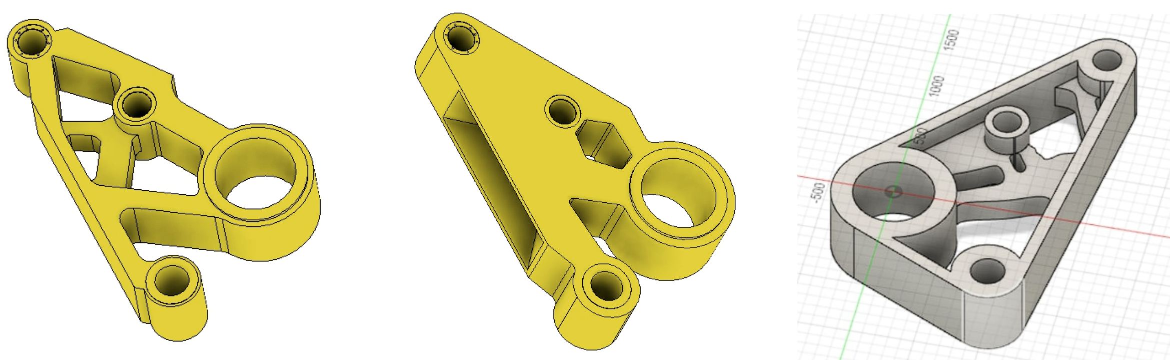


Figure 10.0.1: Three discarded optimizations

We have also used different solvers and hence forced to use different techniques to apply the loads, and we have managed to have several additional meetings in order to work on new development strategies, to find an analysis model that would allow us to compare the results. The training provided by BETA CAE was not scheduled in a optimal manner and we have been forced to study and use different softwares and solvers in order to start working on the challenge. Particularly preference to topological design training which has been delivered almost at the and of the challenge.

Limits and future work

The optimization was successful since reach CMV goal by considerably reducing both the mass and the production costs of the linkage.

Thanks to the work carried out by the team, the company will be more commercially competitive; in fact the geometries that emerged during the challenge will be adopted by CMV in future designs. Unfortunately the company was unable to produce the optimized linkage, as the delivery deadline expired a few weeks ago.

Finally, in agreement with *CMV*, the use of innovative alloys to further contain the weight was not explored mainly due to their stocks and manufacturing constrains. Despite this, the results are more than satisfactory even using relatively standard materials and leave space for future improvements.