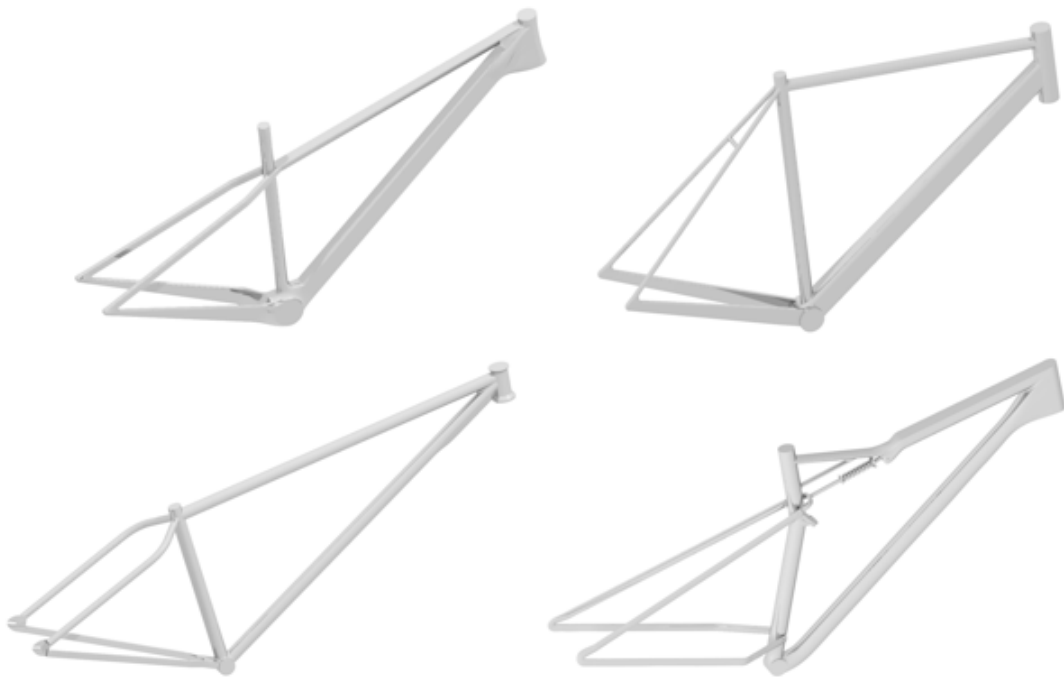


Stress Optimization of Bike Frames

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ABSTRACT

The interest towards design optimization has always been a constant within the industry, and this is the motivation for the accomplishment of this Bachelor Thesis. The purpose of this one is to model and optimize the geometry of four different models of bike frames available in the market.

The project is divided into two segments: design, and stress analysis and optimization. The first consists on the creation of the bike frames in CATIA V5® from the data that the different brands give of their bike geometries. These bike frames must have their nine variables parameterized, in order to be able to change them in a determined range.

The next step is to perform the stress analysis under an external force using also the program CATIA V5® and, by coupling with the multi objective optimization program Mode FRONTIER 2017®, to find out what is the bike frame design with the optimal stress to weight ratio.

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To my parents and sister,

Best crew ever.

David Recasens

To my mum,

Without you this would not make sense.

Juan Brión

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Finally, I want to say thank you to my co-worker in this thesis, Juan Brión, who I have shared so many hours with in the labs.

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Juan Brión

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1. INTRODUCTION

The model of healthy lifestyle and social awareness about the conservation of the environment is causing a boom in cycling, which is leading to a great expansion of the bike market. In an ongoing search of better bike frame designs, the classic methodology of real essays is outdated. The necessities of the industry are converging towards faster and more advanced productivity. This is encouraging increasingly to the companies to use Computer-Aided Engineering (CAE) systems in the design processes previous to prototype testing, involving a notorious reduction of time and costs.

1.1. Computer-Aided Engineering (CAE)

Computer-Aided Engineering is the process of solving engineering problems through the use of sophisticated, interactive graphical software. A CAE system consists on engineering analysis tasks, as for instance, finite element analysis (FEA), computational fluid dynamics (CFD) and multibody dynamics (MBD), as well as, durability and optimization. Any CAE task has three phases which it implements. These tasks are shown at Figure 1:

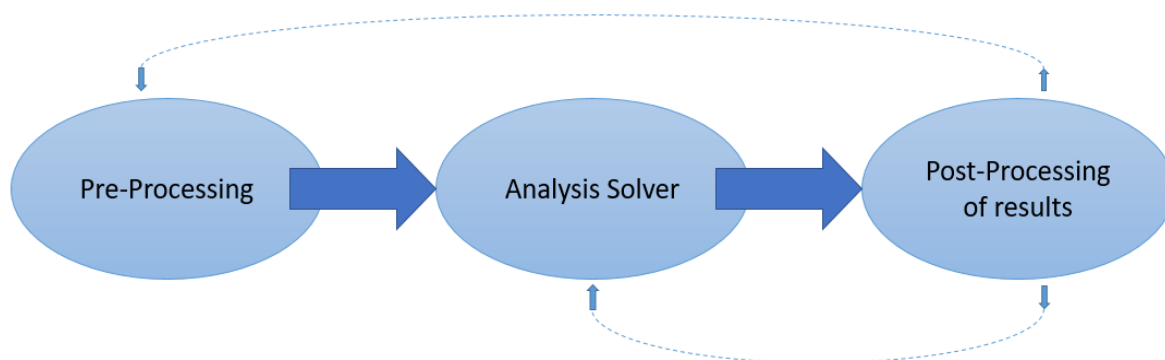


Figure 1: Phases in a Computer-Aided Engineering task.

- Pre-processing: In this first phase of a CAE system, we define the model (geometry and the physical properties) and the environmental factors that we are going to apply on it. It is typical to apply a finite element model. In this project, this phase was developed with CATIA V5®.
- Analysis Solver: This second phase means the use of a, for instance, FEM program, optimization program, and so on. The model is solved using an appropriate mathematical formulation of the underlying physics.
- Post-Processing of results: Once we have all the information needed after implement the design model in different programs to get a better design, we must review it carefully and take decisions.

At Figure 1, we can see how, from the third phase, two lines that go to the first and the second phase. This means that after getting the results and studying them, we have to decide if the model is good enough or if we have to modify something from it in order to get other results.

Another affair is that the model could be done, but we need to modify something according to the variable or, on the other hand, something related to the algorithms used for the solver.

Nowadays the CAE systems are fundamental in the process of creating a product for a company. This is because CAE systems can reduce the time needed to develop new product and increase productivity by optimizing production flow and scheduling. It also provides great flexibility in altering machine operations.

The benefits of CAE include reduced product development cost and time, with improved product quality and durability. We can summarize the benefits of CAE in the following points (Siemens, 2018):

- CAE helps engineering teams manage risk and understand the performance implications of the design that were done.
- Designs can be evaluated and refined using computer simulations rather than physical prototype testing, saving money and time.
- CAE can provide performance insights earlier in the development process when the design changes are less expensive to make.
- CAE can enable earlier problem resolution, which reduces the costs associated with the product lifestyle.

In the case that concerns our bike frames, everything starts with the problem statement, achieve the design with the best stress to weight ratio. In order to accomplish this objective, it is necessary to make a first approximation of what you want to create through hand sketching, determining the measures to be used. Once you have this, it is the turn to build the CAD design, with CATIA V5® for this thesis. But, we have to take into account that the frame variables must have some flexibility, thus the CAD model has to be able to adapt to the new characteristics through the insertion of parameters if the input parameters change. The next step is to implement the FEM analysis and thanks to the program CATIA V5® itself has a workbench with this finality, no another program is required for this task. Arrived at this point is when the optimization process starts. This aspect is carried out by a program, called Mode FRONTIER 2017®, which is able to simulate hundreds of designs so as to facilitate the task of selecting the best geometry. Finally, it only remains the realization of a prototype and its testing to real efforts.

1.2. Optimization

One of the simplest definitions of optimization can be the one said by Alberto Pérez-Gómez: "Optimization is doing the most with the least".

Optimization was first seen around the year 300 bc. by Euclid or Zenodorus with the Did's Problem. These optimization problems developed by the Greek mathematicians were related to geometrical studies. Over time, these researches were improving but it was not until the 17th and 18th century where these optimization problems started changing.

A big change was the creation of the mathematical analysis that forms the basis of Calculus of Variations (CoV), developed by I. Newton in 1660s. This continued over years until these days, where the optimization is one of the most important things in a product (Mitrikitti, 2018).

In this project we have to work with a topological optimization. For this, we used tools that integrates some of the calculations that previous people studied to achieve different goals.

We can divide a structural optimization problem in three different classes: (An Introduction to Structural Optimization, 2009).

- Sizing optimization: this type of optimizations changes the thickness distribution of the structure.
- Shape optimization: In this optimization, what changes is the boundary of the structural domain. The optimization consists in choosing the integration domain for the differential equations in an optimal way.
- Topology optimization: This is the most general case in an optimization problem. In this type, the material takes the best place where the conditions of the structure do not change. This is always made by the performance under loads and boundary conditions.

A general structural optimization problem usually takes the form:

$$(SO) \quad \left\{ \begin{array}{l} \text{Minimize } f(x, y) \text{ with respect to } x \text{ and } y \\ \text{Subject to } \left\{ \begin{array}{l} \text{Behavioral constraints on } y \\ \text{Design constraint on } x \\ \text{Equilibrium constraint} \end{array} \right. \end{array} \right.$$

- Objective function (f): it is a function used to clarify designs. f measures weight, displacement in a given direction, effective stress or even cost of production. For every possible design, f returns a number which indicates the goodness of the design.
- Design variable (x): it can be a function or a vector. It describes the design and can be changed during the optimization. It may represent geometry or choice of material.
- State variable (y): is a function or vector that represents the response of a given structure. In a mechanical structure (which is the report case), the response means displacement, stress, strain or force.

As our problem is a topology optimization problem we can write the general form but with the usual equations that are used.

$$\text{Minimize } x : F = F(u(\rho), \rho) = \int_{\Omega} f(u(\rho), \rho) dV$$

$$\text{Subject to: } G_o(\rho) = \int_{\Omega} \rho dV - V_o \leq 0$$

$$G_j(u(\rho), \rho) \leq 0 \quad \text{with } j = 1, \dots, m$$

In this case, the equations are made by the following elements:

- $F(u(\rho), \rho) \rightarrow$ Objective Function. It is described by the density of the material at each location $\rho(u)$.
- $(\Omega) \rightarrow$ Design Space. It indicates the allowable volume within which the design can exist.
- M constraints $G_j(u(\rho), \rho) \leq 0 \rightarrow$ Is a characteristic that the solution must satisfy.

1.3. Importance of optimization

Engineering optimization forms key part of the success of 21st-century technology (Schilling, 2018). This is due to optimization techniques let bring the characteristics of a product to the extreme, chasing perfection. The optimization means for a company improved design elaborations, manufacturing processes and products, which in turn results in a better use of available resources. In short, it is in this current world so extremely competitive where knowing how to waste the least possible while always looking for the best result is a sign of success

2. METHODOLOGY

The followed path to perform this project was raised for the first time in the beginning of the project through a Gantt, chart but the real way was adapted to the circumstances and the adversities founded. All these aspects are reunited in Course of Action section. In addition, an explanation of the used programmes in this thesis, CATIA V5® and Mode FRONTIER 2017®, is described in the software section.

2.1. Course of Action

The three phases mentioned before are the line action of this thesis.

The first thing we did to achieve this Bachelor Thesis is to have so clear the idea we are going to elaborate. As the main topic of the thesis is to optimize different bike frame, to optimize them you must know what you want to optimize and how are you going to do it. That means what are the things you are going to change to get that good optimization. Also, while we decide the parameters we want to change, we have to talk with several companies to see if they can help us. This is because they only have the common and simple geometry of the bike for the public.

Knowing this is a fact that you can model the frame in a CAD program, but not as the real one, if we are talking with the whole possible fidelity.

The second thing we do, to be able to achieve this Bachelor Thesis, is to become familiar with all the software we use in this case. This thesis uses two software, CATIA V5® and Mode FRONTIER 2017®. Firstly, and more important, we must know how CATIA V5® works. Even though the main task of the project is the optimization, if you do not have a good design to optimize, you cannot even use it, because it will be for nothing and you will not be able to use the results you obtained because they are not real at all.

Once we have all the four bike frames modelled, it is time to start analyzing these frames and then optimizing them. The analysis of the frames is made with CATIA V5® as well, but is not as complicated as the model because it is not so complex.

The third, and we could say last phase, is the optimization part, which is made with Mode FRONTIER 2017®. First of all, we have to know how this software works and get on well with the interface. Once we have the optimized structures, we have to check them and see if they are feasible or not. In the case they are not good, we must change the original model and make another analysis, as well as another optimization.

Once we have all the results, we can start doing the report. This last part can also be done while the process of the three phases is carrying on, but until you do not have all the information structured, you cannot “assembly”.

At the beginning of the thesis, a Gantt chart (Figure 2) is done to make an estimation of the work project we have to do and in the dates we have to complete these tasks. This is just an estimation and it can have variations during the project.

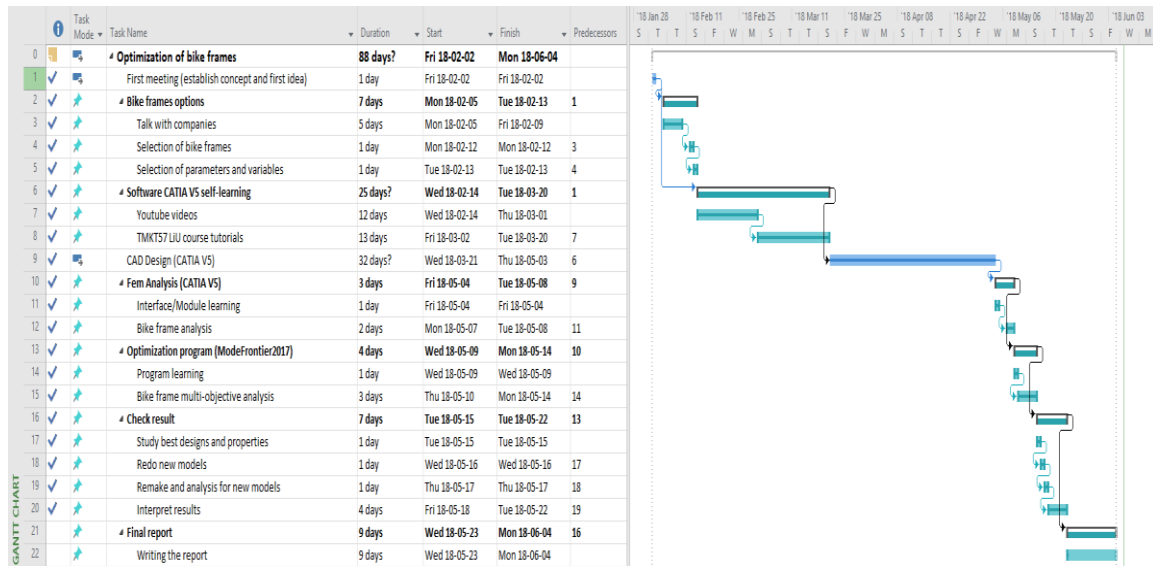


Figure 2: Process Gantt chart.

2.2. Software

2.2.1. CATIA V5®

In the course action we could see that a specialized software is required to make this thesis. In order to perform 2/3 parts of the project we used CATIA V5® (Figure 3). This software was chosen after someday watching pros and cons in comparison with another CAD software, as PTC Creo Parametric®. At the end we concluded that, in part because our supervisor domains this software, we saw that CATIA V5® gives you a lot of freedom and it makes you so flexible.

We used it, as well as to model the frames, as to analyze them once they were done. As we know, CATIA V5® has several workbenches that you can use. We saw that the module of the analysis was so intuitive and easy to use. Another thing is that for the analysis needed in this thesis, the module of CATIA V5®, Generative Structural Analysis, was enough.



Figure 3: CATIA logo (Dassault Systèmes, 2017).

2.2.2.MODE FRONTIER 2017®

Mode FRONTIER 2017® was the software for the optimization which we decided to use. As well as for CATIA V5®, we were thinking in different types of optimization software, but with the help of our supervisor, we finally decided to use this as our software.

Mode FRONTIER 2017® is a software that gives you too much flexibility, this means that you can work with the parameters you want. Once the optimization is done, its interface is so simple and easy to understand, as well, as the information given by it.

The program is based in three buttons where you have all the information the user needs.

- Workflow: is where you put the file you want to optimize, the properties for the optimization and the variables/parameter you want that the program works with.
- Run analysis: you can see how the implementation is going and which optimized models are good or not. You can also see several plots according to the inserted file.
- Design Space: you can see the first values the program need to start the optimization. While the optimization is running, it can be seen the new values for the optimized designs in tables, as well as several plots of that new values of the new designs.

In Figure 4 we can see, how Mode FRONTIER 2017® works, in a small and simple way.

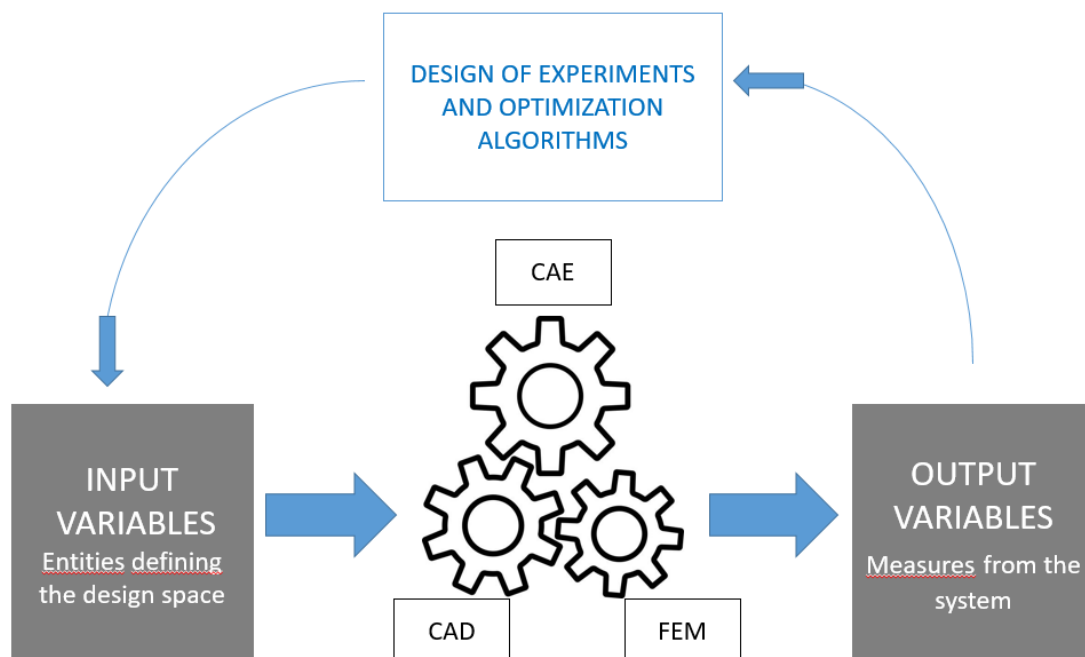


Figure 4: Mode FRONTIER 2017® integration and process automation (adapted from Esteco Mode FRONTIER, 2018).

3. BIKE FRAMES DESIGNING WITH CATIA V5®

3.1. Data collection

First of all, it is necessary to collect the values of the nine variables (designated at Figure 5) of each bike frame in order to build the basic geometry. These data can be found at the respective official web pages of each bike brand always selecting M frame size: Canyon MTB (Canyon, 2018), Canyon Road (Canyon, 2018), Dirt Love (YT Industries, 2018) and S Works Epic (Specialized, 2018). These values are represented in Table 1.

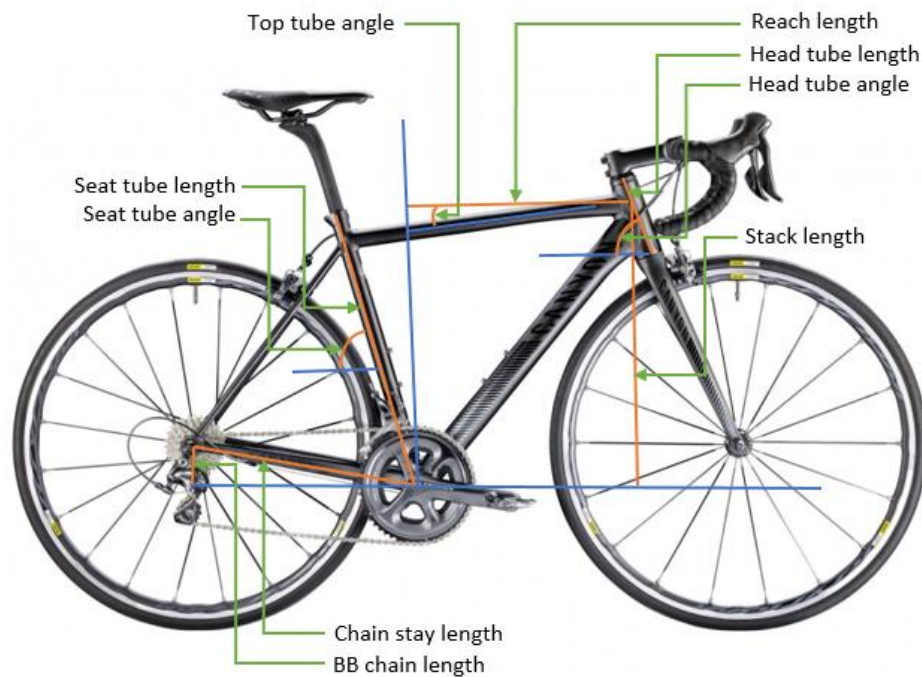


Figure 5: Bike variables (bike photo from Canyon, 2018).

Table 1: Basic geometry data.

	Canyon MTB	Canyon Road	Dirt Love	S-Works Epic
Horizontal top angle [deg]	30	9	28	28
BB chain length [mm]	63	61	22	38,9
Chain stay length [mm]	437	415	376,636	435
Head length [mm]	100	157,5	60	95
Head tube angle [deg]	69,5	73,25	69	69,5
Seat tube length [mm]	440	530	313,8	434
Reach length [mm]	425	391	404,583	433
Stack length [mm]	611,3	567	563	597
Seat tube angle [deg]	74	73,5	62	71

In some bikes the values do not appear, such as BB chain length or horizontal top angle. Therefore, they are calculated based on other geometry characteristics given or through approximation using a size comparison method (Appendix 1).

The modelling of the four bike frames has been carried out in parallel, David Recasens has developed Canyon MTB and Canyon Road and Juan Brión has performed the Dirt Love and the S-Works Epic. Due to this, each one has followed his own design method. In the following headland, the followed methodologies to accomplish the bike frames with CATIA V5® will be explained.

3.2. Canyon MTB modelling

This was the first bike frame designed (real bike frame at Figure 6), which carried a high amount of trial and error. First of all, we tried to perform it in Part Design workbench but the impossibility of getting an acceptable quality of finishing touches, disappointed us. This problem can be visualized with the comparison of a previous frame bike model which was discarded (Giant Propel Advanced) and the quality reached with Part Design (Figure 7).



Figure 6: Canyon Exceed CF SLX 9.0 Pro Race LTD frame (Canyon, 2018).



Figure 7: Axis zone of Giant Propel Advanced in: a) Reality (H2Gear, 2018). b) CATIA V5®.

Other option was to use Imagine and Shape Design workbench, where is possible to get a great fidelity in the hardest parts of the frame. But, the impossibility of parameterization made us to reject this option.

The final decision was to choose Generative Shape Design workbench due to let us to accomplish better details in the connections between tubes and, also, it is possible the parameterization. This is precisely the core aspect with which we started the modelling. First step was to create the basic geometry of the frame so that it could be able to change any variable thanks to the parameters. This was performed by the creation of the points in a reference plane which define the basic geometry (Figure 8).

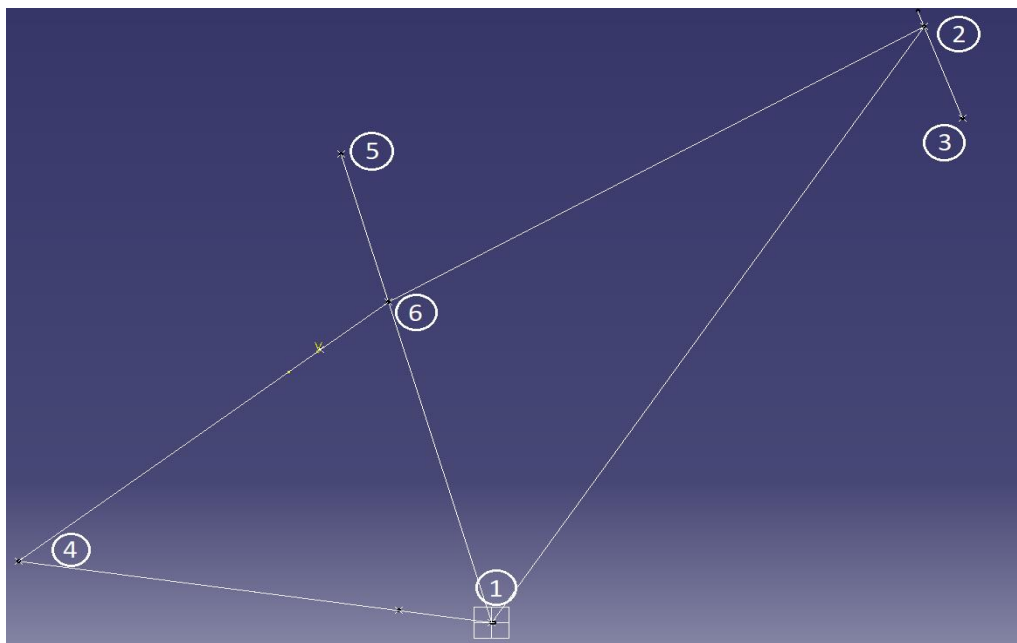


Figure 8: Basic geometry defining points.

The vertical and horizontal coordinates of each point are explained at the following Table 2:

Table 2: Basic geometry points coordinates.

	Reference	Horizontal	Vertical
Point 1	Origin	0	0
Point 2	Origin	`Reach length`	`Stack length`
Point 3	Point 2	`Head length` · cos (`Head tube angle`)	-`Head length` · sin (`Head tube angle`)
Point 4	Origin	$\sqrt{(\text{Chain stay length})^2 - (\text{BB Chain length})^2}$	`BB Chain length`
Point 5	Origin	-cos (`Seat tube angle`) · `Seat tube length`	sin (`Seat tube angle`) · `Seat tube length`
Point 6	Origin	1	2

$$1 = \frac{\text{'Point 2 vertical'} - \tan(\text{'Horizontal top angle'}) \cdot \text{'Point 2 horizontal'}}{\frac{\text{'Point 6 vertical'}}{\text{'Point 6 horizontal'}} - \tan(\text{'Horizontal top angle'})}$$

$$2 = \frac{\text{'Point 6 vertical'}}{\text{'Point 6 horizontal'}} \cdot \frac{\text{'Point 2 vertical'} - \tan(\text{'Horizontal top angle'}) \cdot \text{'Point 2 horizontal'}}{\frac{\text{'Point 6 vertical'}}{\text{'Point 6 horizontal'}} - \tan(\text{'Horizontal top angle'})}$$

The point 6 coordinates have been calculated through the intersection of the line equation defined by the points 5 and 1 (origin):

$$y = \frac{\text{'Point 5 vertical'}}{\text{'Point 5 horizontal'}} \cdot x$$

And the line that starts at point 2 with an inclination equal to 'Horizontal top angle':

$$y = \text{'Point 2 vertical'} + \tan(\text{'Horizontal top angle'}) \cdot (x - \text{'Point 2 horizontal'})$$

The second step was to make the tubes using the most appropriated tool *Extrude*, *Sweep*, *Adaptive Sweep* or *Multi-Sections Surface* (Figure 9).

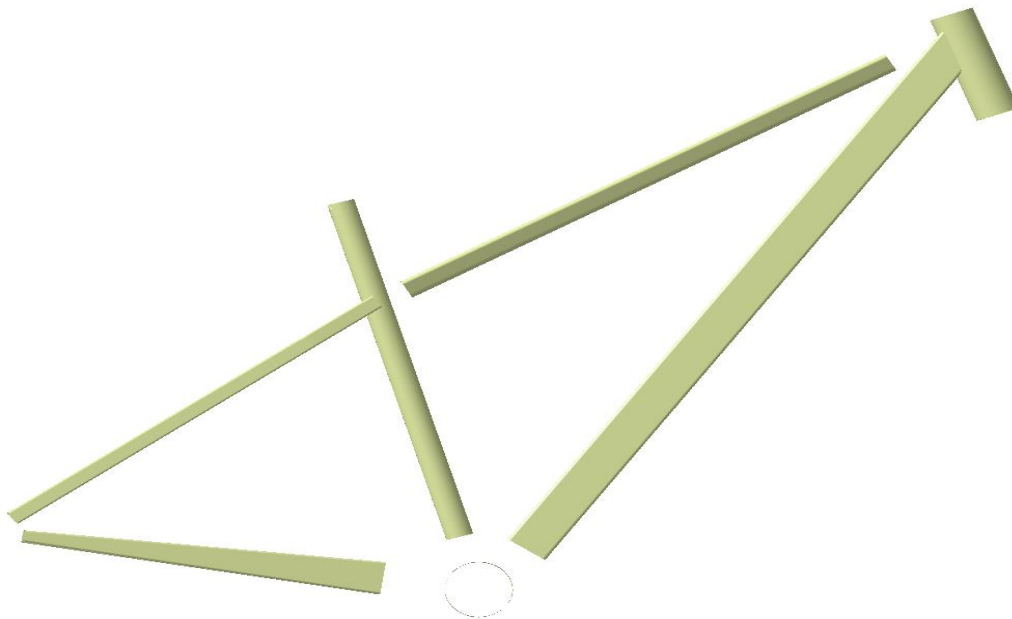
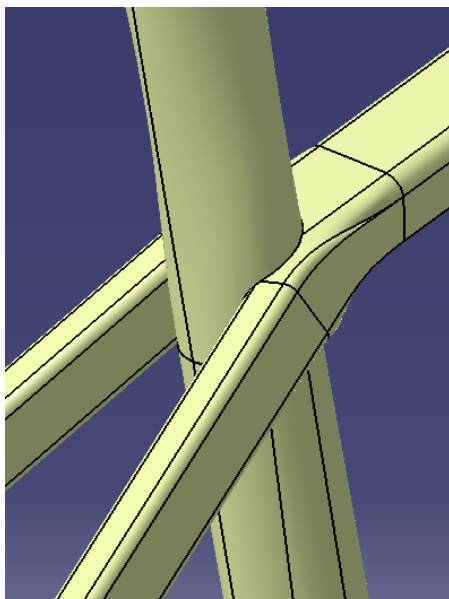
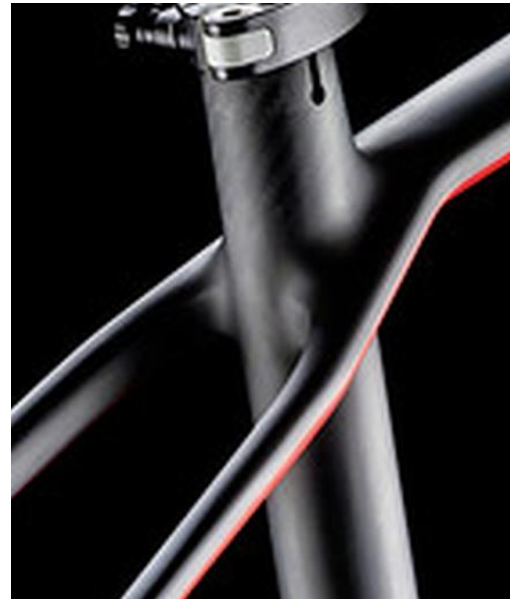


Figure 9: Tube of the Canyon MTB.

The last task, and the hardest, was to accomplish the connections between the tubes with the enough quality level to be representative of the real bikes. This was achieved through the application of *splines* and *fills* which should be able to adapt to the geometry when this changed, and it is here precisely where biggest amount of time was wasted. This is due to when the geometry changes, the splines orientation changes and can induce a complex perimeter that the fill cannot resolve. In addition, the orientation and intersection between tubes changes and this may provoke that the splines and fills definitions, which worked before, do not work after, becoming an arduous task of trial and error. Some simplifications had to be done due to the limitations of the workbench, nevertheless the result is quite satisfactory as can be seen in the followings comparisons.

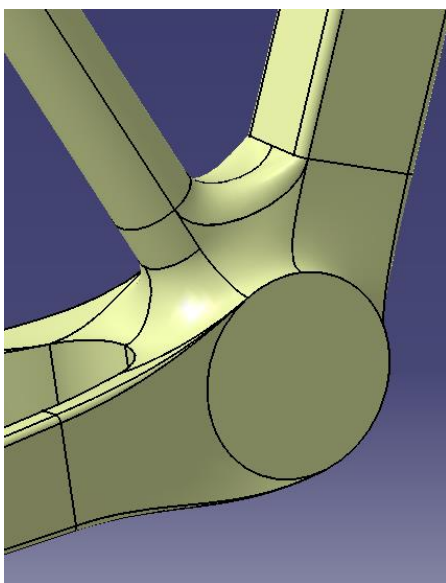


a)



b)

Figure 10: Seat tube intersection in: a) Modelled frame. b) Real frame (Canyon, 2018).



a)



b)

Figure 11: Axis intersection in: a) Modelled frame. b) Real frame (Canyon, 2018).

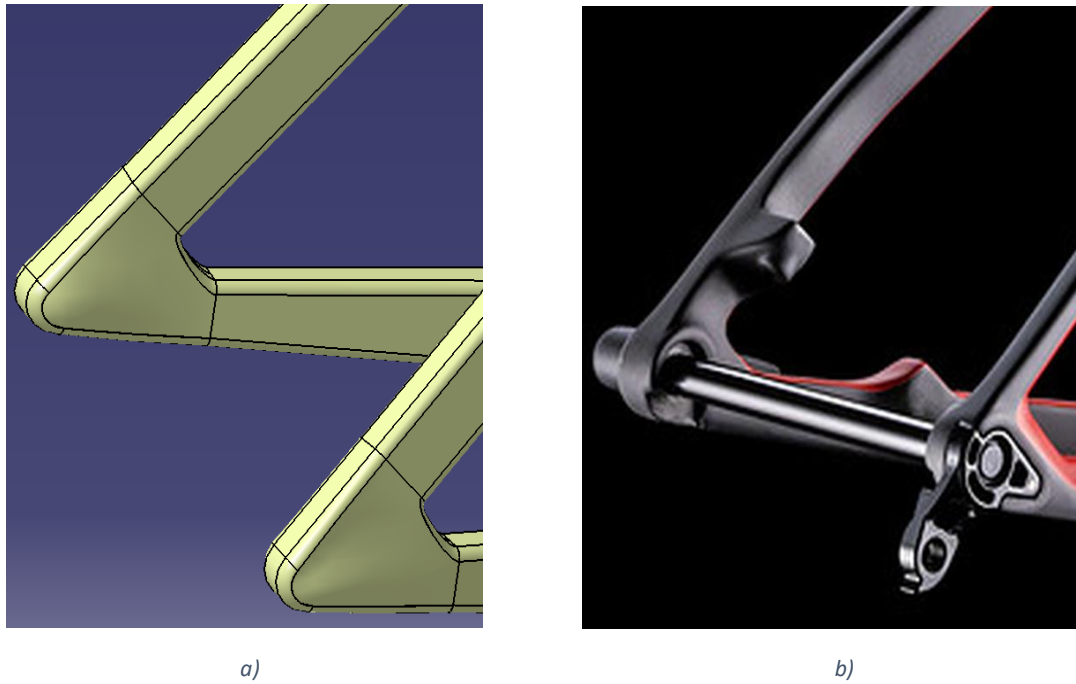


Figure 12: Rear wheel axis intersection in: a) Modelled frame. b) Real frame (Canyon, 2018).

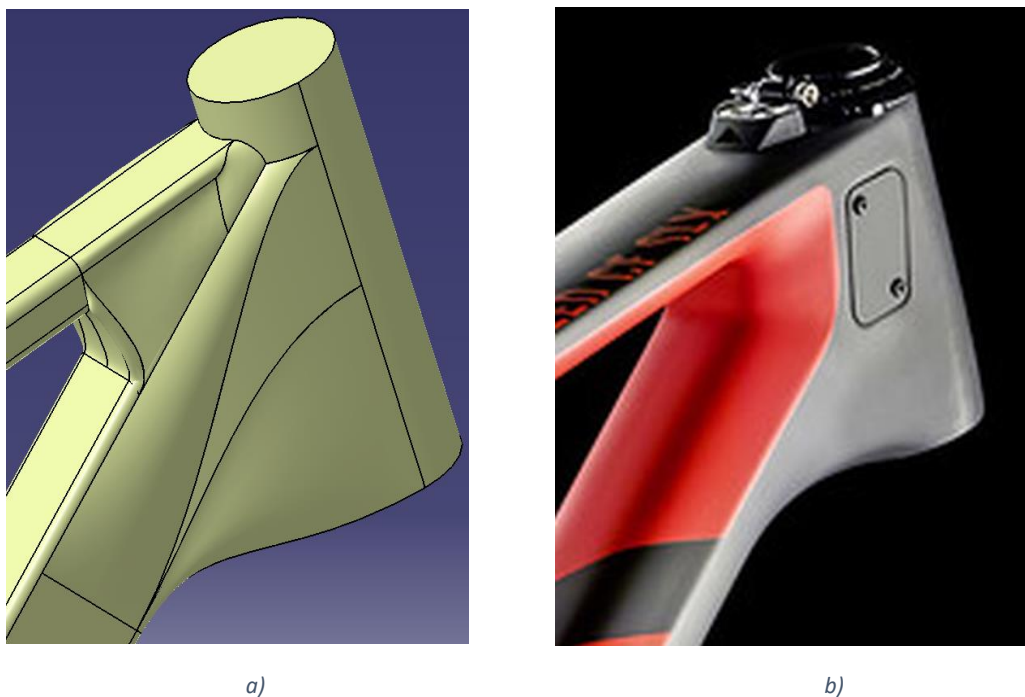


Figure 13: Head tube intersection in: a) Modelled frame. b) Real frame (Canyon, 2018).

Once the surfaces were done, we did individual *Joins* or *Healings* for each closed part to be able to use the tool *Close Surface* in Part Design workbench in order to turn them into solid. Some problems appeared with the axis and the head tube when this method was applied and the geometry changed, apparently, some little hole emerged. This annoying issue was solved building a big solid *Extrude* that covered the closed surface of the part and, then, using the tool *Split* in Part Design workbench create the solid part. Another problem arose from the fact

that this trick cannot be implemented more than once in a Body, and the answer was to do this method in separated Bodies. But in order to execute the analysis is compulsory to have the whole solid bike in Part Body, so we extracted the global surface of the whole solid bike with the tool *Extract* presents in Generative Shape Design. After this, we made a *Healing* of the obtained and we repeated the method of the *Extrude* plus *Split* obtaining the whole solid bike in Part Body (final result at Figure 14).

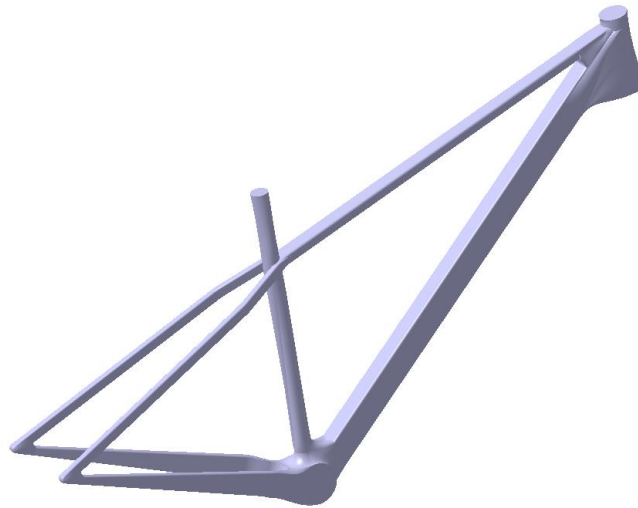


Figure 14: Canyon MTB modelled.

3.3. Canyon Road modelling

This bike turned out to be less time waster than Canyon MTB, in part as we could apply our previous knowledge to model the bike frame and use the calculations to create the basic geometry. Furthermore, the Canyon Road frame is notoriously simpler as can be seen at Figure 15.



Figure 15: Canyon Ultimate Al SLX frame (Canyon, 2018).

We performed exactly the same calculations that in Canyon MTB to set up the basic geometry. The tubes were created with the tools either *Extrude* or *Multi-Sections Surface* in Generative Shape Design workbench. The connection between seat stay and chain stay tube were made with *Spline* and *Fill*, following the same way as in MTB Canyon. Once the global surface was made with *Healing*, to fill little possible holes, the whole solid bike was produced using the method of *Extrude* and *Split*. In this case, it was not necessary to do separately solids since the connections between tubes is quite easier and they did not require to do *Splines* and *Fills*, just with the tool *Face-Face Fillet* was enough. This avoided that the frame model broke due to little holes or surface intersections when the geometry changed. The final result appears at Figure 16.



Figure 16: Canyon Road modelled.

3.4. YT Industries Dirt Love modelling

This is the first bike created by the hand of Juan Brión. It is not the most difficult one if we compare it with the complexity of the Specialized S-Works Epic. It is all made in the module of Part Design. The comparison between the real bike frame with the one which was modelled can be seen in the following pictures.

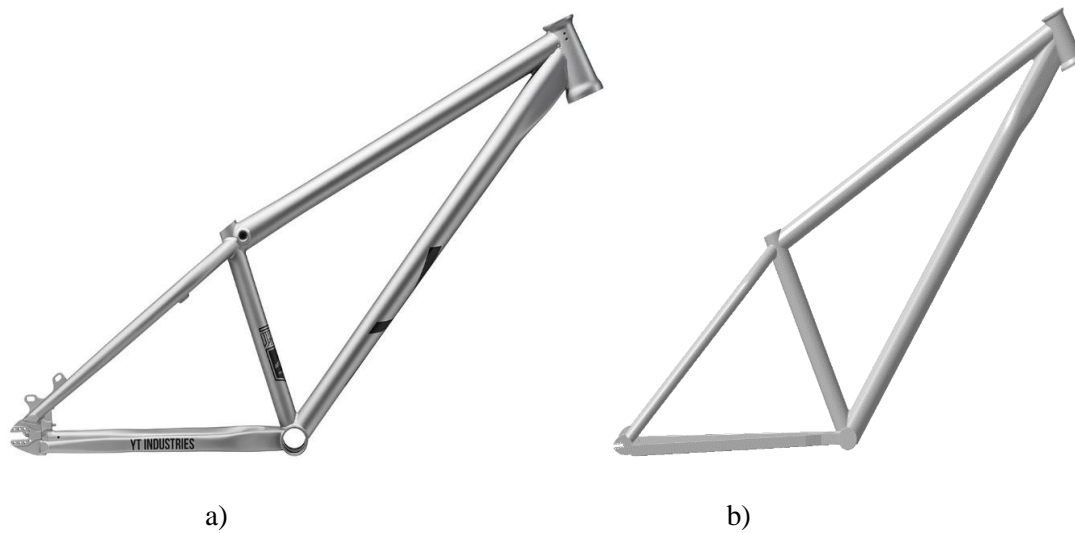


Figure 17: Dirt Love: a) real frame . b) modelled frame.

The first step we accomplished to get the structure of this frame bike is to make the general sketch of the basic geometry (given in the main page of the bike brand). We can see the basic geometry in the next figure.

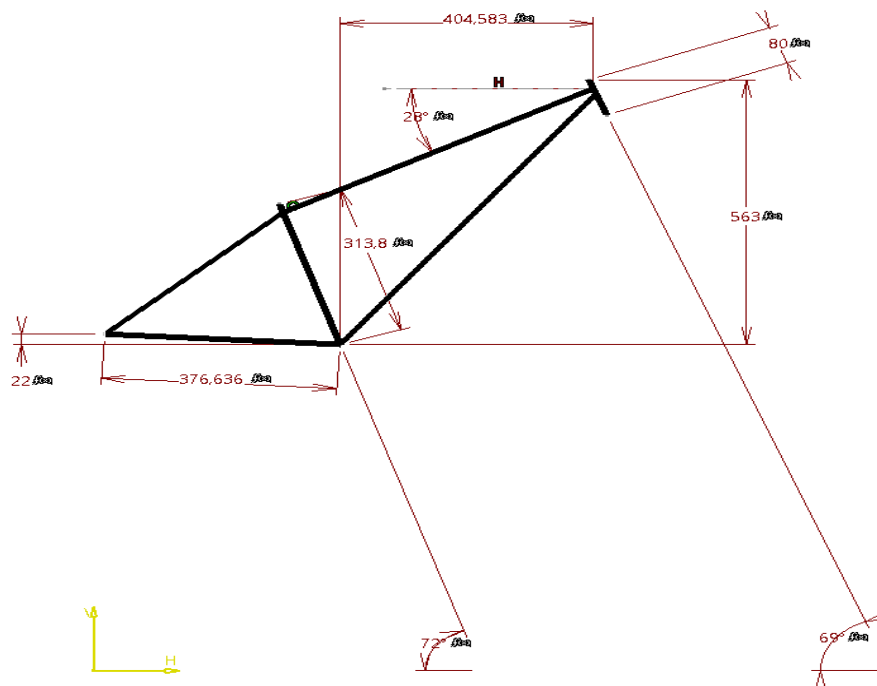


Figure 18: Basic geometry with the defined points.

As we can see all the lines are parametrized, so if we change any parameter, the whole structure will modify. With this basic and principle sketch, we cannot make any pad, rib or something like these options to get the tubes. What we did to achieve this is create different sketches for each line. With this we will be able to create any tube independently. But as the whole structure must be modify at the same time we should have put any condition to these little sketches. What we did is to make the line of the little sketch coincidence with the line of the principle sketch. As we make a coincidence between lines, in multiple occasions we had to coincidence points as well.

Doing this is like we were multiplying the basic structure, but now we have every line in an independent sketch, so we can manipulate with the options of *Sketch-Based Feature*.

For this bike we did not have too many complications because, as we can see, it has not a very complex structure. The most difficult parts to model were the “belly” the bike has in the diagonal tube and the elements that attach the back wheel.

To achieve the “belly” we used the option of *Multi-Sections*. What happened is that we could not know which the dimensions of that part of the structure were (as the diameters of the tubes), so we did it trying to look the same as the one in the photo, and we think we got it.

As we said, we did not know the measures, so we had to think how to achieve that form. And the best way to did it is thinking in an easy way. As we can see the top part is always a straight line during the whole tube, while the bottom part changes at a determined point. This means that the top part must continue being a circle, but not the bottom which is larger than a circle. Once you see this, the way to create that surface is not so difficult.

When we used the *Multi-Sections* we used the option *Coupling*. Instead of doing the splines to use them as guides, we preferred to create some points in the geometry and use them as the points for the coupling which delimit the section. This can be seen in Figure 19 and Figure 20.

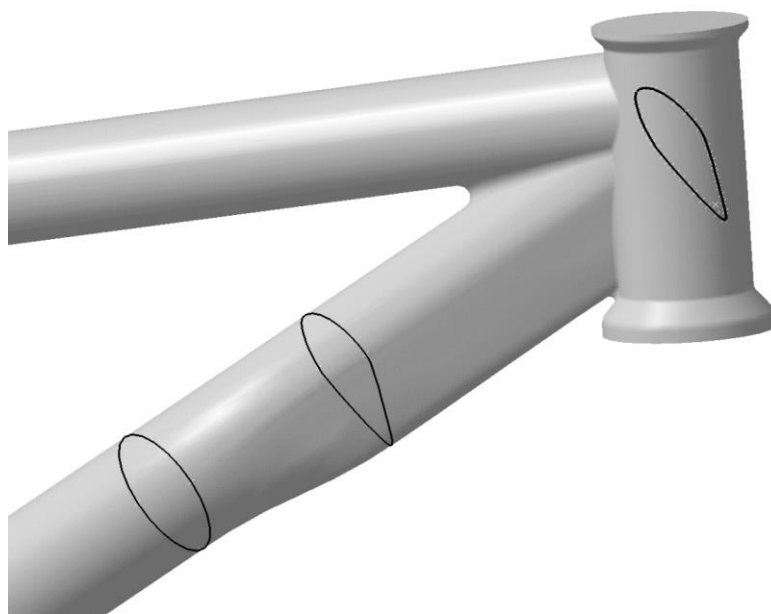


Figure 19: "Belly" shape sketch.

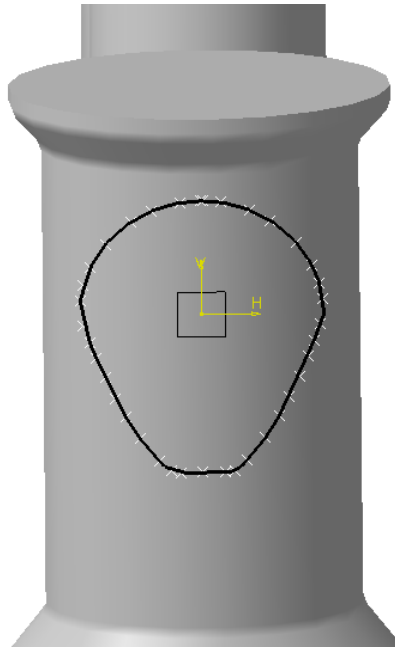


Figure 20: Front view of the "belly" sketch.

The other difficult thing from this bike was the back part, even though the complexity was not that much. How we created these two elements can be seen in the next figure, where we can see the sketches of each part. For the two tubes, we used a *Rib* after creating a new plane getting the direction needed. For the bottom part we used a *Pad* after a sketch done by a plane creation with the lines of the chain stay direction. This is shown in Figure 21.

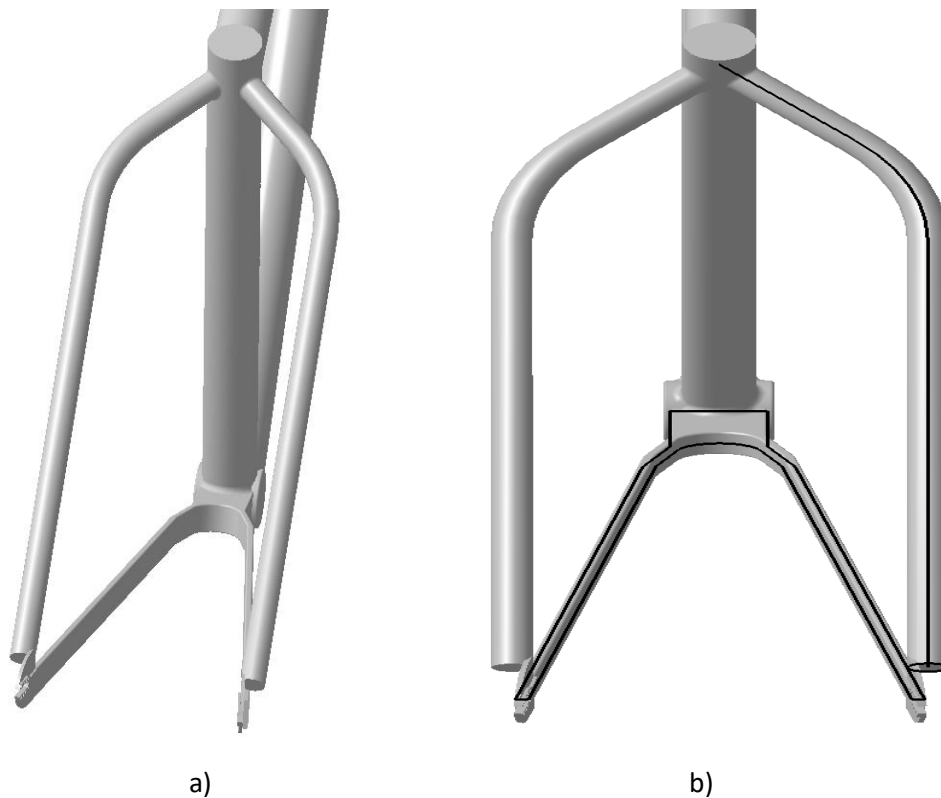


Figure 21: Frame's back part: a) Back part of the frame. b) Front view of the back part and its sketch.

The two elements that attach the back wheel were one of the difficult things to model. Because the difficult thing is that is not just to model them, the fact is that when we change the parameters, these two elements must move if the tubes move.

We had to create some planes to try just the element look like is inside the other 2 elements, but at the same time.

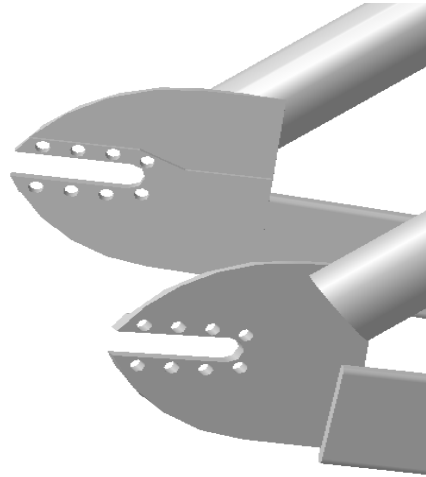


Figure 22: Elements that attach the back wheel.

3.5. Specialized S-Works Epic XTR Di2 modelling

This bike frame was a big challenge to model because of its weird geometry and different shapes. After start modelling in CATIA V5®, we spent two days searching the best and the easiest way to make the frame, as we saw that it was not only straight tubes. The real frame and the modelled one can be seen in Figure 23 and Figure 24, respectively.



Figure 23: Specialized S-Works Epic XTR Di2 real frame.

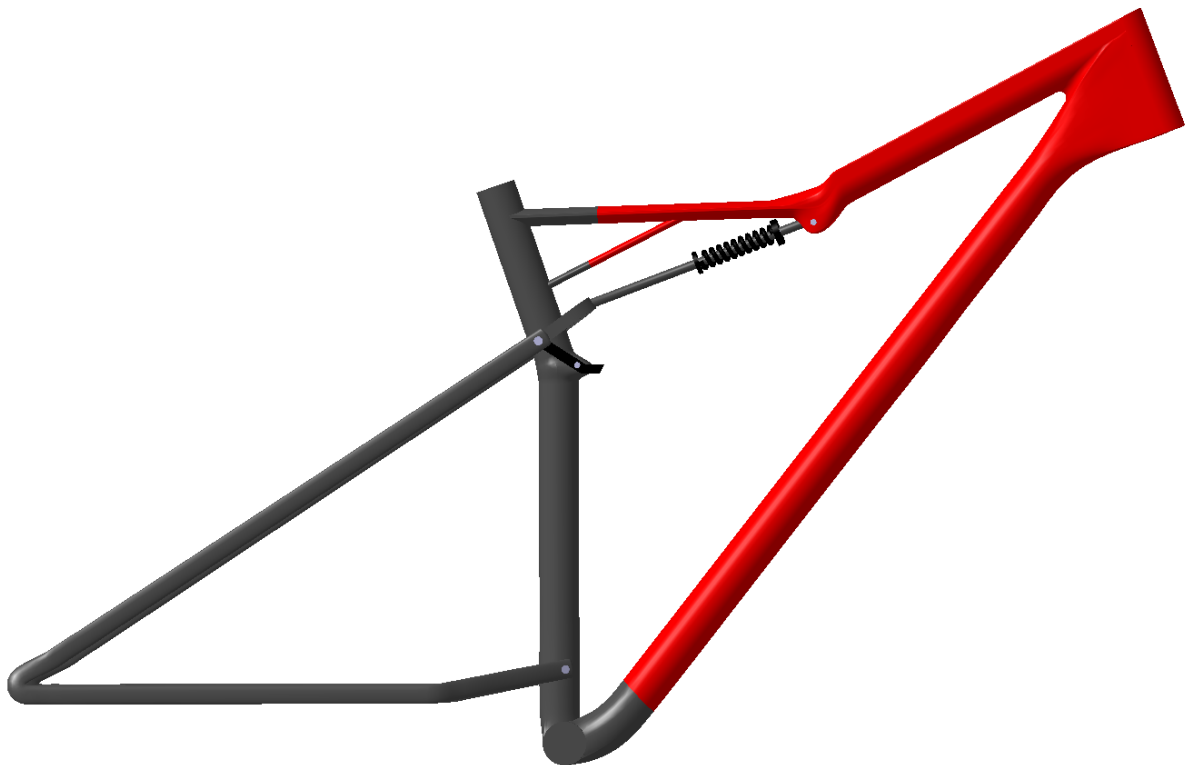


Figure 24: Specialized S-Works Epic XTR Di2 modelled frame.

We started with the idea of doing an assembly of three different parts; the main body of the frame, the spring and the screws. Once we have the idea clearly in our heads we started to model, but the problem came when we wanted to put all the parts in a product.

As the frame was made with multi-sections, we could not find the solution to put coincidences between the parts, so at the end, we had to redo everything just in on part.

Another big challenge is that we do not just have to make a frame, we must get that these parameters and measures can change according to get the best model of the bike frame. At the beginning this was so difficult as we were working with *Multi-Sections*, because they adapt its shape depending of the form and the position of the taken sections.

As we did with the Dirt Love, first we design the general sketch to have all the measures. This sketch can be seen in the following figure.

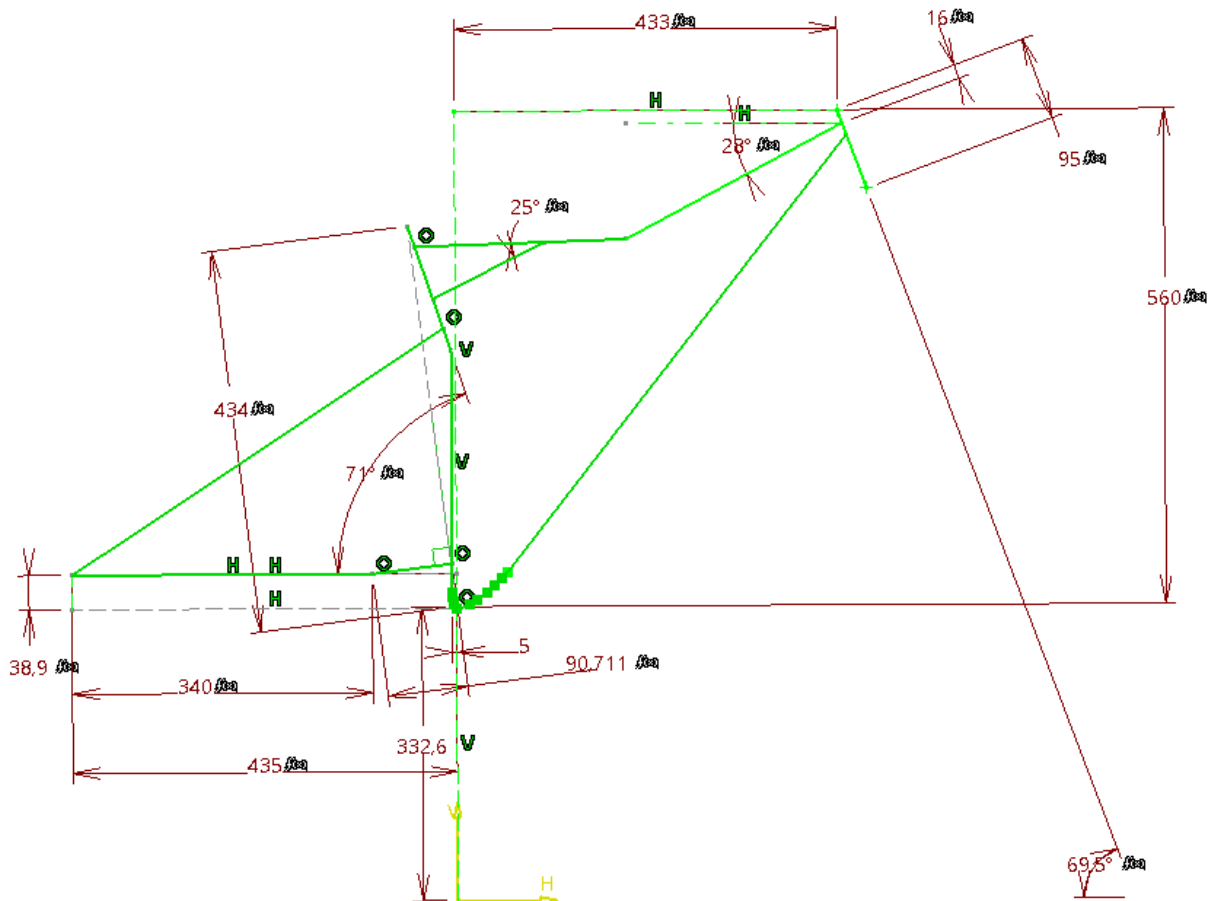


Figure 25: Basic geometry sketch.

3.5.1.Part by part

As every part of the bike is completely different (the shape and the way of model it) we are going to explain, to make it sure, how we do the whole frame. We are going to present all the parts in the order we made them.

3.5.1.1. Seat tube

This tube seems a bit easier if we compare with the rest tubes of the bike. The fact is that, until you do not simplify the problem of the “belly” you will not achieve that shape. Obviously, this was made by the multi-sections option, because it gives you too

much freedom according to weird forms. Unless there is an option, much easier to use or more effective than the multi-sections in these cases, is the one we used for the whole frame.

As we commented in the *YT Industries DirtLove*, when you use multi-sections, you have to think in the easiest sketch to get that shape, but for that you must have so clearly the idea of how multi-sections works.

We achieved that form with the geometry drew on the sketch that we can be seen in Figure 26.

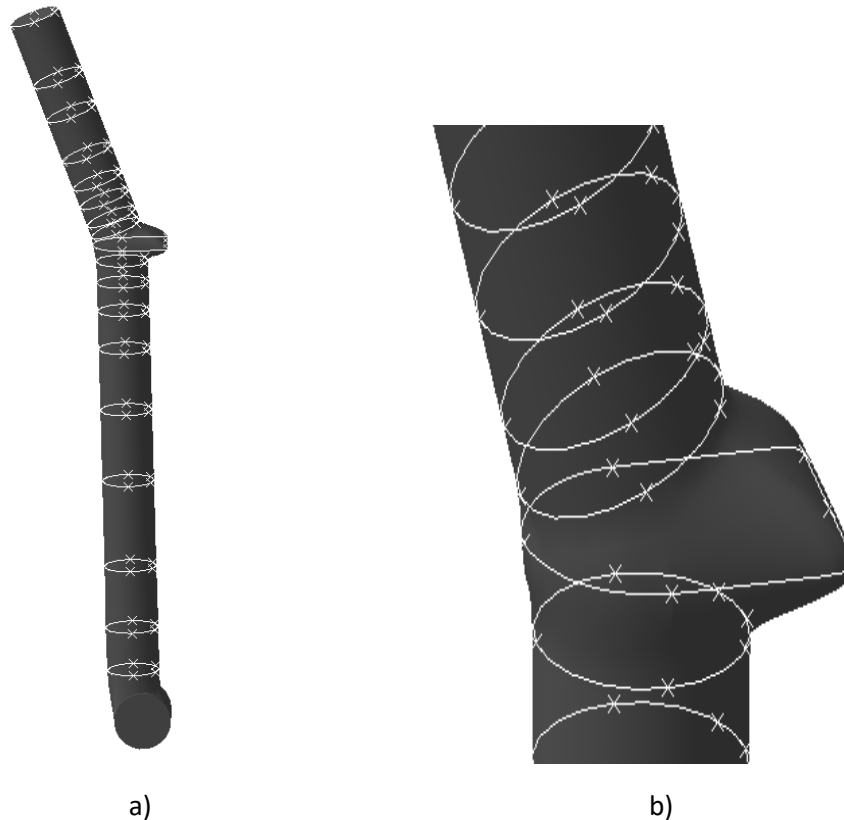


Figure 26: Seat tube part: a) Seat tube geometry sketch. b) Belly geometry sketch.

Another thing to achieve, was how we could do to get the shape from the bottom bracket, because as we can see in the real one, that the tube does not end with a circle shape. Therefore, what we did was to make a rectangle, which was the intersection between the bottom bracket and an offset of the plane ZX in that point.

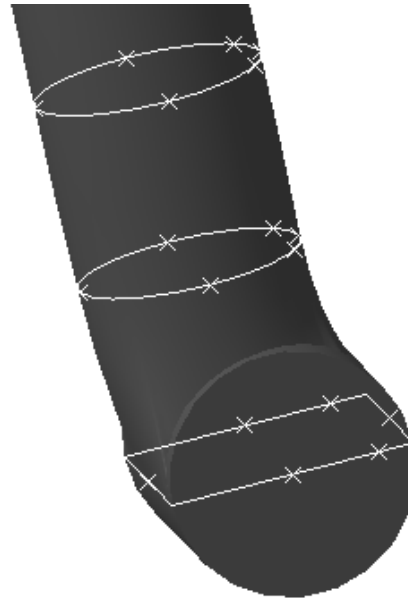


Figure 27: Geometry for the seat tube in the bottom bracket.

We have to point out that the idea of the intersection with the bottom bracket did not come into our minds until we made the diagonal tube.

3.5.1.2. Diagonal tube

This part of the frame had two challenges. The first one was to achieve the form that connects the tube with the direction tube and the second one was how to get that curve near the bottom bracket.

We had a clear idea that most part of the diagonal tube must be in a straight line, so that what we did first. This gave us a vision in the space of how we could do it to get the rest of the tube.

We tried different things until we got the definitive one. At the end, we made it with *guides in Multi-Sections* as we can see at Figure 28.



Figure 28: Diagonal tube geometry sketch.

After several tries, we finally achieved with the shape of both sides during exactly the same. What we did to get the form of that tube was to make the intersection between a transversal plane with the tubes where the diagonal tube is attached, in this case with the bottom bracket and the direction tube.

For the one in the bottom bracket we used the *ZX Plane* to make the intersection. We did not know if we needed more than one intersection or we had to make intersections as long the bottom bracket surface. At the end, the best option was one intersection in the middle of the bottom bracket.

In order to create a *Multi-Sections* we need splines or contours which are created continuously. This means that, for instance, you cannot create a rectangle with lines, you must use the option rectangle or make it with a spline, which is this case.

The final sketch which we achieved the geometry with, can be seen at Figure 29.

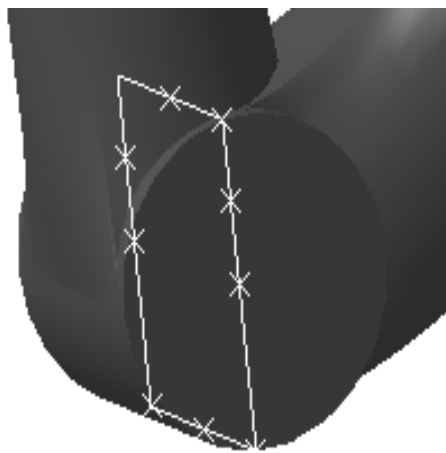


Figure 29: Diagonal tube geometry sketch in the bottom bracket.

For the shape in the direction tube we did the same. We used a created plane which is normal to the guide that ends horizontal. With that plane we created an *intersection* and we could create the *spline* which allowed us to make the *Multi-Sections*.

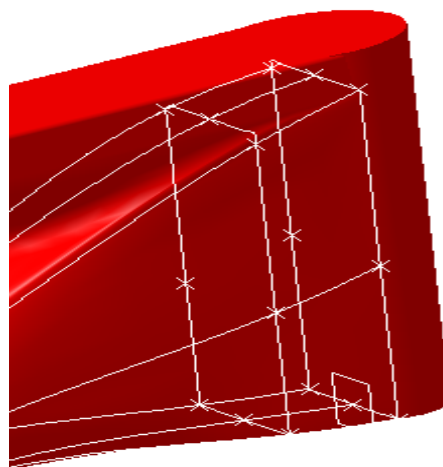


Figure 30: Diagonal tube geometry sketch in the direction tube.

3.5.1.3. Back Part

This section of the frame was really difficult because it works in 3 different planes. We can see in Figure 31 three different parts with the planes in red. This is because in that space we have to put the back wheel and also the gears and the chain.

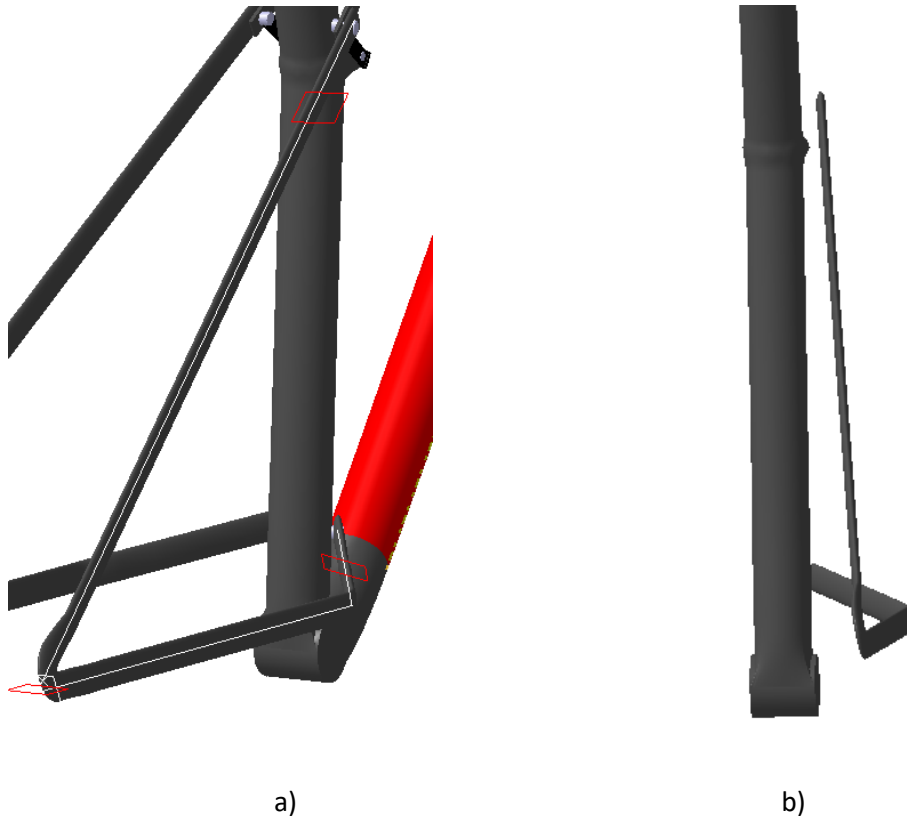


Figure 31: S-Works Back part: a) Back part shape sketch and used planes. b) Back part front view.

At the end this was made in two different *Multi-Sections*. The first one is until the part where the back wheel is attached. The second part is from where the back wheel is until the top.

This part was, as well, made by the option *Multi-Sections*. The shape of the tubes was made with an *ellipse*, except where the back wheel is attached. That was the most dramatical section of this thing. As we can see, the curve ratio is so small, that means that normally the option *Multi-Sections* cannot be completed because it leads into a cup. Therefore, for this reason, it was so difficult to get the final shape, which is shown at Figure 32.

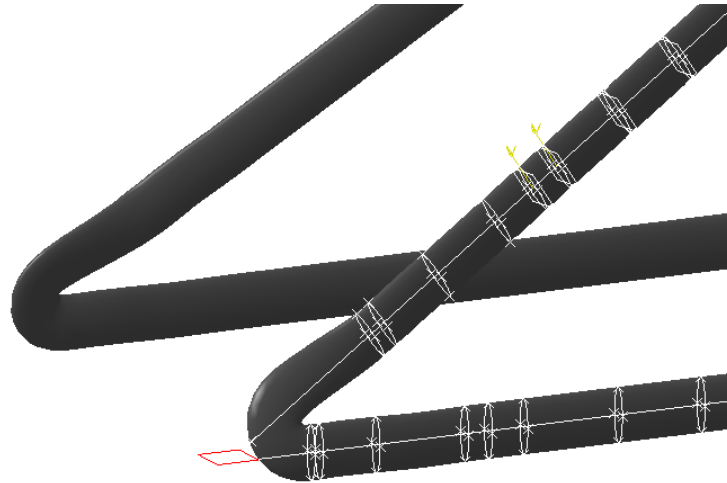


Figure 32: Ellipses for the geometry of the back part.

As we were changing the position of the planes the shape of it was changing as well. At the end we got the best possible solution which it looks like the same as the real bike.

3.5.1.4. Top tube

This part was a pain in the neck, because as we do not have measures enough to model the bike frame as it is, you have to play with different shapes and measures, until the form of the geometry looks like it.

This last part was divided in 2 (3 if we count where the color changes) parts. The first part starts in the direction tube. We can see in Figure 33 the geometry used for that first part. We used the option *Pad* to get this straight geometry until the second sketch (if we count from the right).

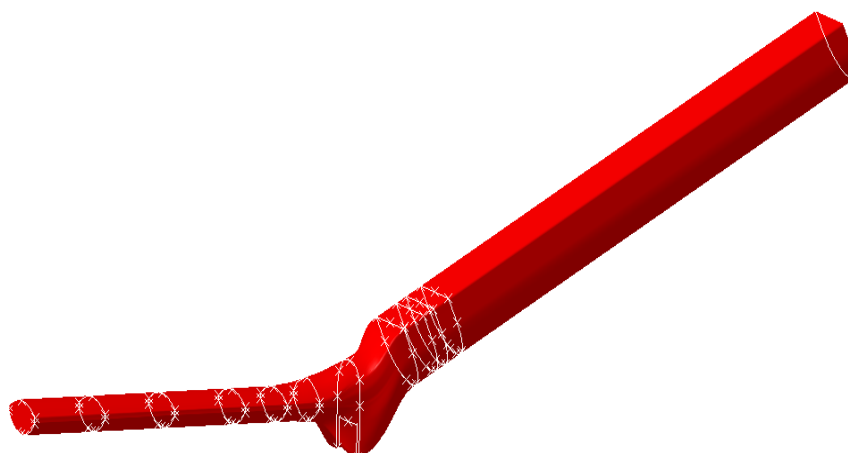


Figure 33: Top tube shape with its geometry.

From this point, we started doing a *Multi-Section* because the shape we wanted to do could not be done with anything else in CATIA V5®. These “ears” that the geometry

has, we did it before for the seat tube (seen in Figure 34). At the beginning, we thought that the seat tube had a division in the middle, but after watching different points of view, we concluded that the structure was closed, no like this.

With this, we want to say that it was not as difficult as we thought in the beginning. We can see clearly this shape at the following figure.

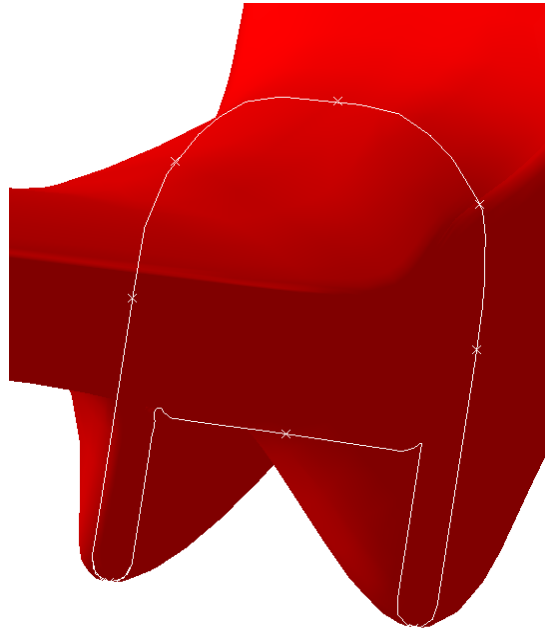


Figure 34: Geometry used for the "ears" in the top tube.

The rest of the shape can be shown in Figure 33, that is a kind of ellipse, but with a vertical line in the left and right sides of the ellipse. With this line, we got more width in that part. That is why the coupling we did to get this shape was made with 8 points as we can see at the figure above.

3.5.1.5. Spring and other elements

As we said in the beginning of this section, we tried to do an assembly for these parts. At the end we could not reach it, so we had to do again in the main part, where the main body was.

This part was so tough because, as the back part, the needed points and planes to use references were very difficult to get. But the good thing was that it was not so difficult to model.

The hardest thing was the element that is attached in the seat tube and in the black part (the one which is blacker). With this element we had the issue that, when the geometry changes, the planes used to draw this geometry inverts itself. This made that the geometry drew in the sketch inverted itself as well. So, when we changed the parameters, this element moved depending on the parameters, instead of moving with the elements attached.

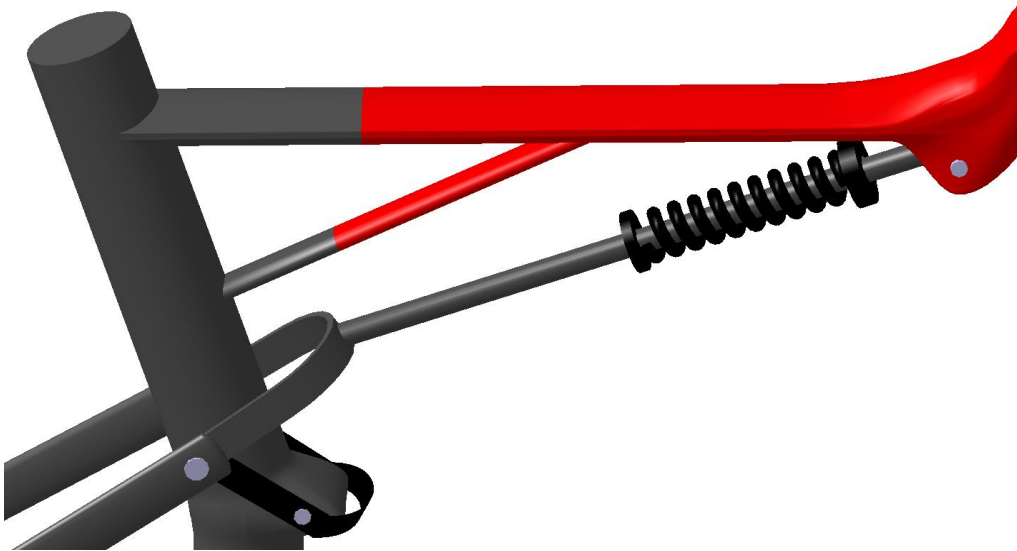


Figure 35: View of the spring and the other elements left.

Creating the spring was the easiest part of the two different elements as we can clearly see. It was done with the command *helix* and then a *rib*.

On the other side, the tube where the spring is, is attached with a screw that is along the “ears” of the top tube. This is shown at Figure 36.

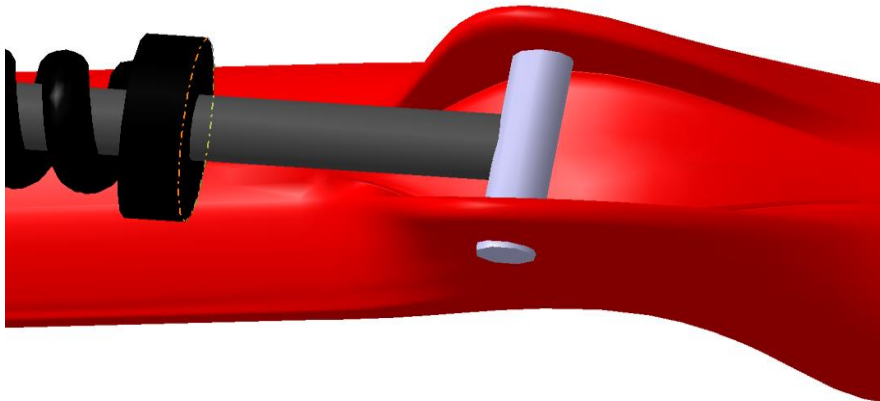


Figure 36: Attachment between spring and top tube.

The element which is attached to the “belly” of the seat tube can be seen clearly in the following figure, where the colors were changed to distinguish how was created.

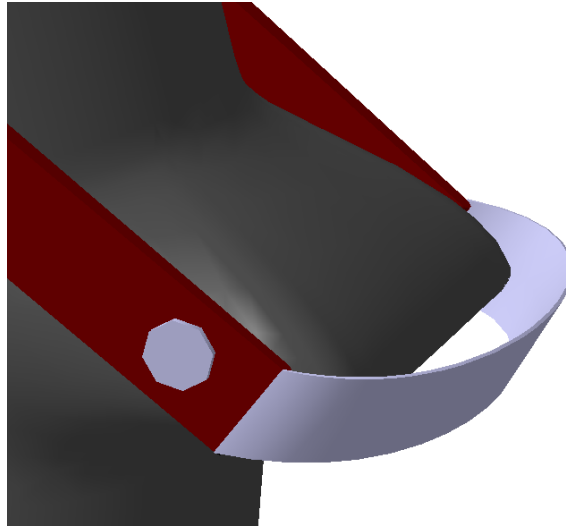


Figure 37 "Belly" reinforcement.

We can say that the grey part is a reinforcement for the “belly” of the tube. This was made with two *splines* with tangency in the Y-direction and then a *fill*.

The red element is to allow the back part to move when the bike goes through a jump and the spring enters to do its job. That is why this bike has this weird geometry, because of the position of the spring.

The last thing we created were the screws. These were made just with the options *slot* and *rib* or *pad*.

4. STRESS ANALYSIS WITH CATIA V5®

Once the bike frames were modelled we started doing the analysis. The bike frames are subjected to a stress test in Generative Structural Analysis workbench in CATIA V5®. To carry the analysis, we had to mesh the frames and then put all the constraints and loads we wanted to work with. To use this workbench, as we worked with just one part, everything must be inside one *Part Body*.

4.1. Canyon MTB & Canyon Road analysis

The meshing characteristics depend on each bike frame, Canyon MTB and Canyon Road use 5 mm of mesh size. The bike frames are fixed through the colocation of four *Clamps* at the rear wheel axis zone and one in the head tube bottom. Furthermore, all the frames endure a vertical force of -2000 N located at the seat tube top.

In the case of the Canyon MTB and the Canyon Road, the applied force induces a high stress concentration at the triple connection between seat stay, seat and top tubes as it is expected due to the force is closely applied and, also, thanks to the geometry of the bike. In addition, there are concentrations at the rear wheel axis and at the top tube bottom in account of the clamps. The force provokes that the seat tube flexes in the same direction and the seat stay tubes bend out. This can be viewed at Figure 38(a), where it is increased by a scale of 100, and at Figure 38(d) Canyon Road distribution has a scale of 500.

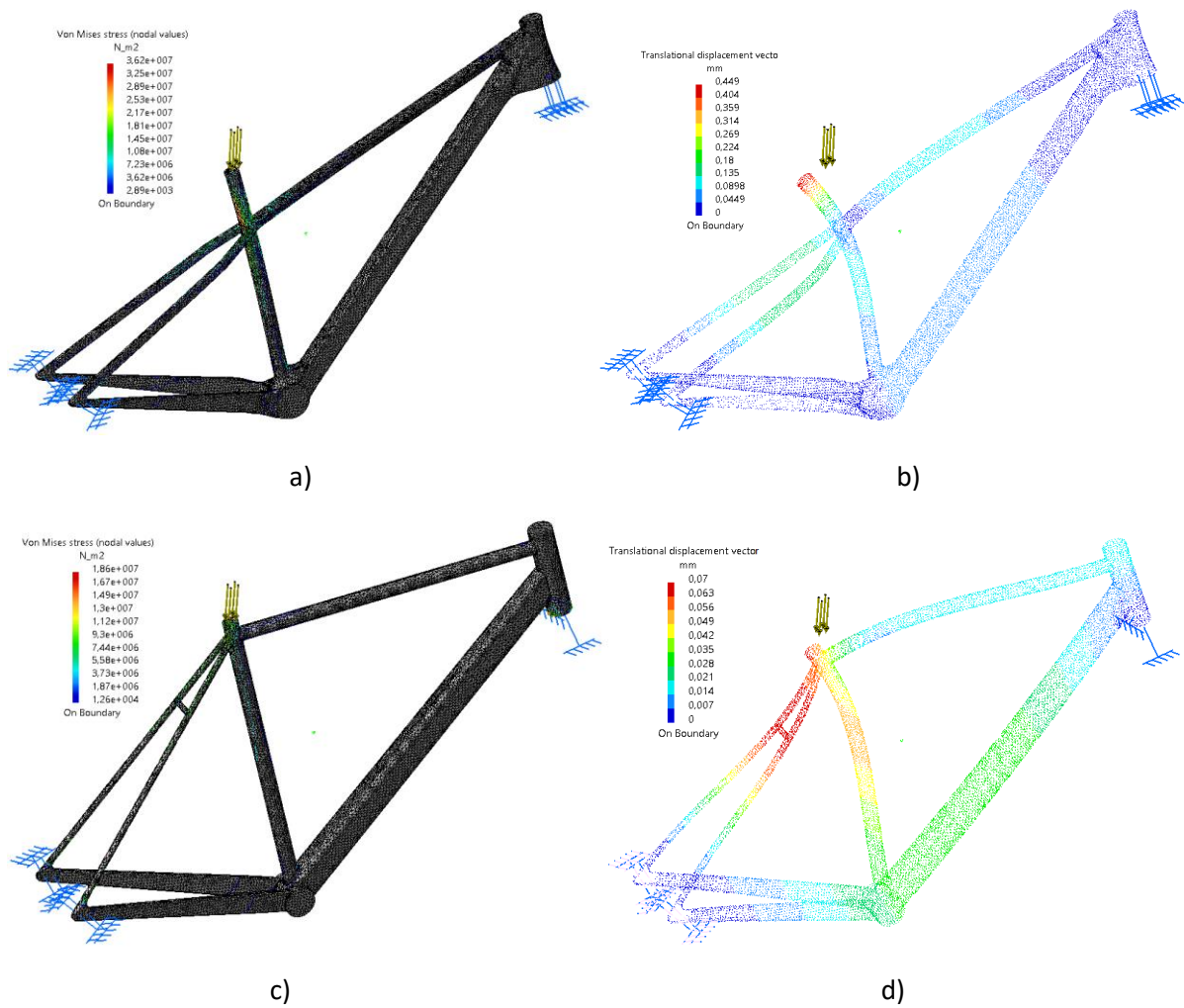


Figure 38: Stress and Displacement distribution: a) Stress distribution of Canyon MTB. b) Displacement distribution of Canyon MTB. c) Stress distribution of Canyon Road. d) Displacement distribution in Canyon Road.

The displacements and the Von Mises stress are not the same for the two following bikes.

4.2. Dirt Love analysis

The Dirt Love was analyzed with a mesh of 1mm. The maximum Von Mises Stress can be seen at Figure 39(a), it is in the intersection between the bottom back part, the bottom bracket and the seat tube.

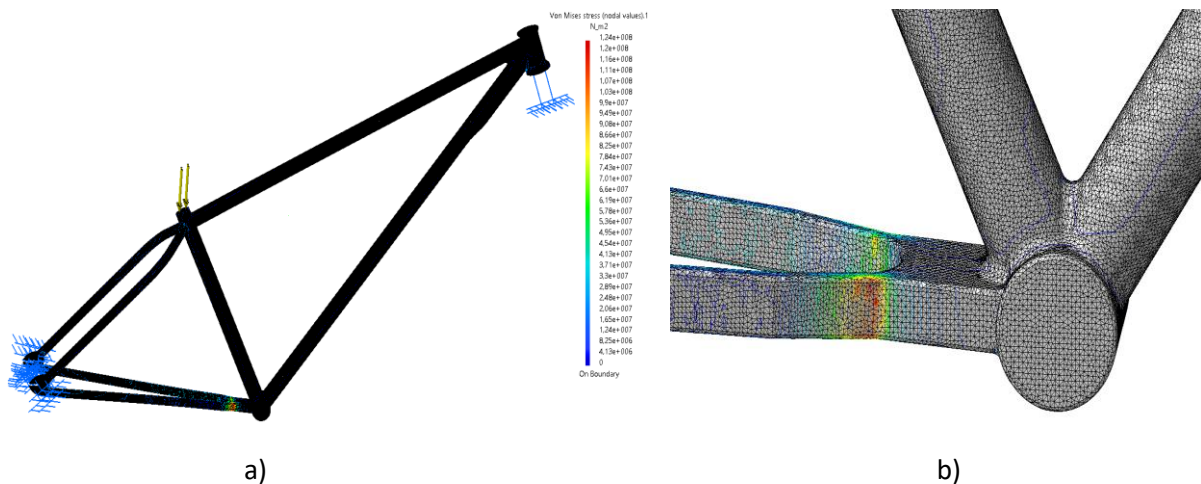


Figure 39: Dirt Love's Stress distribution a) Full frame distribution. b) Most affected area.

This is caused, probably, because of the width of that part of the bike. Maybe to solve it we could do it or with a more resistant material (we are using aluminum) or we could model it with more width.

Another is where we have to take a look, but it cannot be appreciated so well in Figure 39(b) is the intersection between the seat tube and the tubes of the back part. This is caused because the load put on the seat is so high for that tube diameters.

With this analysis we can see that the most stresses are in the *Edge Fillets*, the curved parts or the sections that their widths are not so high.

In the following figure we will see the displacement of the frame, which has a scale. We also see a comparison between the modelled frame and the frame once the load is put on it and with the deformation.

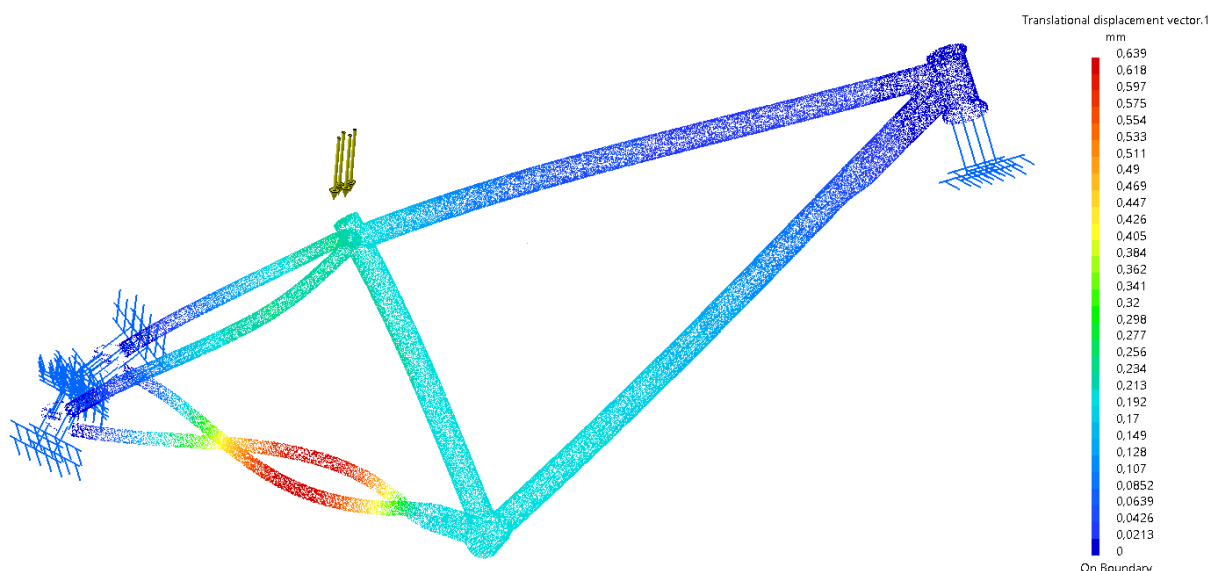


Figure 40: Dirt Love's Displacement.

As we did in the first two frame, we put a scale of 100 for the displacement to see it clearly.

We can see that the deformation in the chain stay is enormous. What happens is that both sides completely bend in the other sides. This cannot happen in a bike which is designed for jumping.

As the same reason for the Von Mises part, this displacement is caused because the width of the chain stay is so little. We wanted to see if this assumption was true. Therefore, we modify the model and we do it with more width but just in that part of the chain stay. What we got can be seen in the next figure.

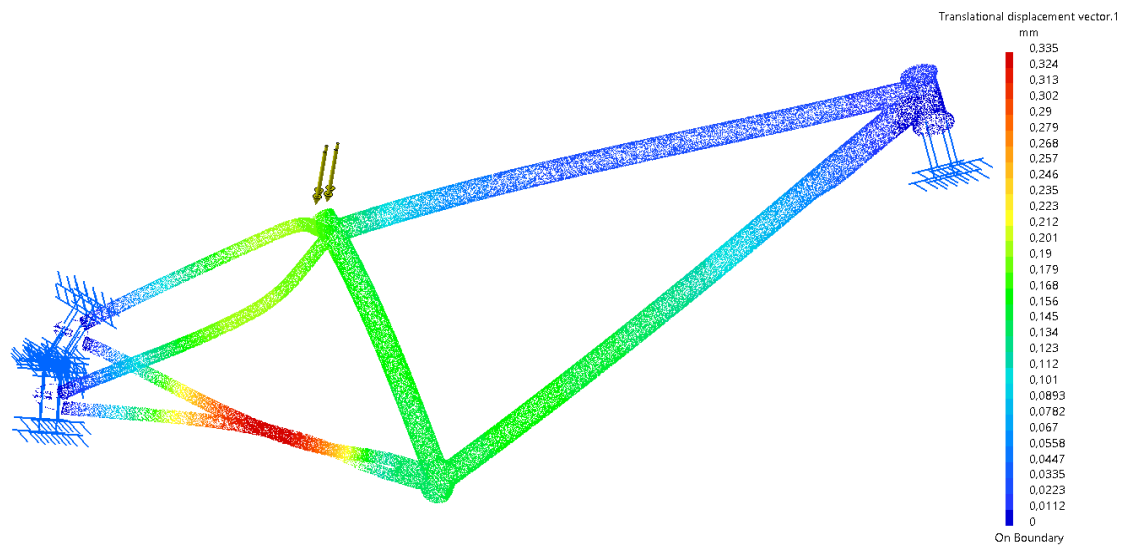


Figure 41: Dirt Love's modified Displacement.

We can see how that part improved, so if we still putting more width there, the issue is solved. Obviously, there are other ways, like for instance, do the semi-circle smaller, so we are increasing that zona and making it stronger.

Even though the colors the program uses are the same, the value for the displacement is the half of the model we worked with. Therefore, this means that, although the seat tube now is in green color the displacement is the same or less as before. We made the bike stronger in this case, but also because we put more material, so we also increased the mass of the bike.

In Figure 42 we show a comparison between the model with the one which has the deformation.

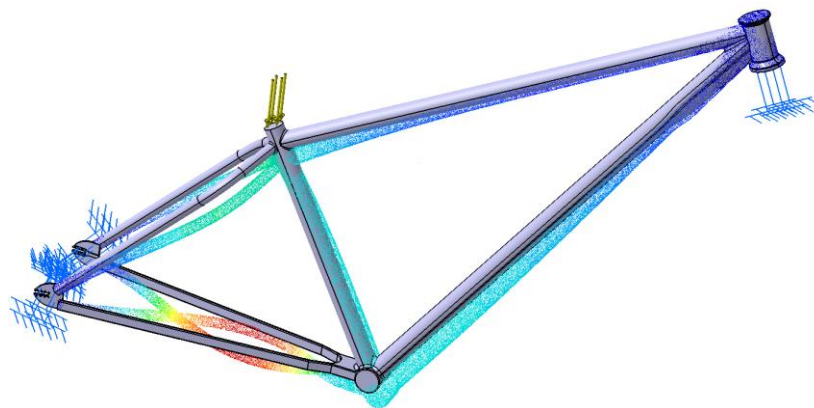


Figure 42: Comparison between modelled frame with bended frame.

4.3. S-Works Epic analysis

The next and last bike which is the Specialized S-Works Epic was analyzed with a mesh the 3 mm. As we said before, the clamps are not in the same position as the rest of the bikes due to the model form we did. CATIA V5® does not allow to put the thing as clamps, loads, temperatures, and so on in exact points. It only allows you to put these things in parts. So, as we modelled the back part in two multi –sections, we had to decide where to put the clamps, but it was not so difficult to decide it due to the result of both analysis.

The maximum Von Mises value is shown in Figure 43. We can appreciate how the maximum Von Mises value is in the intersection where the screws are. Another hard area is the “belly” in the seat tube and where the shape of the seat tube changes.

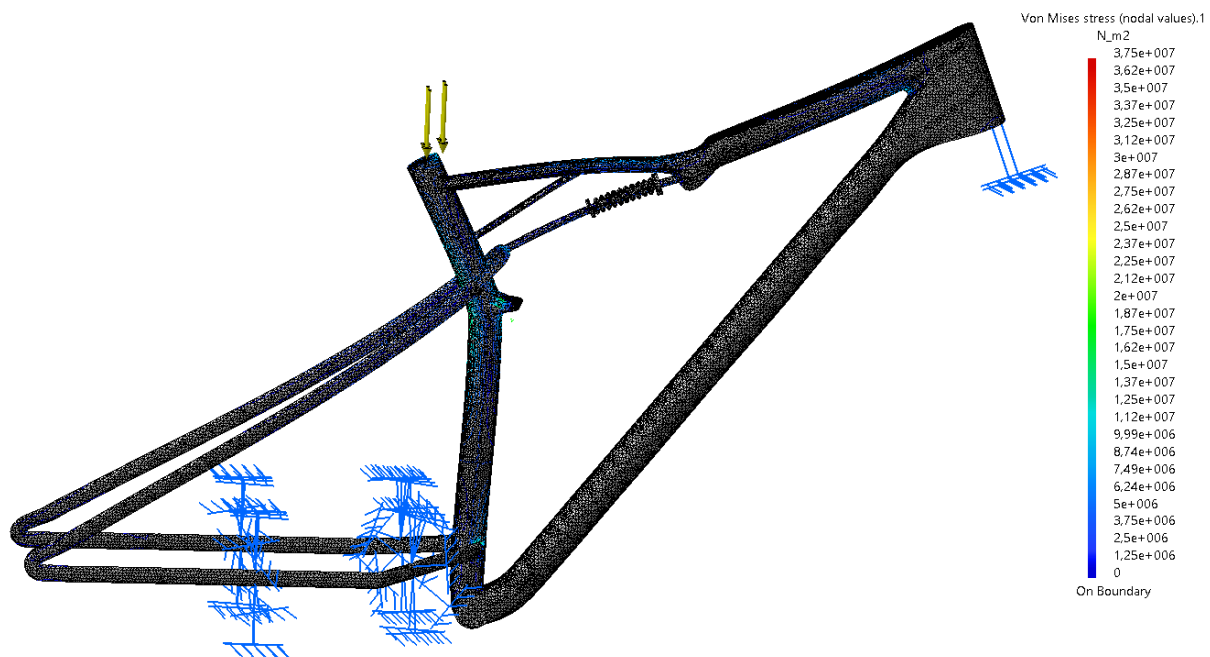


Figure 43: Von Misses in the Specialized S-Works Epic.

Even in the figure above, we can see so clear the deformation it took with that load in the seat tube. This deformation can be seen in Figure 44.

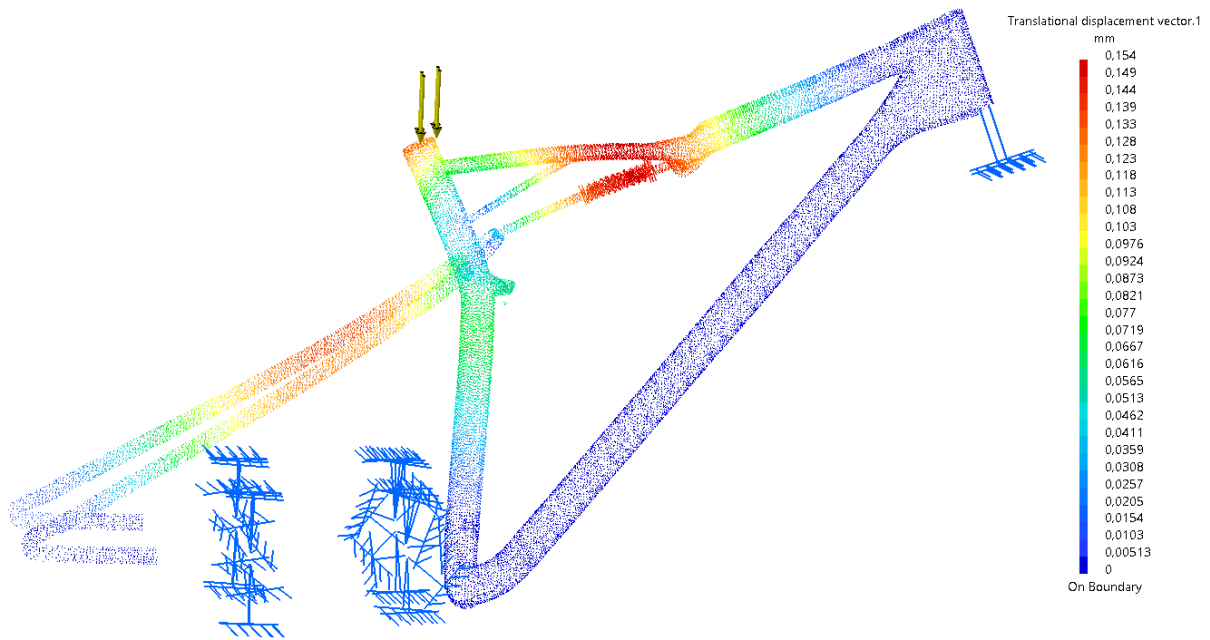


Figure 44: Displacement of the Specialized S-Works Epic.

We can see how the left part of the top tube is bent and also how the back part is bent downwards. With the Figure 45 we can see the comparison between both frame as we could see in the Dirt Love.

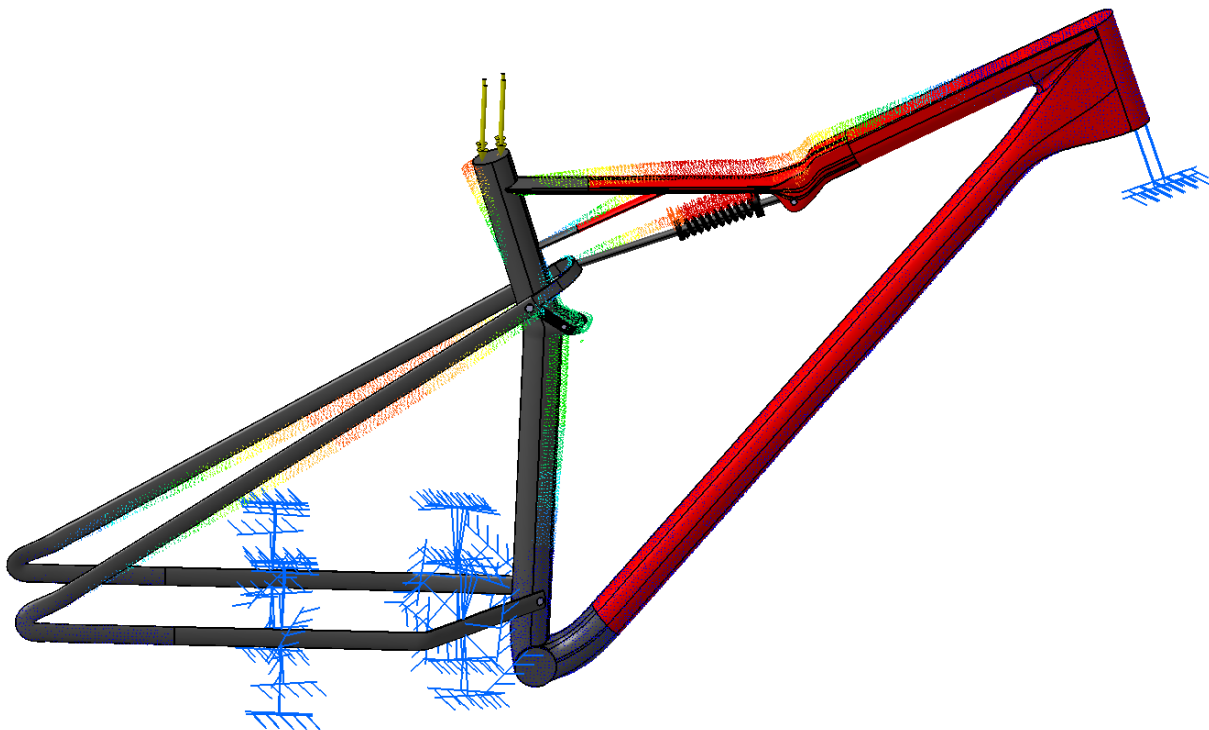


Figure 45: Comparison between modelled frame and bended frame.

It looks like the spring did a good job and the deformation is in the direction it says. It looks like the spring is cushioning the load we put on the seat of the frame.

We also did the analysis with the clamps in the other part of the back part, but the results we got was not enough for us and we prefer to use the ones shown above. The results got with the other clamps can be seen in the next figures.

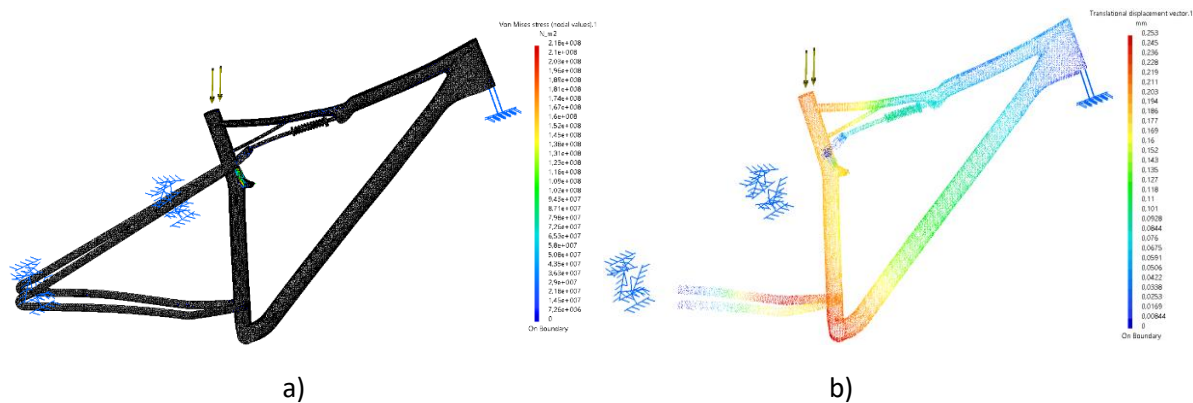


Figure 46: Von Mises and Displacement with other clamp position: a) Von Mises stress. b) Displacement.

Where we saw clearly that the other option was better was in the comparison between the two frames. We can see that the displacement is different than with the other clamps and these ones are not so realistic with the load we are using. The figure of the comparison is shown at Figure 47.

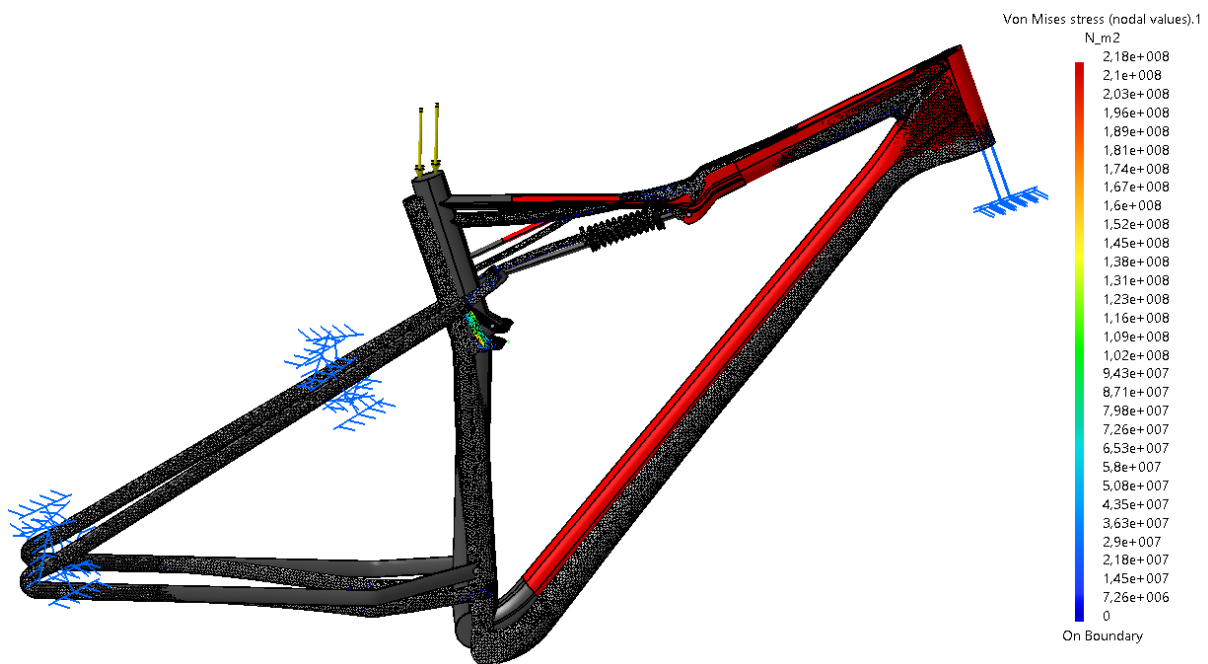


Figure 47: Comparison between modelled frame and bended frame with other clamp position.

We can see how the element that is attached in the “belly” of the seat tube gets larger while the deformation of the tube where the spring is upwards. At the same time, the deformation of the left part of the top tube goes downwards.

5. GEOMETRY OPTIMIZATION WITH Mode FRONTIER 2017®

As we said in the sections above, we used Mode FRONTIER 2017® as the optimization program. Once we had, in a good quality, the bike frames and the analysis are done, it is time to get the best structures possible according to stress and weight.

5.1. Optimization program setup

The objective of the project is to find the best geometry configuration for each bike frame, focusing the search on minimize the weight and the stress suffered. The search of the optimum geometry design was carried out with the aid of Mode FRONTIER 2017®. This program is a multi-objective optimization environment that incorporates an easy coupling to almost any CAE tool, among which is CATIA V5®. Mode FRONTIER 2017® consists basically in a wrapper around CATIA V5®, executing the optimization by switching the value to the input variables (bike frame parameters) between bounds and allowing monitoring the outputs results, helping to find the best solution reducing the waste of time.

The workflow (Figure 48) of the program consists of nine inputs (nine bike frame variables) which lead to two outputs (weight and stress through the maximum Von Mises) with minimizing objectives. We used Random configuration at DOE properties with 30 number of designs and NSGA-II with 50 number of generations at the scheduler. As result, there are 1500 evaluated designs. This is due to there is only over 30 % of feasible results at the simulations and in order to have a decent estimation around 500 feasible results are needed.

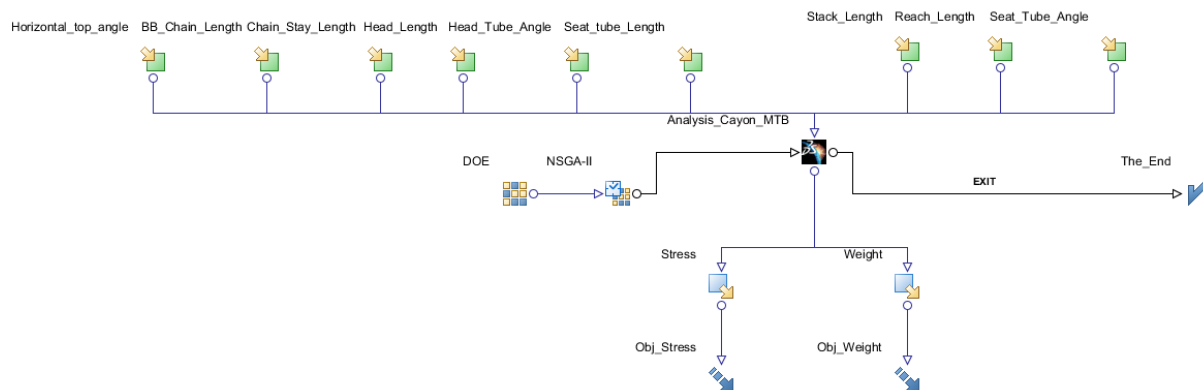


Figure 48: Workflow used for the optimization part.

5.2. Input parameters and optimization goals

It is necessary to establish a lower and upper bound to the inputs. These ones were determined changing manually the parameters of the bike frame models until the model broke. This is not a perfect way due to when we evaluate a parameter to find its limits the other parameters are fixed, so it is probably that when the other variable values change these

limits changes. Therefore, we must be a little flexible with the limits, which entails the appearance of a high percentage of error in the simulations. This provokes the necessity of increasing the number of evaluated designs to get over 500 feasible results to can perform a good estimation. The lack of enough RAM in the used computers is the cause of which there is usually one feasible result followed by an error one (Figure 49), because the computer are not able to process so much information. The bounds used are indicated at Table 3 and Table 4.

1422	1423	1424	1425	1426	1427
1428	1429	1430	1431	1432	1433
1434	1435	1436	1437	1438	1439
1440	1441	1442	1443	1444	1445
1446	1447	1448	1449	1450	1451
1452	1453	1454	1455	1456	1457
1458	1459	1460	1461	1462	1463
1464	1465	1466	1467	1468	1469
1470	1471	1472	1473	1474	1475
1476	1477	1478	1479	1480	1481
1482	1483	1484	1485	1486	1487
1488	1489	1490	1491	1492	1493
1494	1495	1496	1497	1498	1499

Figure 49: Feasible & Unfeasible models in Mode FRONTIER®.

Table 3: Canyon MTB & MTB Road value bounds.

	Canyon MTB		Canyon Road	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Horizontal top angle [deg]	5	35	0	50
BB chain length [mm]	0	130	0	150
Chain stay length [mm]	410	450	400	440
Head length [mm]	69	144	130	300
Head tube angle [deg]	42	79	50	80
Seat tube length [mm]	500	700	550	700
Reach length [mm]	490	644	280	700
Stack length [mm]	300	500	350	700
Seat tube angle [deg]	65	73.5	64	89

Table 4: Dirt Love & S-Works Epic value bounds.

	YT Industries Dirt Love		Specialized S-Works Epic	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Horizontal top angle [deg]	27.5	35.0	24.0	30.5
BB chain length [mm]	21.5	130.0	28.0	65.0
Chain stay length [mm]	332.0	387.0	432.0	436.0
Head length [mm]	60.0	60.0	81.0	105.0
Head tube angle [deg]	64.0	73.0	66.0	73.0
Seat tube length [mm]	305.0	500.0	415.0	460.0
Reach length [mm]	389.0	410.0	410.0	500.0
Stack length [mm]	556.0	599.0	580.0	615.0
Seat tube angle [deg]	48.0	72.5	71.0	71.0

5.3. Analysis of the results

Once we have run the optimization process it is time to analyze the results achieved through the tools that Mode FRONTIER 2017® provides. There are two relevant charts that let us to discriminate the results and make conclusions: scatter and parallel coordinate charts.

5.3.1. Scatter charts

Once we have run the simulations, the program makes available several kinds of charts. With a scatter, where stress is located at X-axis and weight at Y-axis, we can visualize easily which geometries provide the best stress to weight ratio for each bike frame, being stress in Pa and weight in Kg). In these plots we can see that the best results are disposed at the left-down corner (rounded in red), since they have the lower stresses and weights. The question here is to decide which of these designs are the best ones. Owing to the fact that we ignore the security coefficient that companies use to evaluate their own bikes and because we have to assume the approximation that the bike frames are completely solid, it does not exist a limit for the maximum stress that a bike frame can resist. Therefore, the lower the weight the better, but having into account that in the reality exists a limit, if there is a design with a lower weight that another one, but with a much higher stress, will be discard.

In these scatter plots, it can be seen how the evaluated designs are concentrated in the left-down corner. In that zone, the bike frames with the lower stress and weight are located, and especially those that have not any point that has lower weight and stress simultaneously are the best ones. These points delimit what is known as Pareto Frontier (Barr, 2012), indicated with a red curve, where the geometries with the best characteristics are found.

It is useful to extract a comparison of the stress and weight between the original geometry and the geometry with the best stress to weight ratio and the geometries with the best results of stress and weight. In Table 5, Table 7, Table 9 and Table 11 we can have a look at these variations. The selection criteria of each bike frame has been the following.

In the Canyon MTB (Figure 50), we can see how there are two interesting concentrations separated by a gap. The best design has been chosen where the blue circle is located due to the points of that zone have over 0,2 Kg more than in the other zone, no a really high difference, but the stress suffered rounds 400% less. If we compare the best option with the less stressed one (Table 5), it is a 43,2 % more stressed, but an astonishing 428 % less than the lightest one. The best geometry is 54,4 % less stressed and counts with an incredible 9,3 % less of weight than the original one, which says a lot about the optimization achieved. The variable values of the original geometry, best one, the less stressed one and the lightest one are indicated at Table 6, and it is possible to compare visually the differences between the different options at Figure 51.

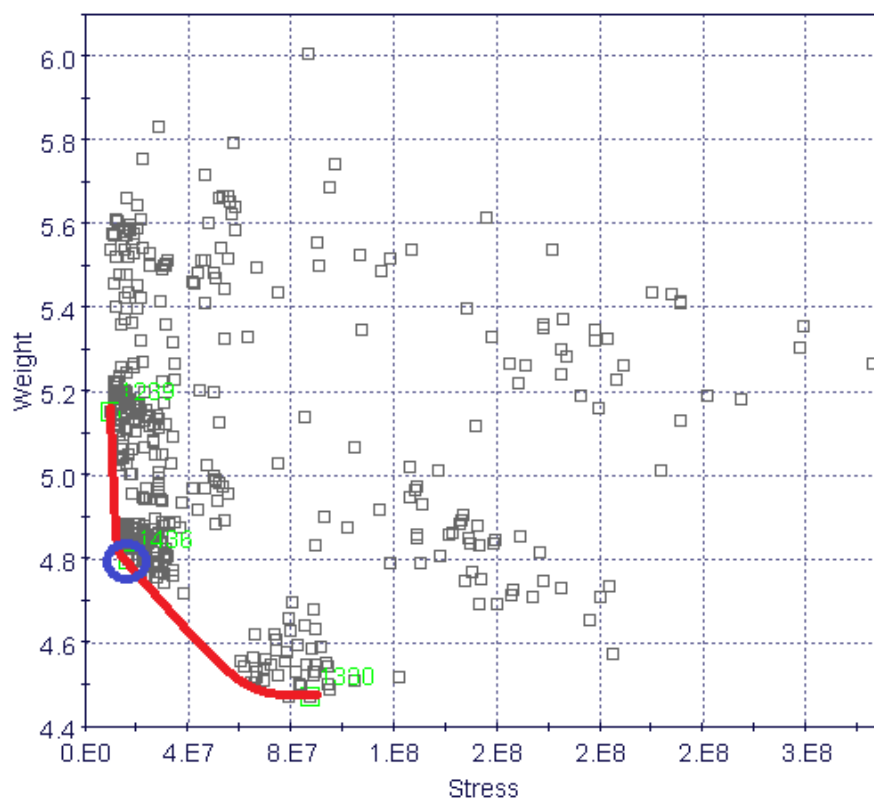


Figure 50: Canyon MTB Stress-Weight scatter chart with Pareto Frontier.

Table 5: Extreme designs Canyon MTB with deviations.

	Stress [$\frac{N}{m^2}$]	Weight [Kg]
Original geometry	$3,616 \cdot 10^7$	5,291
Best geometry	$1,6495 \cdot 10^7$ (-54,4 %)	4,7977 (-9,3 %)
Less stressed geometry	$9,3703 \cdot 10^6$ (-43,2 %)	5,1525 (+7,4 %)
Lightest geometry	$8,7086 \cdot 10^7$ (+428 %)	4,4702 (-6,8 %)

Table 6: Variable values of original, best, less stressed and lightest geometry of Canyon MTB.

	Original geometry	Best geometry	Less stressed geometry	Lightest geometry
Horizontal top angle [deg]	30	17	12	28
BB chain length [mm]	63	125	21	52
Chain stay length [mm]	437	415	423	423
Head length [mm]	100	74	118	86
Head tube angle [deg]	69,5	57	72	76
Seat tube length [mm]	440	512	528	514
Reach length [mm]	425	308	314	308
Stack length [mm]	611,3	581	579	493
Seat tube angle [deg]	74	72,556	71,611	71,611



Figure 51: Best, less and lightest Canyon MTB geometry, respectively.

In the Canyon Road (Figure 52) happens the same, there are two highlighted areas. In this case, the better design (blue circle) is, if we compare with the Canyon MTB, in the other area because it is close in stress terms to the less stressed geometry (26,5 %, Table 7) and has practically the same weight as the lightest one (+0,7 %). The optimized design has seen improved its stress response a 16,1 % and its weight an 22,2 %. The comparison between the three different types of frames are shown at Figure 53.

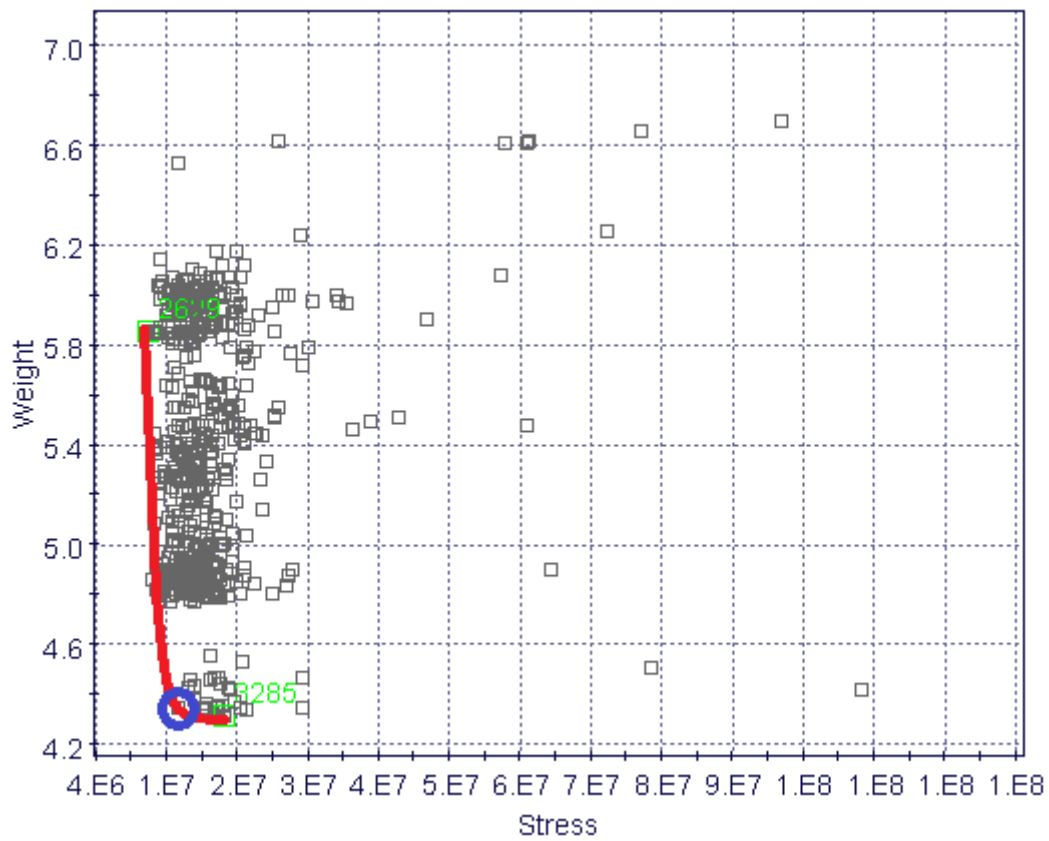


Figure 52: Canyon Road stress-weight scatter chart with Pareto Frontier.

Table 7: Extreme designs Canyon Road with deviations.

	Stress [$\frac{N}{m^2}$]	Weight [Kg]
Original geometry	$1,858 \cdot 10^7$	5,592
Best geometry	$1,5593 \cdot 10^7$ (-16,1 %)	4,3467 (-22,3 %)
Less stressed geometry	$1,1464 \cdot 10^7$ (-26,5 %)	5,8542 (+34,7 %)
Lighter geometry	$2,2232 \cdot 10^7$ (+42,6 %)	4,3169 (-0,7 %)

Table 8: Variable values of original, best, less stressed and lightest geometry of Canyon Road, respectively.

	Original geometry	Best geometry	Less stressed geometry	Lightest geometry
Horizontal top angle [deg]	9	6	7	6
BB chain length [mm]	61	56	139	59
Chain stay length [mm]	415	416	405	400
Head length [mm]	157,5	140	204	140
Head tube angle [deg]	73,25	80	72	80
Seat tube length [mm]	530	555	621	555
Reach length [mm]	391	300	492	301
Stack length [mm]	567	356	501	356
Seat tube angle [deg]	73,5	87	88	87

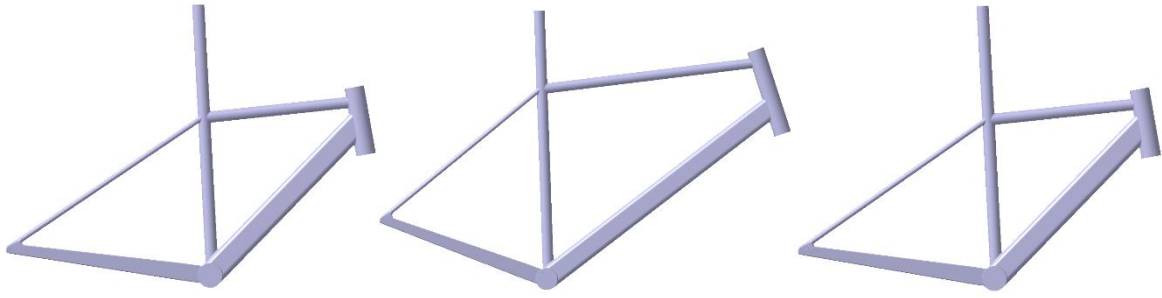


Figure 53: Best, less and lightest stress Canyon Road geometry, respectively.

Nevertheless, in the Dirt Love (Figure 54), the better designs are accumulated in a column in the left-side of the chart. Here the best geometry is readily recognizable since the Pareto Frontier is almost a vertical line, so the best choice will be in the bottom of this one (blue circle). This point is very close to the lightest one (only 0,02 % heavier, Table 9), which means that has an unbeatable weight. In addition, it is also near to less stressed on (5,9 % more), remarking that this geometry has very good properties. The best design has been improved a 28,6 % in stress terms and a 6,4 % in weight.

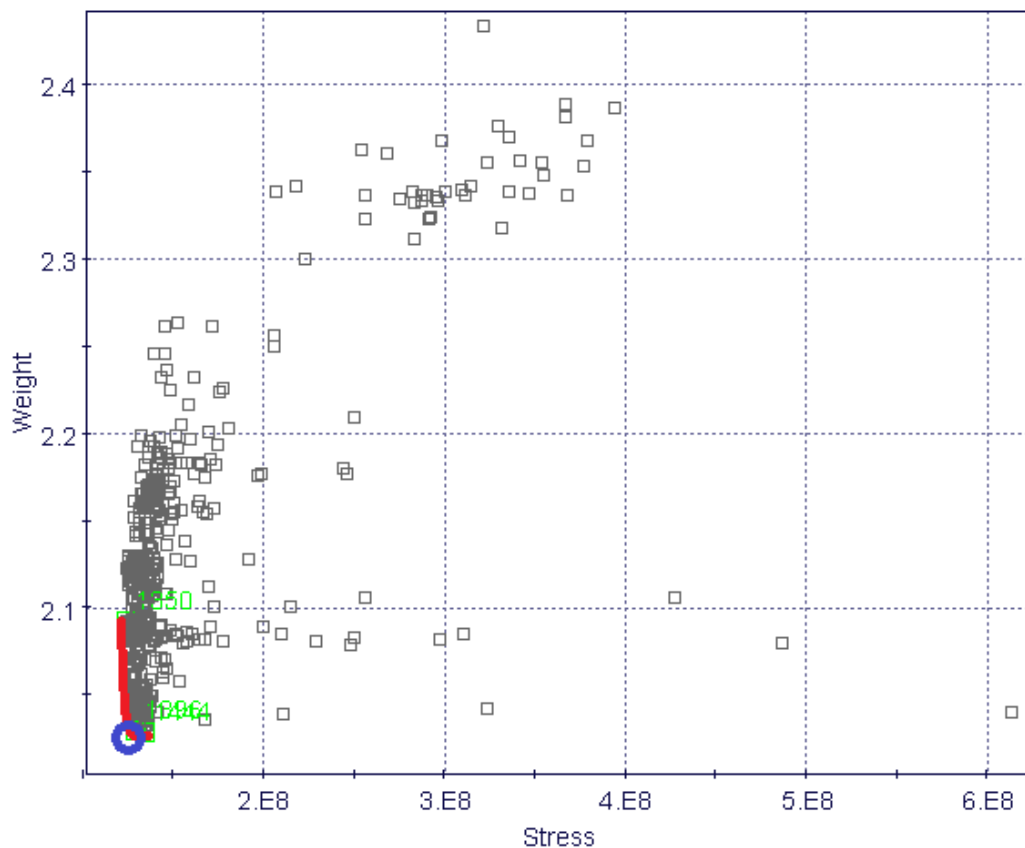


Figure 54: Dirt Love stress-weight scatter chart with Pareto Frontier.

Table 9: Extreme designs Dirt Love with deviations.

	Stress [$\frac{N}{m^2}$]	Weight [Kg]
Original geometry	$1,244 \cdot 10^8$	2,168
Best geometry	$8,8826 \cdot 10^7$ (-28,6 %)	2,0299 (-6,4 %)
Less stressed geometry	$8,3622 \cdot 10^7$ (-5,9 %)	2,0925 (+3,1 %)
Lightest geometry	$9,4569 \cdot 10^7$ (+6,5 %)	2,0295 (-0,02 %)

Table 10: Variable values of original, best, less stressed and lightest geometry of Dirt Love, respectively.

	Original geometry	Best geometry	Less stressed geometry	Lightest geometry
Horizontal top angle [deg]	28	29,375	29,375	29,375
BB chain length [mm]	22	128,01	126,02	128,01
Chain stay length [mm]	376,636	333	337	333
Head length [mm]	60	60	60	60
Head tube angle [deg]	69	72	72	72
Seat tube length [mm]	313,8	305,49	319,32	305,49
Reach length [mm]	404,583	399	402	398
Stack length [mm]	563	556	584	556
Seat tube angle [deg]	62	72,5	72,5	71,52

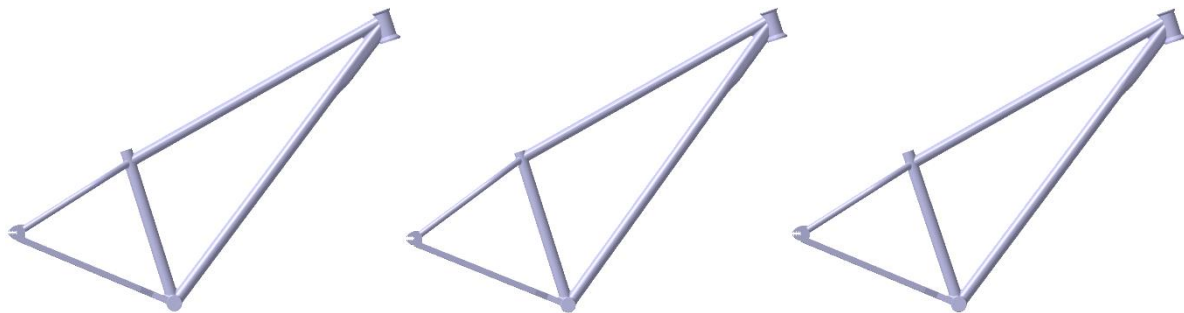


Figure 55: Best, less stressed and lightest Dirt Love, respectively.

If we take a look at the S Works Epic scatter chart (Figure 56), we can see a similar distribution to the Dirt Love one (Figure 54). In this chart there are three discordant points that being removed is obtained a much more understandable distribution (Figure 57). In this way the points of interest are quickly recognizable, being the best one rounded by the circle. It counts with an intermediate stress value between the less stressed and the lightest design (Table 11). The selected as best geometry has gained a great improvement of 38,7 % in stress and of 2,5 % in weight.

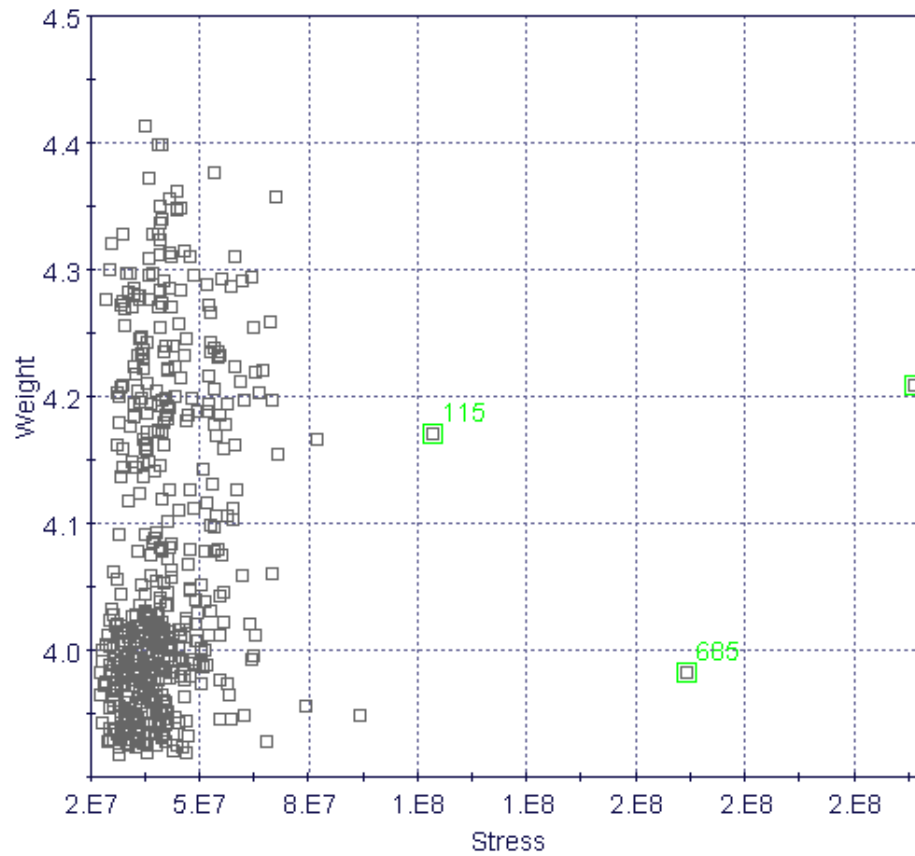


Figure 56: S-Works Epic stress-weight scatter chart with Pareto Frontier.

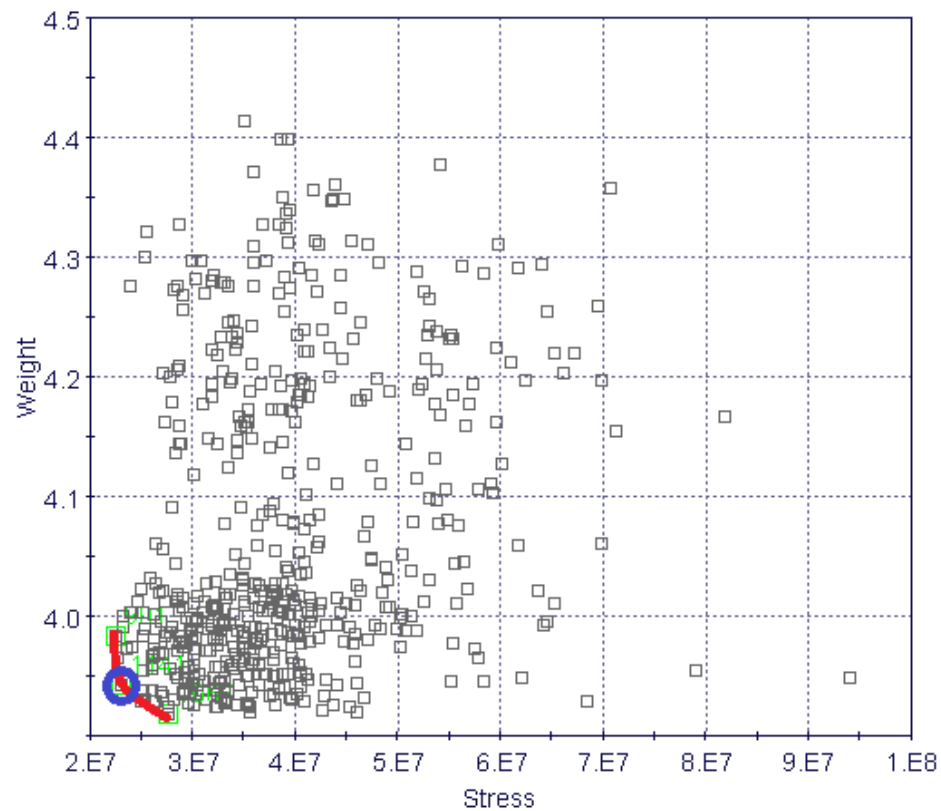


Figure 57: S-Works Epic stress-weight scatter chart with Pareto Frontier without points out of bounds.

Table 11: Extreme designs S Works Epic with deviations.

	Stress [$\frac{N}{m^2}$]	Weight [Kg]
Original geometry	$3,747 \cdot 10^7$	4,044
Best geometry	$2,2962 \cdot 10^7$ (-38,7 %)	3,9431 (-2,5%)
Less stressed geometry	$2,254 \cdot 10^7$ (-1,8 %)	3,9827 (+1 %)
Lightest geometry	$2,7623 \cdot 10^7$ (+20,3 %)	3,918 (-0,6 %)

Table 12: Variable values of original, best, less stressed and lightest geometry of S Works Epic, respectively.

	Original geometry	Best geometry	Less stressed geometry	Lightest geometry
Horizontal top angle [deg]	28	29,571	29,571	30,5
BB chain length [mm]	38,9	44	44	44
Chain stay length [mm]	435	433	432	432
Head length [mm]	95	82	83	81
Head tube angle [deg]	69,5	70	72	73
Seat tube length [mm]	434	417	441	415
Reach length [mm]	433	423	423	424
Stack length [mm]	597	581	581	580
Seat tube angle [deg]	71	73	73	71,333



Figure 58: Best, less stressed and lightest S-Works Epic geometry, respectively.

5.3.2.Parallel coordinate charts

Another relevant graph available is the parallel coordinate chart. In this, it is possible to visualize easily in the same chart the variable values of the geometries with the lower (or maximum) weights and stresses.

If we look at Canyon MTB weight chart (Figure 59), we see how the lightest geometries have a low stress (from $5,8245 \cdot 10^7 Pa$ to $9,8245 \cdot 10^7 Pa$) and reach length (304 mm to 317 mm), since the blue lines (less heavy designs) converge to a reduced area in that variable columns. Reasonable since at a shorter length, less weight. However, in the stress chart (Figure 60), the less stressed designs usually have medium size stack length (between 556 mm and 586 mm), a short seat tube length (505 mm to 570 mm) and a short chain stay length (414 mm to 425 mm). This makes sense because a shorter length means less leverage, reducing the stress, but it is curious how with a medium stack length there is better results.

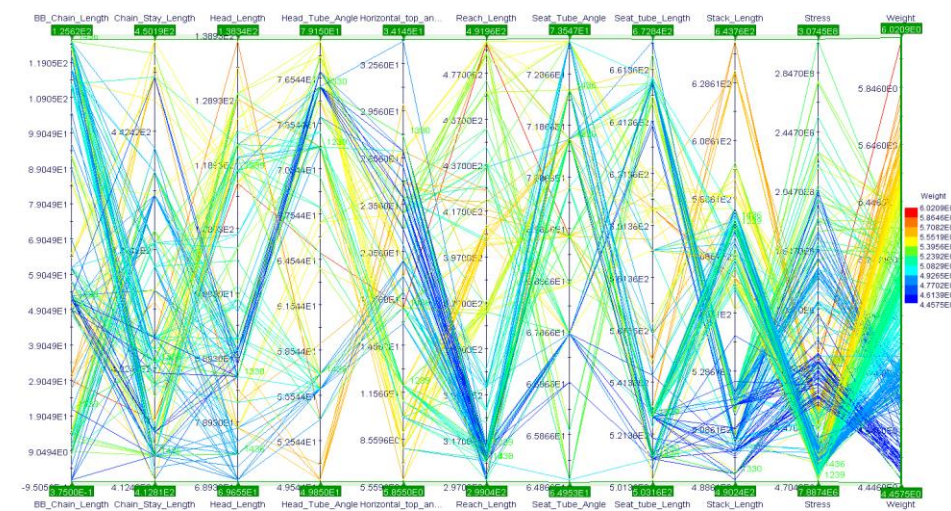


Figure 59: Canyon MTB weight parallel coordinate chart.

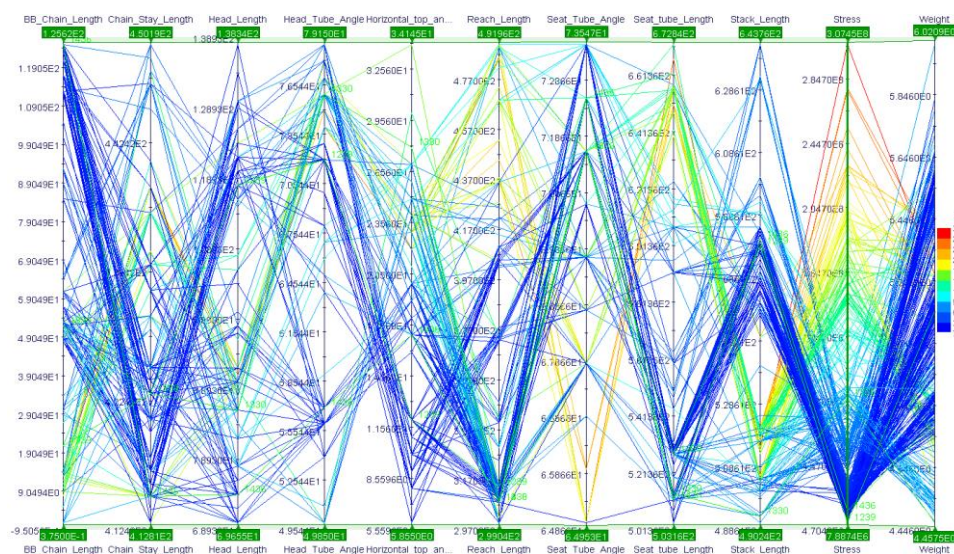


Figure 60: Canyon MTB stress parallel coordinate chart.

As for the Canyon Road weight parallel coordinate chart (Figure 61), the lightest designs have, normally, a low maximum Von Mises (from $1,5132 \cdot 10^7 Pa$ to $1,7262 \cdot 10^7 Pa$), stack length (around 355 mm), seat tube length (551 mm to 590 mm), reach length (300 mm to 333 mm), and chain stay (400 mm to 407 mm). Nevertheless, they have a high head tube angle (74 deg to 80 deg) and a BB chain length values very determined (55 mm to 61 mm). Curiously in the less stressed designs (Figure 63), almost all the lines are blue because there are some points with a stress value very superior, thus, the color scale is unbalanced. But this problem is not an inconvenient since it is possible to move the bar that limits the range of admitted values, changing the scale. Thus, it is possible to eliminate those discordant values, as we can see at Figure 63. There, the less stressed designs have medium sized stack length (475 mm to 525 mm), and a high seat tube angle (82 deg to 89 deg) as in the other chart.

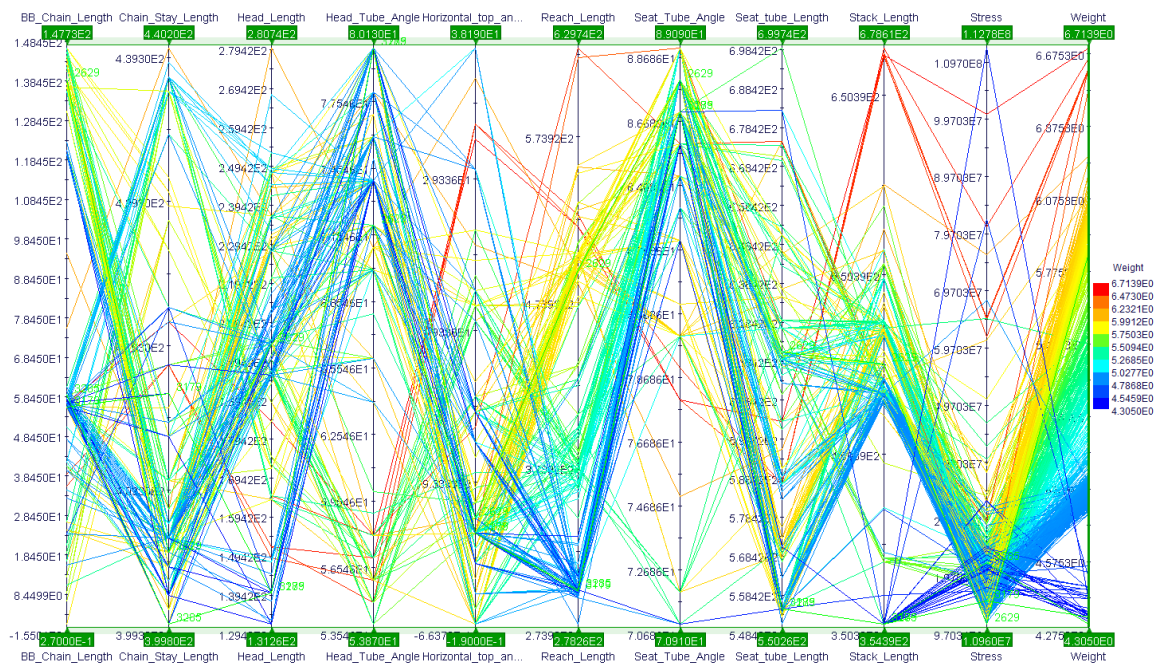


Figure 61: Canyon Road weight parallel coordinate chart.

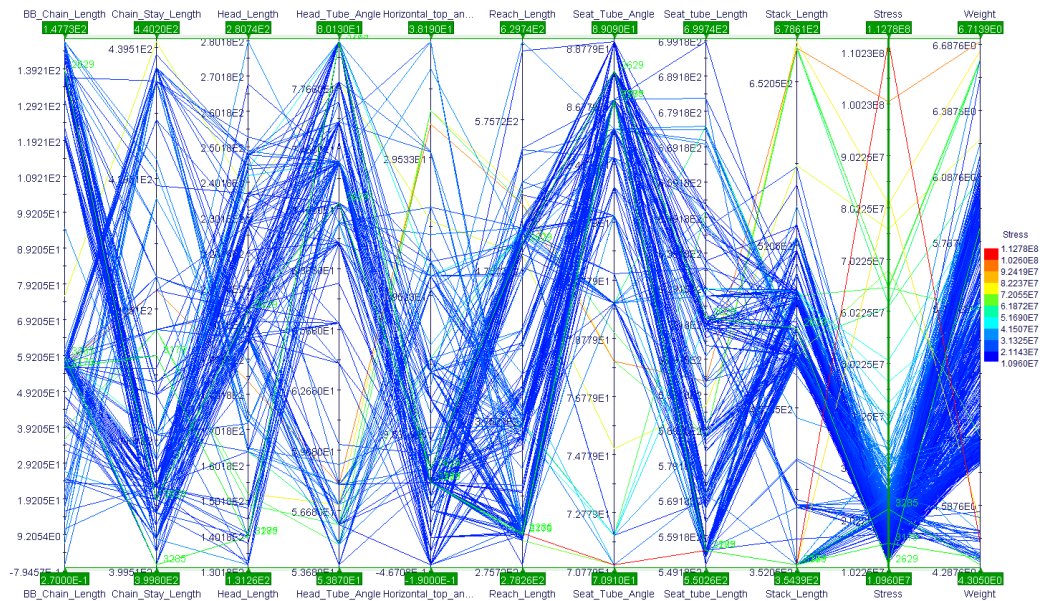


Figure 62: Canyon Road stress parallel coordinate chart.

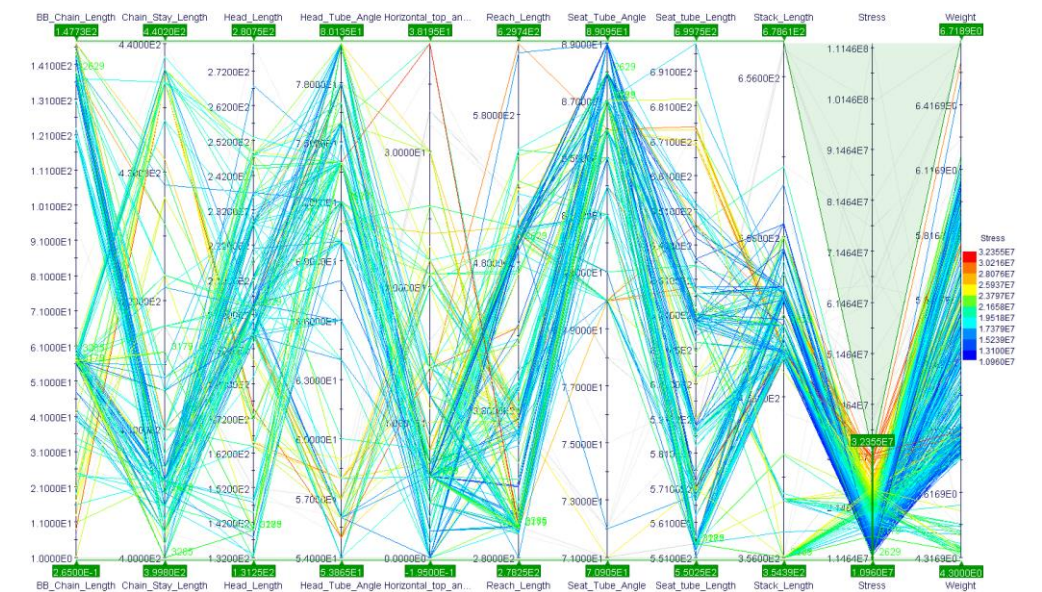


Figure 63: Canyon Road stress parallel coordinate chart filtered.

From the Dirt Love weight chart (Figure 64) we can make it clear that the lightest bike frames have a low maximum stress (from $8,2431 \cdot 10^7 Pa$ to $1,1708 \cdot 10^8 Pa$), seat tube length (304,02 mm to 321,56 mm) and chain stay length (331,73 mm to 346,44 mm). However, they usually have a high head tube angle (72 deg to 73 deg) and BB chain length (115,8 mm to 127,59 mm). Looking at the stress parallel chart (Figure 65), we can see that it happens the same as in the Canyon Road, therefore filtering the chart to improve the result we obtain theFigure 66. There, the less stressed geometries have a high head tube angle (71 deg to 73 deg) and BB chain length (117 mm to 126 mm), just like it happened in the weight chart.

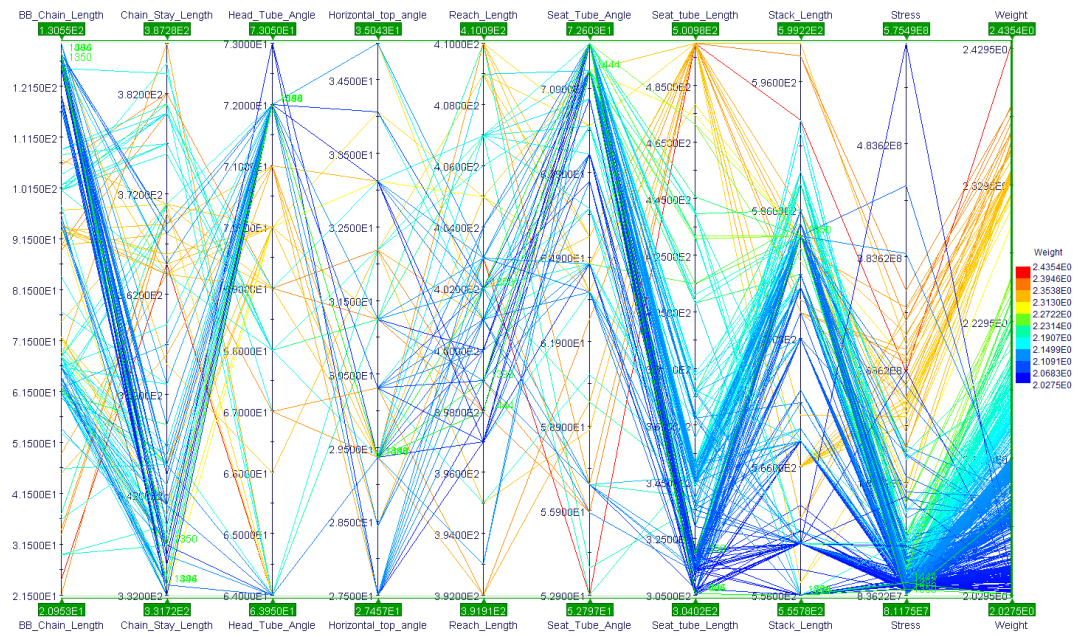


Figure 64: Dirt Love weight parallel coordinate chart.

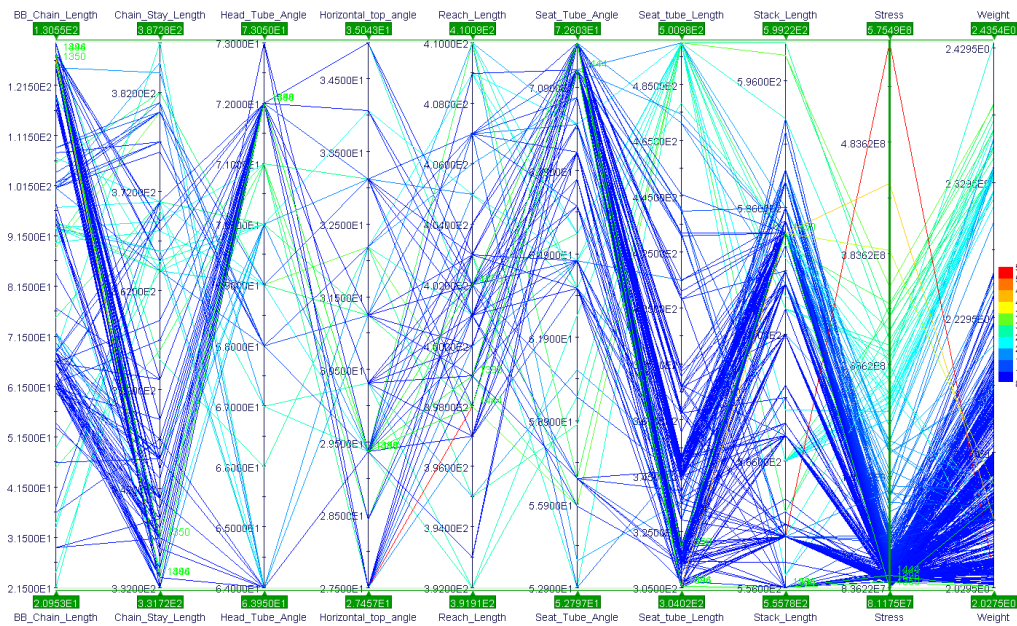


Figure 65: Dirt Love Stress parallel coordinate chart.

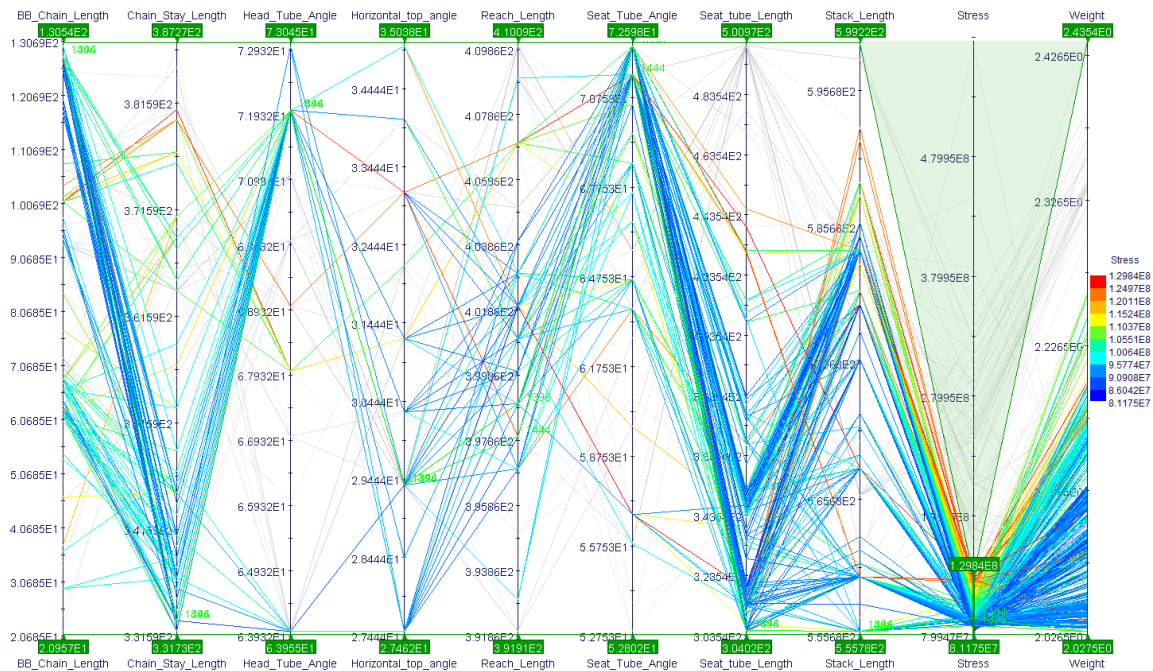


Figure 66: Dirt Love Stress parallel coordinate chart filtered.

From the S Works Epic weight parallel chart (Figure 67), it can be made clear that the lightest designs usually have a low stack length (from 580 mm to 587 mm), reach length (422 mm to 443 mm) and head length (81 mm to 89 mm). As for the stress chart (Figure 68) say that, even eliminating the designs with highest stress values, the less stressed geometries do not have any specific pattern.

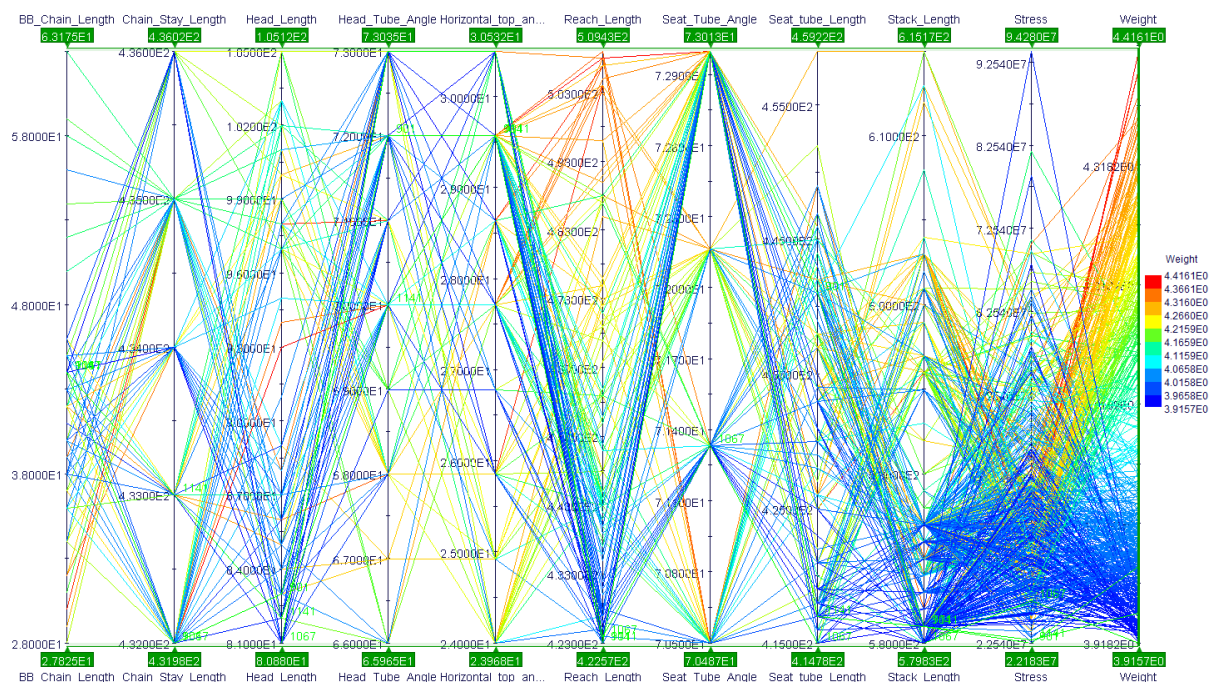


Figure 67: S-Works Epic weight parallel coordinate chart filtered.

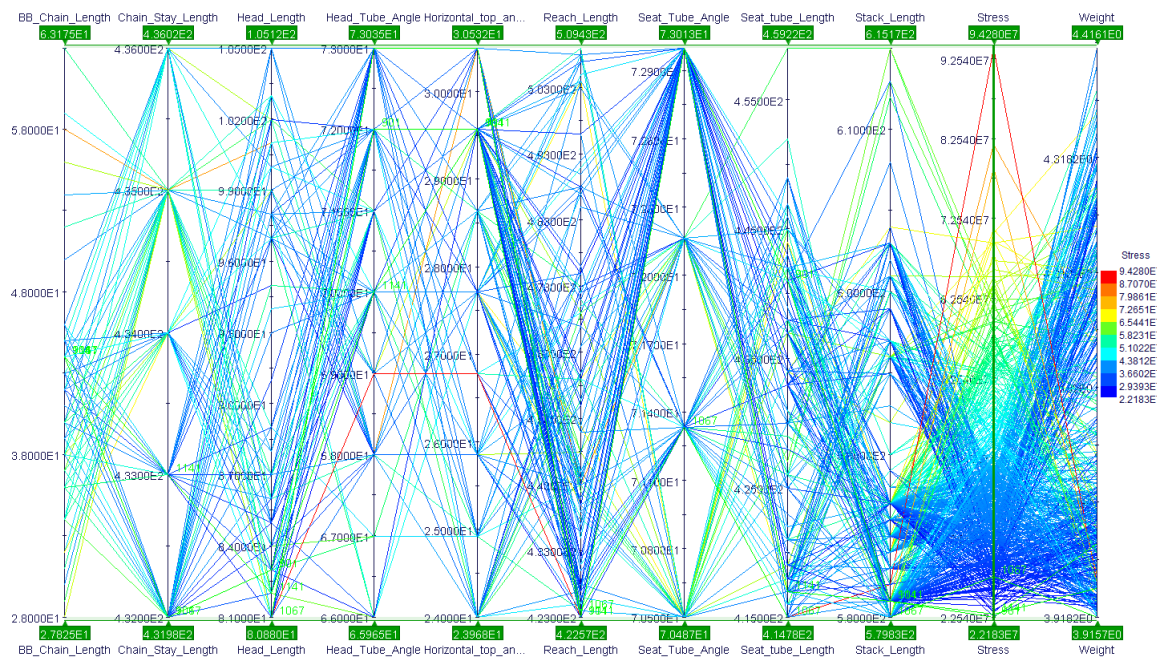


Figure 68: S-Works Epic stress parallel coordinate chart filtered.

5.4. Issues after the first optimization

When you optimize something, there are a lot of times where you realize that your model is not good for every parameter that it can have. This happens because the optimization program tries with every point of the different parameters you are giving it as an input. So, if the created model from the optimization is feasible, but then you put the parameters on your real model and you see that this cannot be like this because, for instance, the elements intersect between them, or there is any geometry which disappear or move itself, you know that this optimized model is not good.

When this happens, you must redo the model from CATIA V5® and try to get a geometry that its elements do not intersect between them with the parameters the optimization gave as the best geometry. We only had a problem with the Specialized S-Works Epic. The rest of the bike could be achieved after the optimization.

The Specialized had three problems once the optimization was done:

- The first and most visual problem was the one shown in Figure 69. At the beginning we thought that it was because we had to do two different sections to get the two colors that the bike has. At the end the problem was not that. The problem was that the geometry sketch to do the *Multi-Sections* (a circle in this part of the geometry) was done with a positioned sketch. This sketch was positioned with a wrong point, so it could move wherever it wanted, and that is why the point went upwards from the line where it should have been.



Figure 69: S-Works Epic failed design problem 1.

- The second problem that we realized it was in the element that is attached in the “belly”. We can see at Figure 70. We saw that the elements intersect between them, something that cannot be possible, so we had to modify the whole structure in that part of the frame.

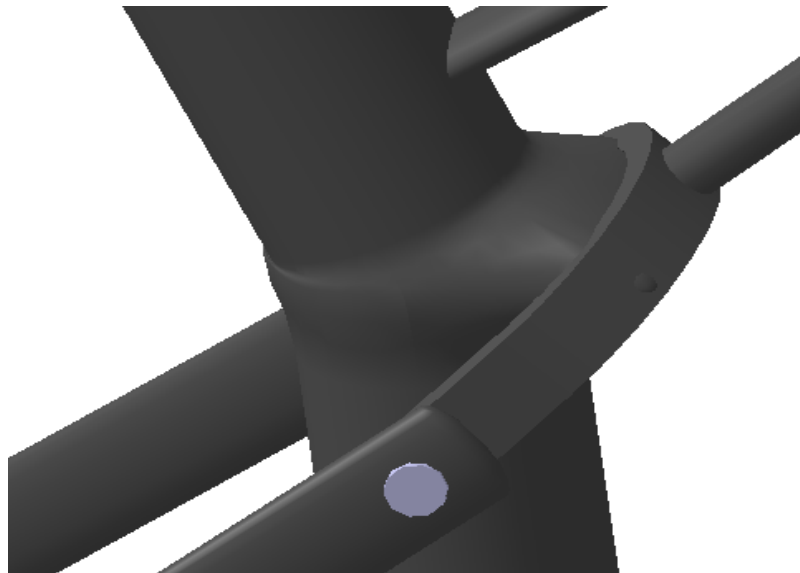


Figure 70: S-Works Epic failed design problem 2.

- The third and last issue was in the part of the spring/top tube. What happened was that the spring went so upwards, therefore it intersected with the top tube. It is something obvious that cannot happen, so you have different options to solve the problem:
 1. You can modify the position of the bar of the spring.
 2. You can modify the dimension of the spring.
 3. You can modify the position of the top tube.



Figure 71: S-Works Epic failed design problem 3.

6. CONCLUSIONS

In this Bachelor Thesis, we have developed the different methodologies followed for the modelling, analysis and optimization processes of four bike frames presented in the market.

Regarding to the modelling, carried out with CATIA V5®, two distinct procedures have been explained. Each one with its pros and cons but with satisfactory results obtained. The beginnings of the project were complicated, with several failed models that because of its complexity and workbench selected they turned out to be unviable. Nevertheless, after several attempts, it ended up finding the right way, achieving thus the four bike frames. The stress analyzes were performed also with CATIA V5®, allowing having both, CAD models and CAE analyses, in the same place facilitating work management.

This can be summed up in what can be called **efficiency**. The efficiency of the work in CATIA V5® could be much better if we would have had the measures of everything we needed to model the bikes. As this could not being possible, we made more *sketches, pads, ribs, slots*, and so forth, that the minimum number we needed in the reality.

About the optimization, employing Mode FRONTIER 2017® it has been possible to analyze hundreds of designs, achieving a great precision to select the best bike frames geometries.

The world of optimizing will still be improving, but there will be someday that some product will not be able to get any improvement because the methodology will have reached the top. That day will have to have a change of mind to continue taking another advantage, but not for the optimized product since it will not can be more optimized.

7. FUTURE RESEARCH

Despite of the fact that in this Bachelor Thesis it has been sought to recreate the bike frames with the highest possible reliability, there are several aspects could be improved to get closer to design process of real bike companies. Some bearings to have into account to continue improving the optimization process are:

1. Apply to the bike frames a thickness and parameterize it individually for each part of the frame, so as to have higher thickness at the critical points (as the triple intersection between seat stay, seat and top tube, where the maximum stress concentration was located in our simulations). By this way, it is possible to reduce the weight even more, maintaining the resistance. Moreover, we could parameterize the measurements, which define the shape of the tubes in order not to change only the frame geometry, but also the patterns of each part. This would imply to have to use either another CATIA V5® workbench or CAE program, insomuch as the tube connections methodology followed of splines plus fills would be really difficult, or even impossible, to adapt to these new circumstances due to the ease of giving errors.
2. Implement more realistic loads on the bike frames, have into account the gravity, the force executed due to fastening of the handlebar and the alternative force exercised over the pedals. In addition, it could study different situations as when the cyclist is going up (to apply more stress over the pedals due to if the cyclist stands up) and going down, as well as introduce in the bike the air resistance depending on the velocity of the cyclist (or in this case, as the study is not dynamic, using an average measure). Another interesting situation to analyze is when the bike land after a jump, considering the height of fall and to calculate the maximum jump that can resist.
3. Assess fatigue resistance due to cyclic vibrations generated by the road imperfections and the cyclist movement. In this way, it is possible to estimate the life cycle of the product, thus adjusting the frame parameters to satisfy the legal framework.
4. Bring all this optimization knowledge to the other bike parts (such as wheels, handlebar, saddle, and so forth) in order to improve a full bike instead of just the frame.
5. Incorporate advanced material properties. Even though our bike frames are made of aluminum, we could use more materials which are being used now, such as carbon fiber, orienting the fibers with the direction of the stress to improve the resistance to weight ratio. Another thing is to implement these materials in every specific part of the frame, instead of just using the material for the whole bike.

APPENDIX

Appendix 1. Method of approaching bike measurements

Sometimes it happens that the official web of the bike does not provide the enough data to get the variable values. In the case that it is not possible to get the value with the others we have resorted to the following method. We paste in the program Paint® a photo of the profile of the bike that we want to know some measurement, in this example it is the Canyon Road [2]. Then, we draw a line over the seat tube since it is a part of the bike quite easy to see the limits of the tube with great precision and because every bike web counts with this measurement. Paint® provides us with the width and height distance of the made line in terms of number of pixels (Figure 1) thus, using the Pythagoras Theorem, we get the value of the line length in pixels:

$$\sqrt{199^2 + 667^2} = 696 \text{ pixels}$$

Now, we can obtain the mm to pixel ratio. If the seat tube measures 530 mm, the ratio turns out:

$$\frac{530 \text{ mm}}{696 \text{ pixels}} = 0,76 \text{ mm/pixel}$$

Once we have this, just drawing a line over the measurement that we want to know its value (the length or width of a tube, for example), getting its length in pixels and multiplying by the ratio, we can acquire it. Furthermore, it is possible to estimate the value of an angle resorting to its tangent.



Figure 72: Calculation of mm from pixels (Allen, 2018).

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