14. Manufacturing and cost study

14.1. Manufacture by direct metal laser sintering

Metal Laser Direct Sintering (DMLS) is an additive metal fabrication technology that refers to selective laser sintering (SLS) or selective laser fusion (SLM), which generates prototypes and metal tools directly from CAD data.

To begin the printing process, the 3D printer fills a chamber with inert gas, argon, and heats up to the optimum printing temperature. A thin layer of powder is then deposited on the tray, according to the height previously defined by the machine software. The laser sweeps the cross section of the part, fusing the metal particles. When the layer is finished, the tray goes down and another layer of powder is added. The process is repeated until the final piece is obtained.

Pass finish, the 3D printer must be allowed to cool to remove the unfused dust from the container and clean the printed part. After a conditioning system this powder is reusable. This piece is attached to the tray, usually by printed supports. These are necessary because they reduce the phenomena of deformation and distortion observed at high processing temperatures. They are usually removed by cutting or machining methods or wire EDM. The parts can be heat-treated to reduce residual stresses and improve their mechanical properties. In addition to the aftertreatment of the part, CNC machining can be included, but also a polishing process to offer better surface quality.

14.2 Chassis manufacturing simulation 1.

In accordance with the design material we proceed to perform a simulation of the manufacture of chassis 1. For the simulations we will use the Autodesk Netfabb program with the configuration of the EOS M 290 printing machine of powder bed technology.

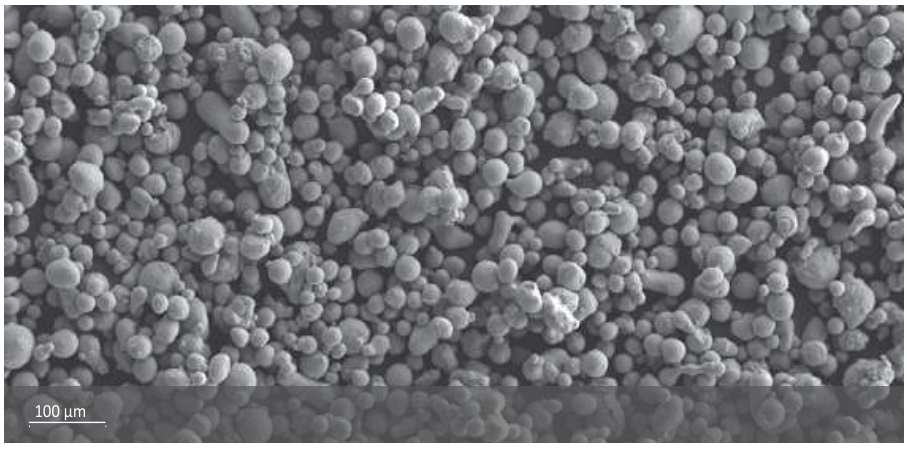
EOS M 290

AlSi10Mg aluminum is a widely used alloy that combines light weight and good mechanical properties. Different heat treatments can be applied to modify the properties, for example, to increase ductility and conductivity. The material has good thermal and electrical conductivity, especially after heat treatment. In addition, the parts made of this material are gas-tight.

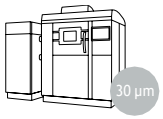
Properties of powder

The chemical composition of EOS Aluminium AlSi10Mg powder is subject to DIN EN 1706 (EN AC—43000)

Chemical composition of the powder	(percentage by weight)			Dust particle size	
Element	Min.		Maximum.	Generic particle size distribution	
					25 - 70 µm
To the	The rest		The rest, (87.1)		
Yes	9.0		11.0		
Faith	-		0.55		
Cu	-		0.05		
Mn	-		0.45		
Mg	0.25		0.45		
Nor	-		0.05		
Zn	-		0.10		
Pb	-		0.05		
Sn	-		0.05		
Thee	-		0.15		



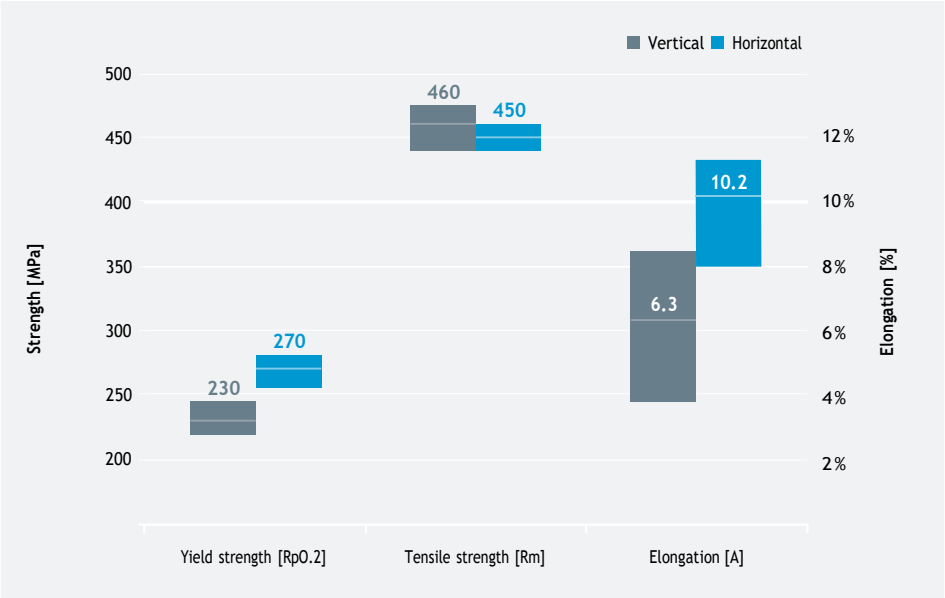
Below we show an snapshot of the mechanical properties of the manufacturer's data sheet. In an explanatory way, in this study the properties of the Fusion360 library have been used and not those shown below.



Mechanical Properties

Mechanical properties (as manufactured state)

	Yield strength Rp0.2 [MPa]	Tensile strength Rm [MPa]	Elongation at break A [%]	Number of samples
Vertical	230	460	6.3	261
Horizontal	270	450	10.2	108



The testing was done according to ISO 6892-1, B10. Machined (turned) samples were used.

Typical mechanical properties (heat treated state, EOS T6)

	Yield strength Rp0.2 [MPa]	Tensile strength Rm [MPa]	Elongation at break A [%]	Number of samples
Vertical	250	310	11	42
Horizontal	260	320	11	36

Looking at this table we can see a considerable anisotropy between the vertical and horizontal axes. The melting process of the powder act alters the properties of the material considerably, creating a kind of microstructure in the horizontal plane that increases the creep tension. The successive sweeps of the laser in the XY plane generate porosity and alter the mechanical properties, according to (Zyguła et al. 2018),who compares in his study the tensile strength of this alloy built by casting and SLM technique, with and without T6 treatment. The results of the study are as follows:

	E, GPa	Elastic limit at 0.2%, MPa	Ultimate breaking stress, MPa	Elongation, %	HV hardness	Impact energy, J//cm^(2)
SLM	32	159	160	1.59	107+-2	3.4
Foundry	114	99	193	6.52	67+-3	3.8
SLM T6	64	171	192	1.77	109+-3	2.6
Foundry T6	104	242	309	6.89	108+-6	3.6

The aforementioned study concludes that the decrease in mechanical properties with respect to the casting specimen is due to the porosity generated by the rapid cooling of the molten metal after laser sweeps. Powder supplied by EOS was used on a Renishaw AM 250 SLM machine.

Note that there is a very considerable difference between the EOS data and those of the Polish study, the breaking deformation is below 2% unlike the 11% promised by the manufacturer, the elastic limit to 2% of 170 mega pascals falls within the range that the manufacturer claims. But since a different machine has been used, the following can be concluded.

The manufacturing process by DMLS technology generates porosity that explains the decrease in breakage elongation and a series of microstructures that increase the elastic limit of the parts manufactured as a localized thermal treatment.

The manufacturer warns us that increasing the temperature of the construction platform can facilitate the manufacturing process but that together with the high energy of the laser, if the manufacturing time is large, excessive aging of the part can occur. Especially if the supports by evacuate enough energy by conduction.

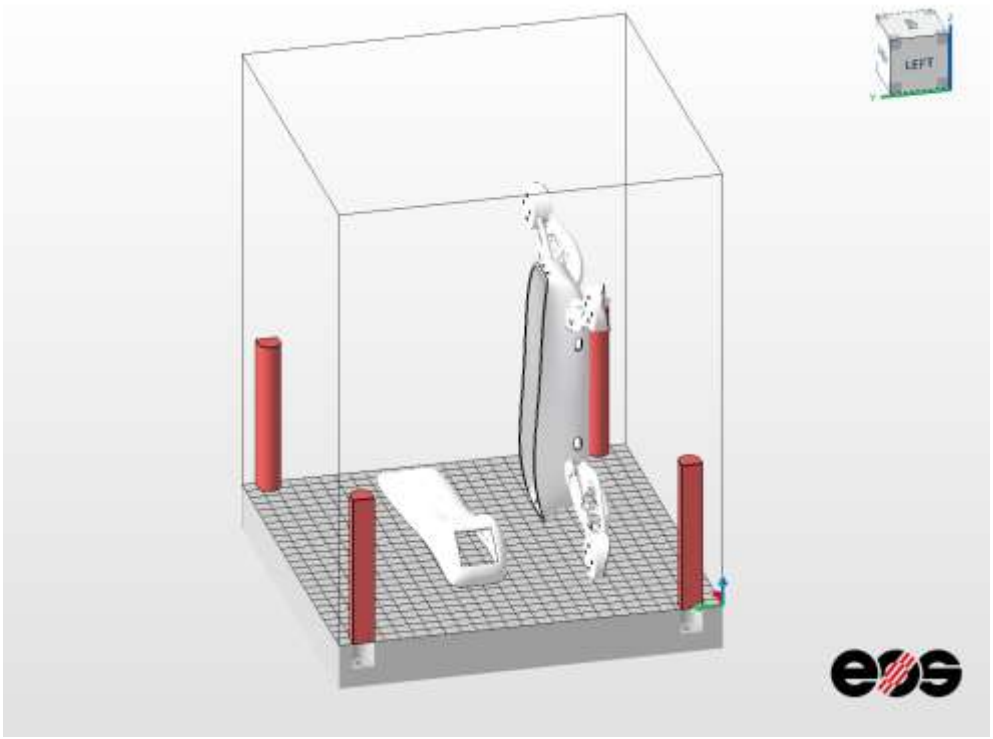
Post-manufacturing heat treatment decisively influences the mechanical properties of the part. To obtain the mechanical performance described above, the pieces must be subjected once printed to a thermal treatment.

The treatment is called T6, it is necessary to obtain homogeneous mechanical properties and avoid anisotropies. Optionally, thermal treatments that increase porosity can be used.

- Annealing for 30 minutes at 530 °C followed by immediate cooling to water or polymer.
- Artificial aging of 6 hours at 165°C followed by air cooling.

For manufacturing authentication we will use the Autodesk Netfabb program with the configuration of the EOS M 290 printing machine of powder bed technology.

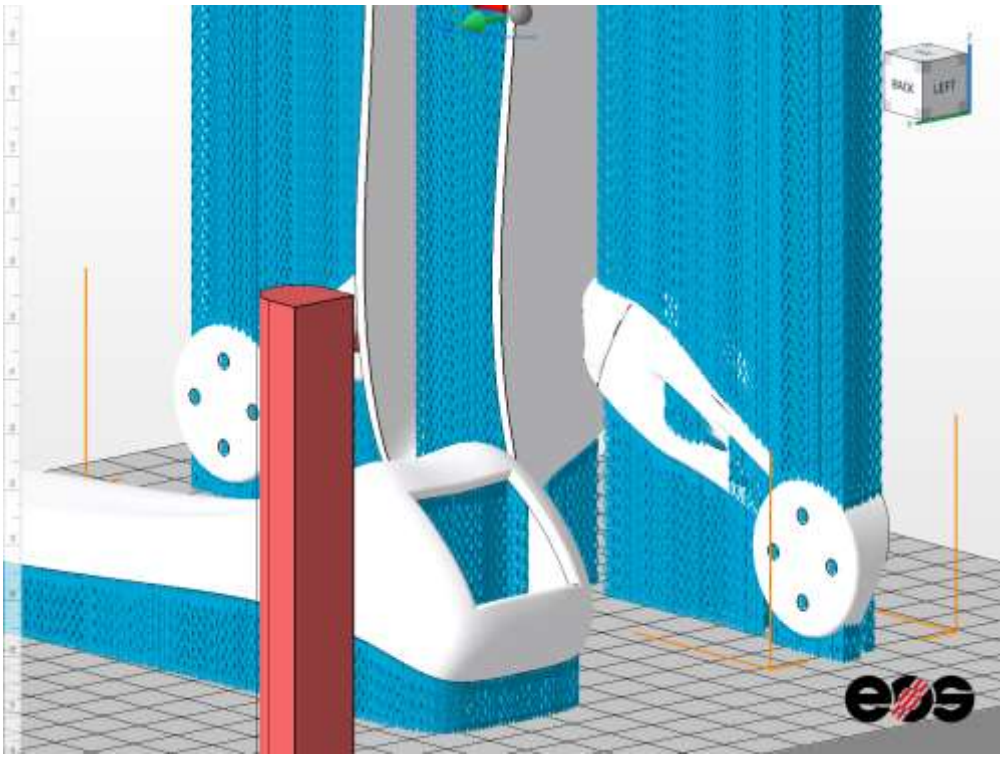
We import the two pieces that make up the chassis in SAT format and place them in position



We configure the machine for the parameters of AlSi10Mg, specifically:

EOSPrint AlSi10Mg_FlexM291 2.01

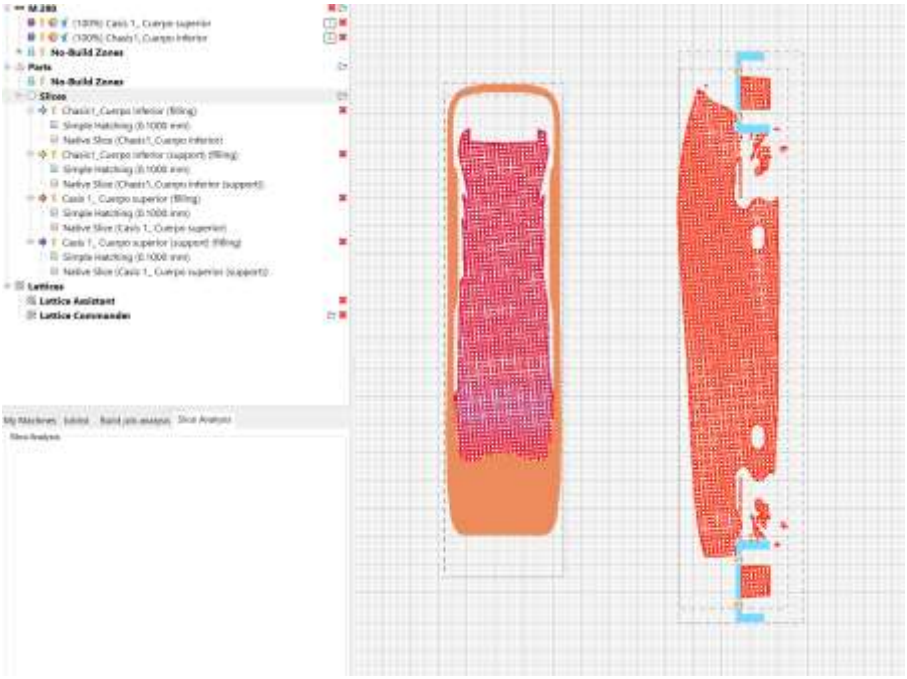
We generate the supports of both pieces using the SML script



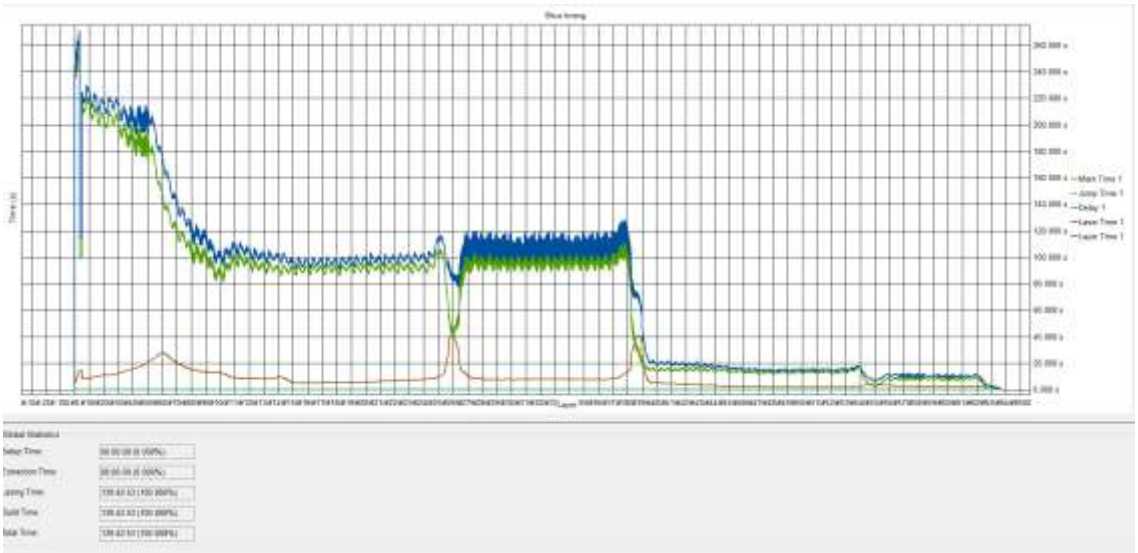
We generate the print layers with the configuration of 30 microns thick.

Once the external profiles of both the supports and the pieces have been generated, they must be filled with a specific pattern, in our case, a simple pattern. If you have a computer of moderate performance, as is the case, it is recommended not to include the original layers or the layer display system will consume all the available RAM and we will not be able to continue with the project.

At the moment before exporting the manufacturing file we will have a slice organization like the one shown below



To obtain a real estimate of the manufacturing time we must recalculate each layer separately and use the tool of the estimation program.



Summary:

Volume	92.02 cm³
Support	76.86 cm³
Maximum height	191.11 mm
Manufacturing time	139h 43 min

14.3 Chassis Costing Table 1

Cost calculation table					
	Power consumption	max. 8.5 kW/ medium 2.4 kW/ with heating platform 3.2 kW	3,2	kW/h	
	Compressed air supply	20 m³/h 102 psi >>>> 0.6 kW/h	0,6	kW/h	
		Total	3,8	kW/h	
Average price kW/h in € 2021	0,253				
	Hours	Minutes	Total hours		
Total printing time	139	40	139,667		
					Costs/part
Cost of printing electricity					134,28
AlSi10 powder cost	134	€/Kg			
Density AlSi10	2,59	g/ cm³			
Volume piece	92,02	cm³			
Support volume	76,86	cm³			
Total volume	168,88	cm³			
Cost of raw materials					58,61
Annealed at 530ºC for 10 min and air cooling	0,5	h			
6-hour artificial ageing at 165 °C	6	h			
Heat treatment cost					2,78
				Total Costs	195,67

14.3 Chassis Manufacturing Simulation 2.

EOS M 290

According to the technical sheet of the brand:

EOS Titanium Ti64 is a titanium alloy powder intended for processing on EOS DMLS™ machines. The following tables provide information and data on parts made from EOS Titania Ti64 powder (EOS art.-no. 9011-0039) in the following system configuration:

EOS Parameter Set: Ti64_PerformanceM291 1.10

Material composition [% by weight]	Element	Min	Maximum
	To the	5.50	6.50
	In	3.50	4.50
	Or	-	0.150
	N	-	0.040
	C	-	0.080
	H	-	0.012
	Faith	-	0.250
	And	-	0.005
	Other elements, each	-	0.10
	Other elements, total	-	0.40
	Thee		The rest(87.96)
Max particle size.			
d50 [1]	39 ± 3 µm		

Layer thickness	30 µm
Volume speed [2]	5 mm^3/s (18 cm^3/h)

Volume rate is a measure of the construction speed during laser exposure of the surface area. The total speed of construction depends on this volume rate and many other factors, such as the exposure parameters of the contours, the supports, the surface up and down, the temperature coating, or the configuration of LPM, "layered powder metallurgy" or stratified powder metallurgy.

Description

Parts manufactured in the EOS Titanium Ti64 have a chemical composition and mechanical properties in accordance with ASTM F1472. Ti64 is a well-known light alloy, characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight. Parts manufactured using this process can be machined and polished. Due to the layered construction method, the parts have a certain anisotropy.

Quality

The quality of EOS Titanium Ti64 powder batches is guaranteed by quality certification procedures. Procedures include sampling (ASTM B215), PSD analysis (ISO 13320), chemical analysis (ASTM E2371, ASTM E1409, ASTM E1941, ASTM E1447) and mechanical testing (ISO 6892-1). The results of the quality assurance tests are given in the specific batch Mill Test Certificates (MTC) according to EN 10204 type 3.1.

Physical and chemical properties of parts

Part density	4.41 g/cm³
Minimum wall thickness	0.3-0.4
Surface roughness after shooting	$_{Ra}$ 5-9 µm; Rcon 20-50 µm

Mechanical stability depends on geometry (wall height, etc.) and application.

The numbers were measured on the horizontal (upward-facing) and vertical surfaces of the test cubes. Due to the layered construction, roughness depends largely on the orientation of the surface, for example, sloping and curved surfaces exhibit a ladder-step effect.

Room temperature tensile test data

	As built	Heat treatment [7]
Maximum tensile strength, R_m	1290 ± 80 MPa	1070 ± 80 MPa
Yield strength, $R_{p0.2}$	1150 ± 80 MPa	1010 ± 80 MPa
Lengthening at rest, A	8 ± 4 %	14 ± 4 %

Tensile tests according to ISO 6892-1:2009 (B) Annex D, proportional test parts, neck area diameter 5 mm (0.2 inches), original gauge length 25 mm (1 inch).

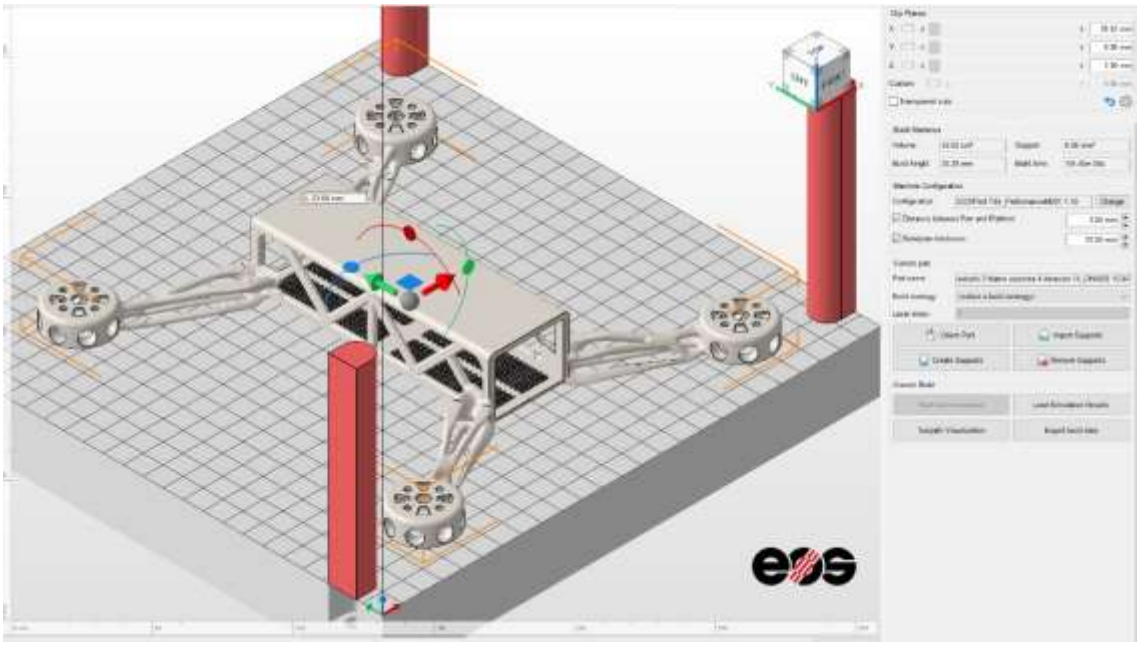
The specimens were heat-treated at 800 °C for 2 hours in an inert argon atmosphere.

Hardness

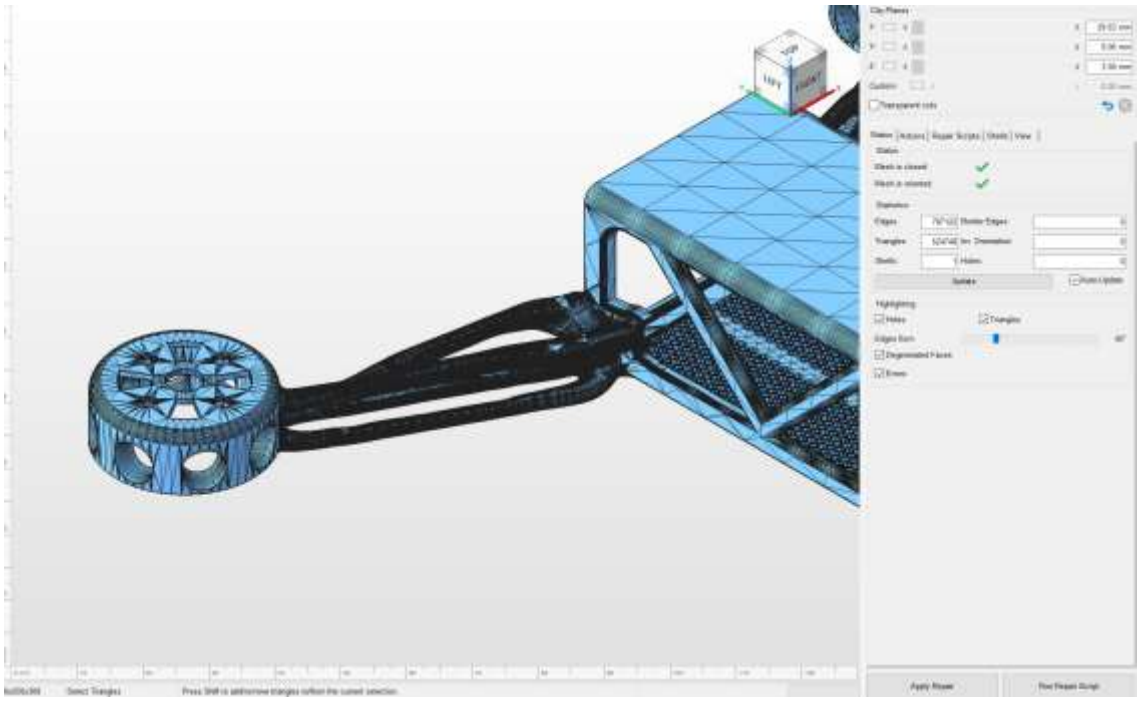
	Hardness as constructed	Heat treatment
Vickers Hardness (HV)	guy. 320 ± 15 HV5	n.a.

Hardness measurement according to EN ISO 6507-1:2005 with load 5kgf (HV5).

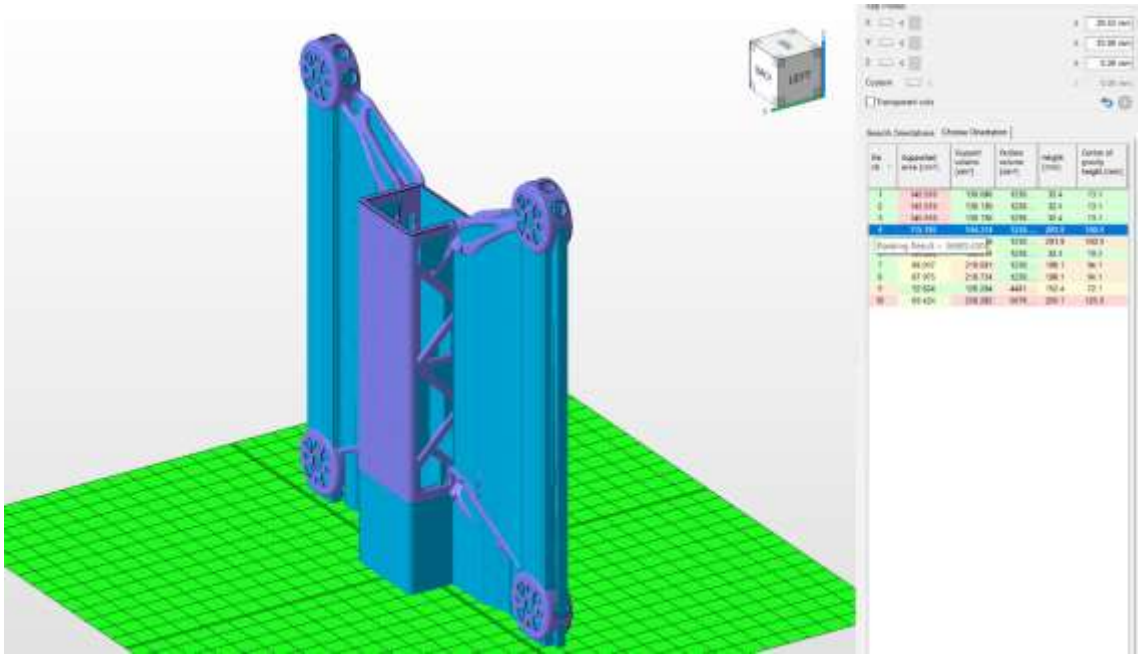
First of all we export the chassis in SAT format in the Fusion360 program.



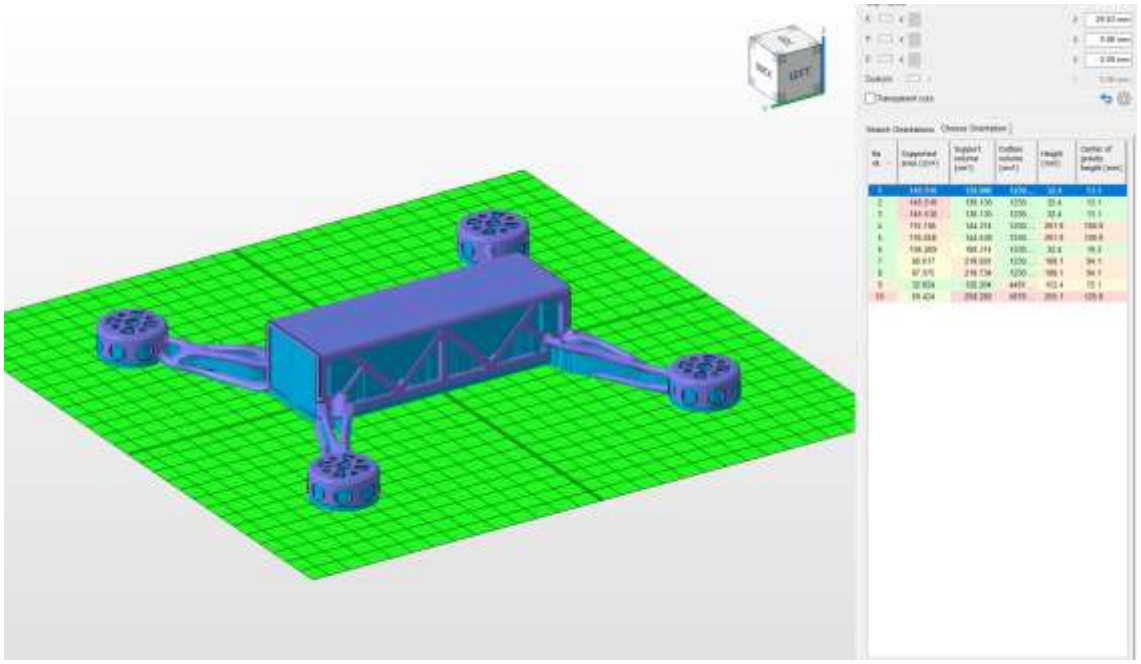
We perform an automatic repair that consists of creating a mesh of the imported geometry.



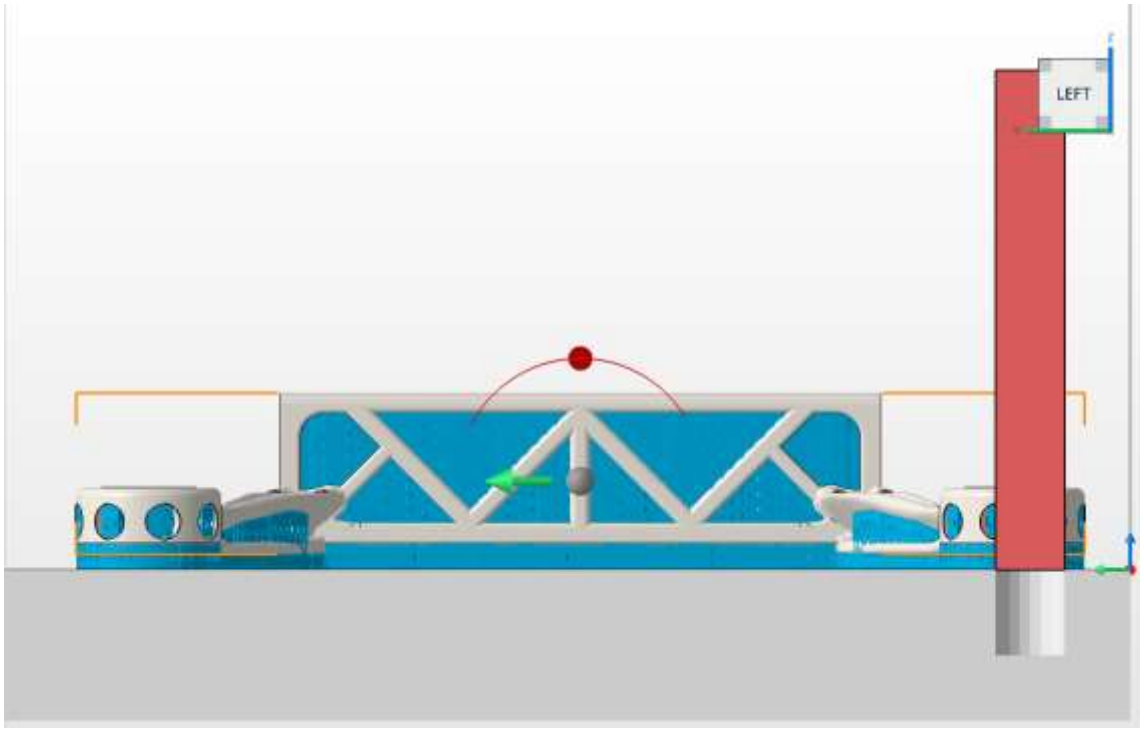
We start the automatic script to search for optimal orientations.

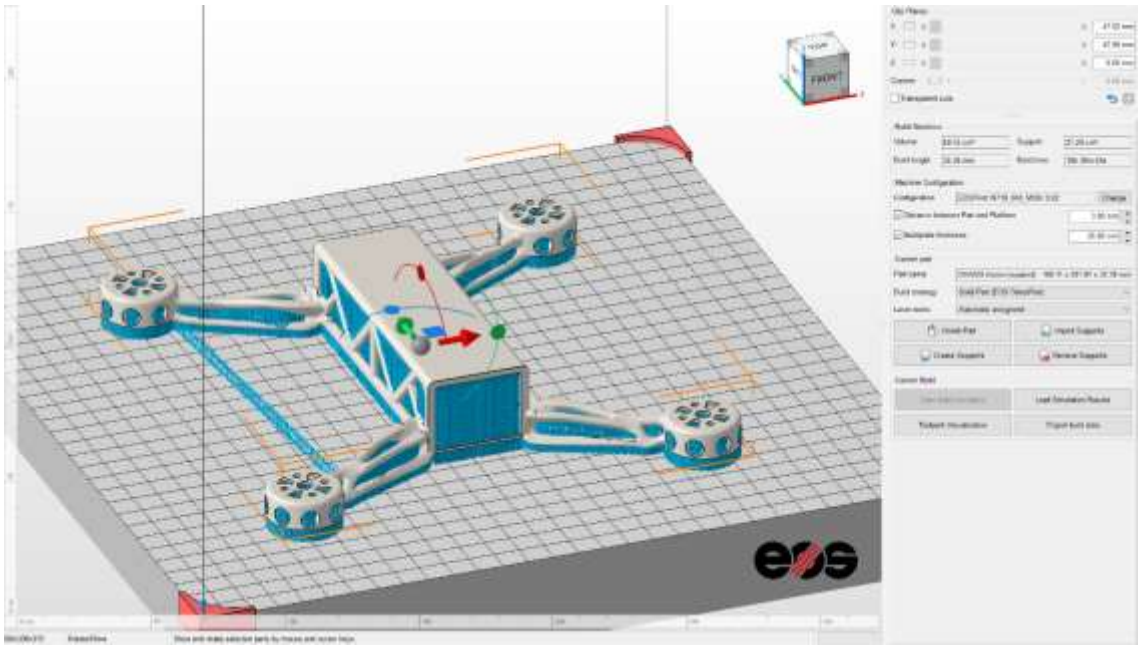


We chose the one with the lowest support volume since we are ready to make a simple print and not several frames at once.

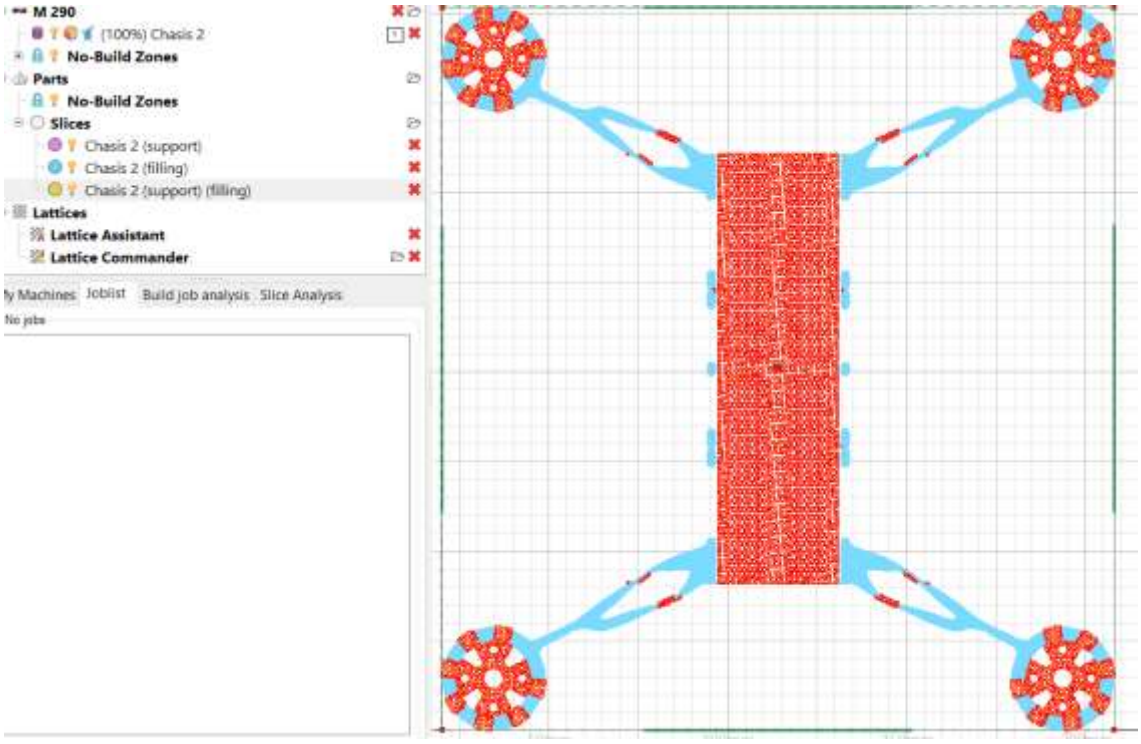


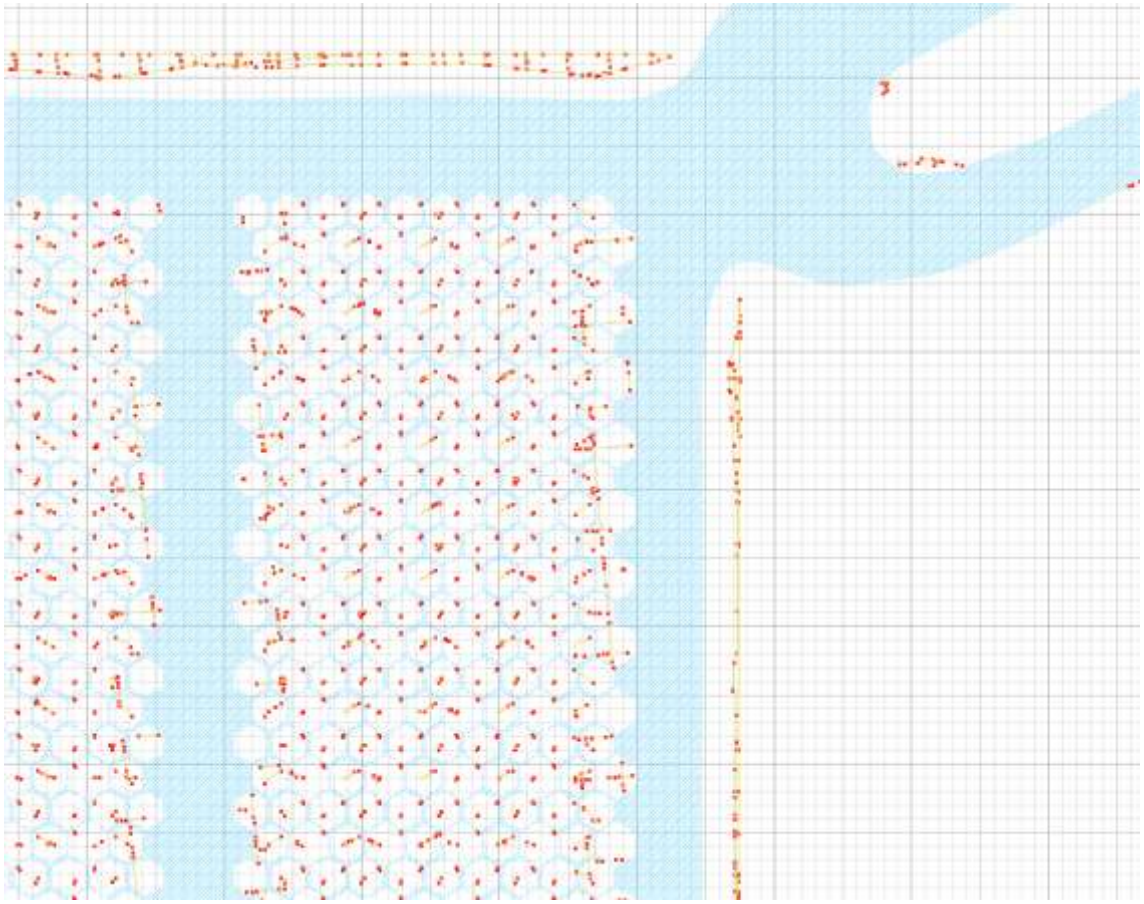
To generate the soporres we must execute a specific script for DML technology



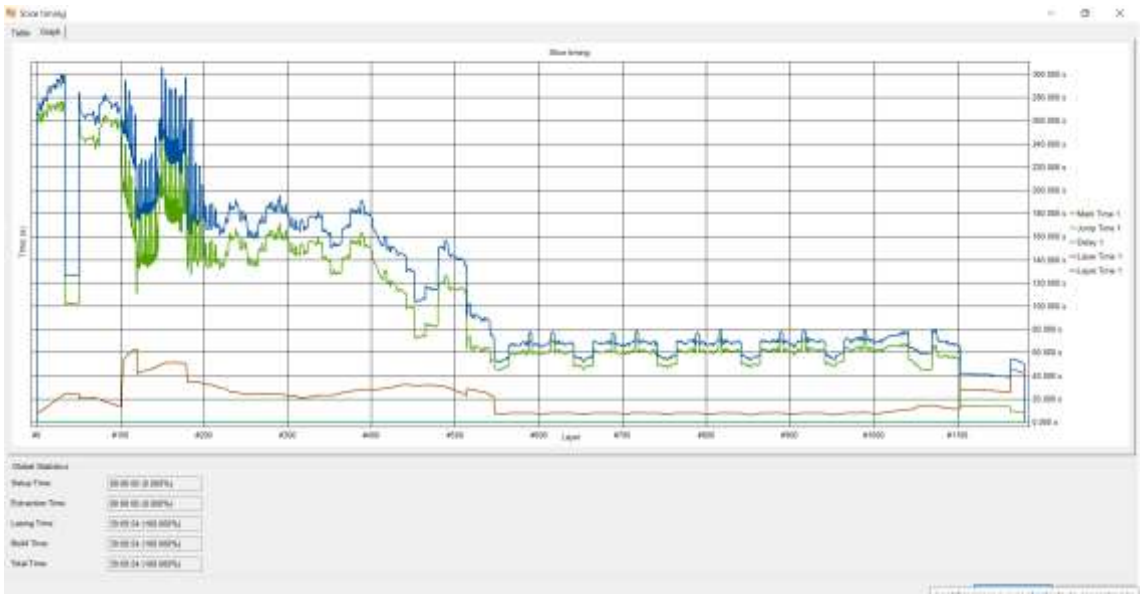


Then, we generate the sweep program by setting a thickness of 30 microns.





In this snapshot you can see how the thickness of the walls of the honeycomb is at the limit of thickness of manufacture of this machine. We generate a manufacturing time simulation for all layers.



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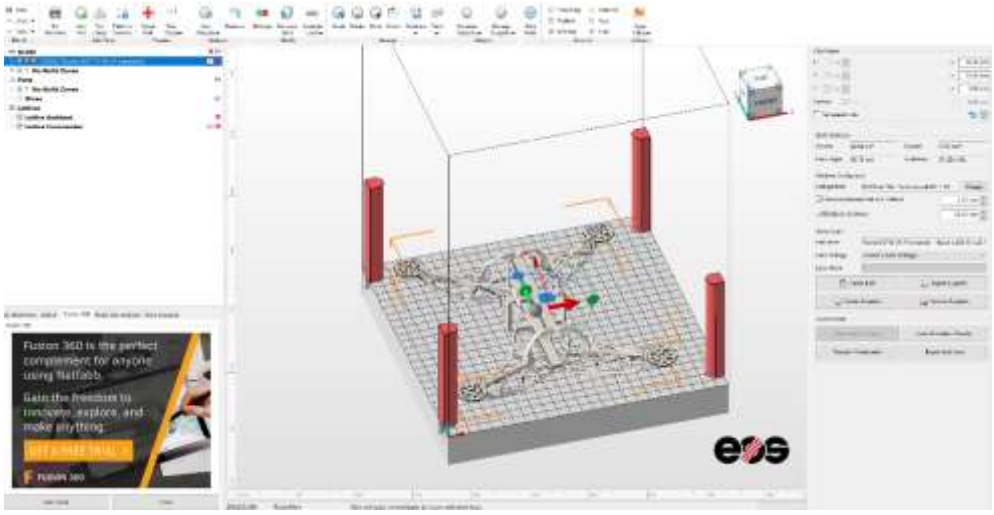
Summary:

Volume	42.02 cm³
Support	19.95 cm³
Max. height	35.39 mm
Manufacturing time	39h 10 min

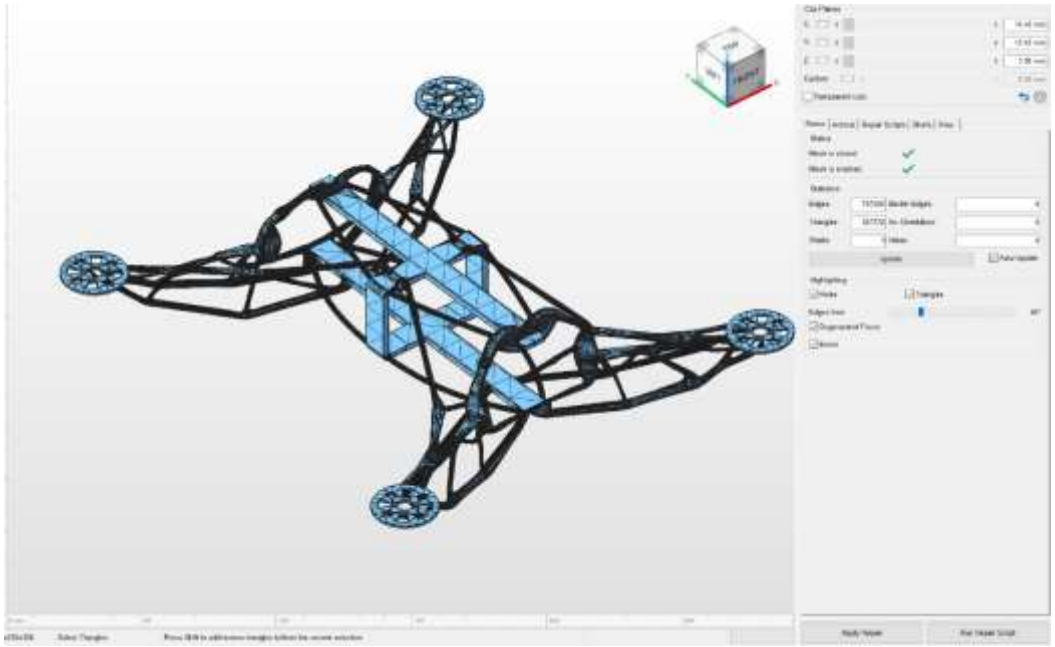
Cost calculation table					
	Power consumption	max. 8.5 kW/ medium 2.4 kW/ with heating platform 3.2 kW	3,2	kW/h	
	Compressed air supply	20 m³/h 102 psi >>>> 0.6 kW/h	0,6	kW/h	
		Total	3,8	kW/h	
Average price kW/h in € 2021	0,253				
	Hours	Minutes	Total hours		
Total printing time	39	10	39,167		
					Costs/part
Cost of printing electricity					37,65
Ti6Al4V powder cost	542,5	€/Kg			
Ti6Al4V Density	4,41	g/ cm³			
Volume piece	42,02	cm³			
Support volume	19,95	cm³			
Total volume	61,97	cm³			
Yield	0,67				
Cost of raw materials					120,93
Annealed at 530ºC for 10 min and air cooling	0,5	h			
6-hour artificial ageing at 165 °C	6	h			
Heat treatment cost					2,78
				Total Costs	161,37

We export the manufacturing file for the printer.

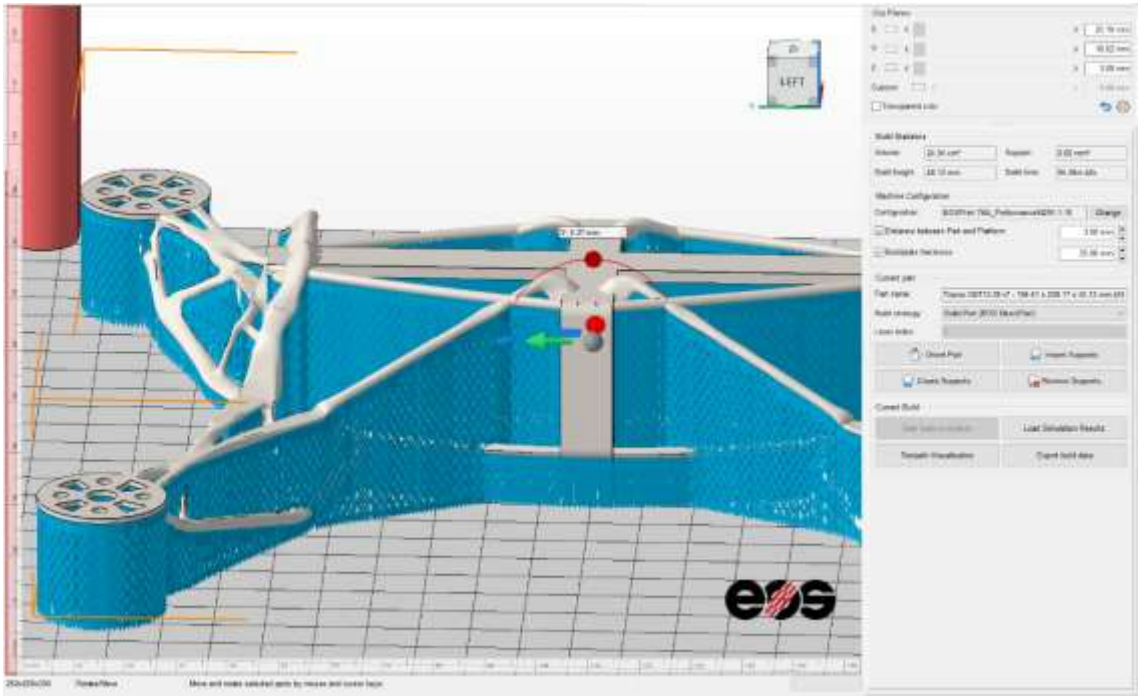
As in the previous analysis we will use the configuration of the EOS M 290 machine for the Ti64 material, we import the file in SAT format



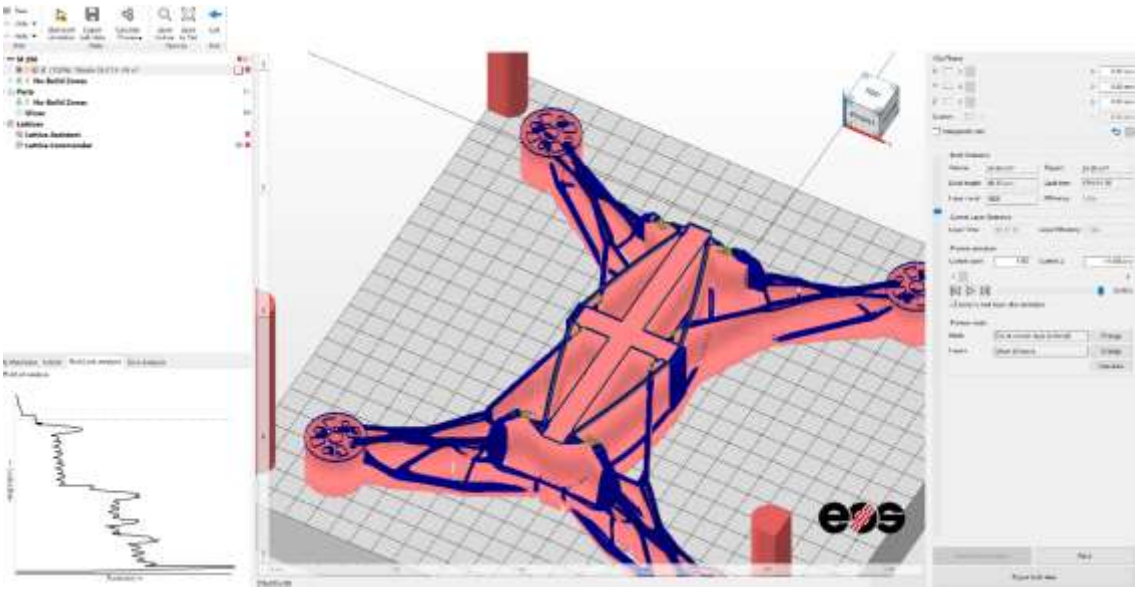
We generate a mesh



Supports are generated with the script for SLM technology



Below, we show a snapshot of one of the layers of the manufacturing process.



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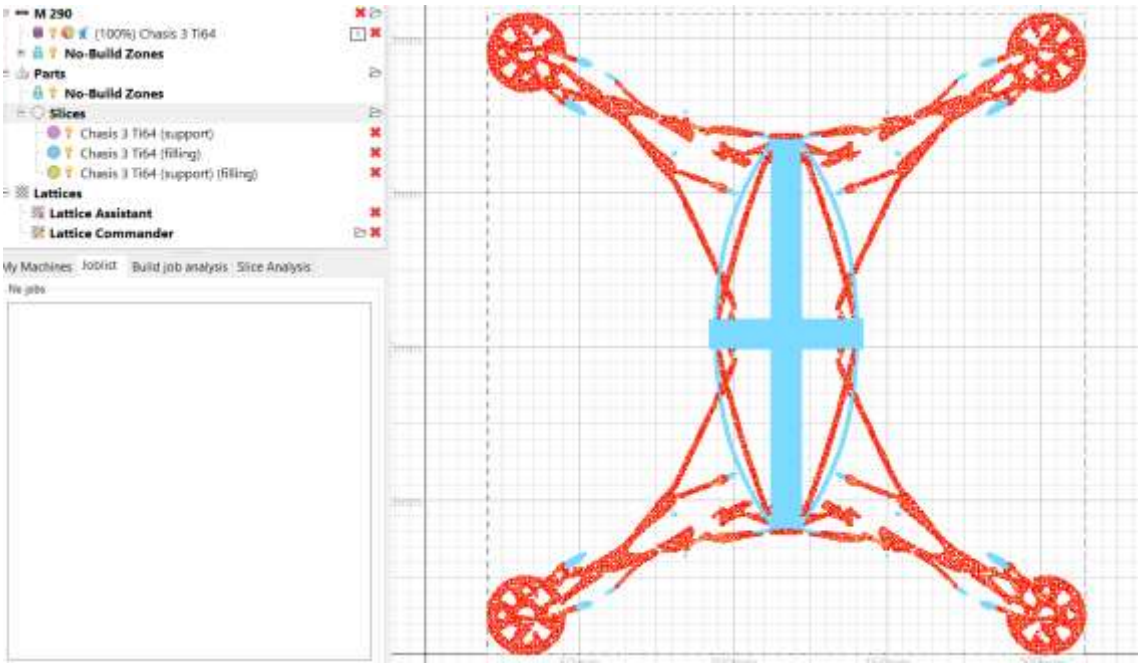
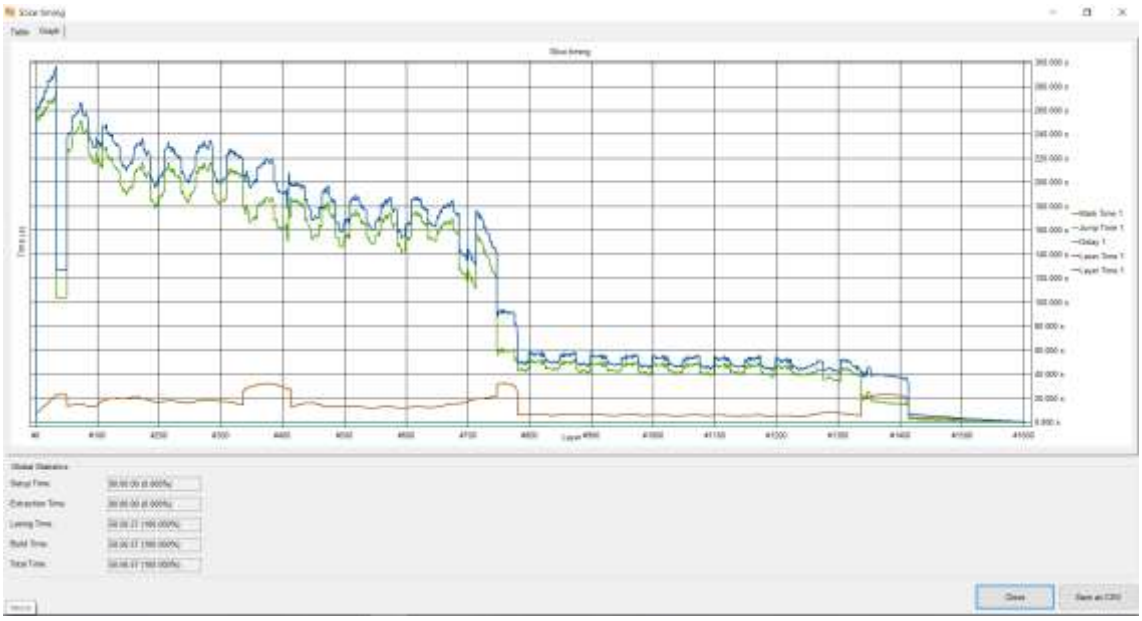


The areas colored blue are the filler, and the red ones the support.

We simulate the manufacturing time of all layers



Summary:

Volume	24.94 cm^3
Support	24.80 cm^3
Max. height	48.13 mm
Manufacturing time	14h 24m

Chassis Costing Table 3					
	Power consumption	max. 8.5 kW/ medium 2.4 kW/ with heating platform 3.2 kW	3,2	kW/h	
	Compressed air supply	20 m³/h 102 psi >>>> 0.6 kW/h	0,6	kW/h	
		Total	3,8	kW/h	
Average price kW/h in € 2021	0,253				
	Hours	Minutes	Total hours		
Total printing time	50	57	50,950		
					Costs/part
Cost of printing electricity					48,98
Ti6AI4V powder cost	542,5	€/Kg			
Ti6AI4V Density	4,41	g/ cm³			
Volume piece	24,94	cm³			
Support volume	28,8	cm³			
Total volume	53,74	cm³			
Yield	0,46				
Cost of raw materials					128,57
Annealed at 530ºC for 10 min and air cooling	0,5	h			
6-hour artificial ageing at 165 °C	6	h			
Heat treatment cost					2,78
				Total Costs	180,34

It is an additive manufacturing system where a computer-controlled extrusion head extrudes a thread of thermoplastic material. This type of modeling constructs the parts three-dimensionally by advancing a plastic thread to an extrusion head where it is melted and extruded. To print ABS plastic the printing environment is confined and an approximate temperature of 90 °C is maintained.

The automated head produces two flat X and Y movements on a platform with vertical movement. The head performs the function of extruder, heating the filament of thermoplastic material, from which it is fed, until it melts at an approximate temperature of 250 ° C. The deposition of the material on the base performs the construction of each section or layer of the piece. each time a layer is completed the extruder changes the z dimension and repeats the process

Depending on the shape of the object or piece to be manufactured, it is necessary to consider the need to build supports while the piece is built. These must be done in a way that allows them to be removed without excessive complications once the creation process is finished.

14.6 Chassis Manufacturing Simulation 4

To perform the cost calculation of chassis four in ABS we will perform the simulation using Fusion360 of a print on an Aycubic 4Max machine. This printer implements fused filament manufacturing (FDM) modeling.

We select the bodies to be printed and position them in the work area of the printer.

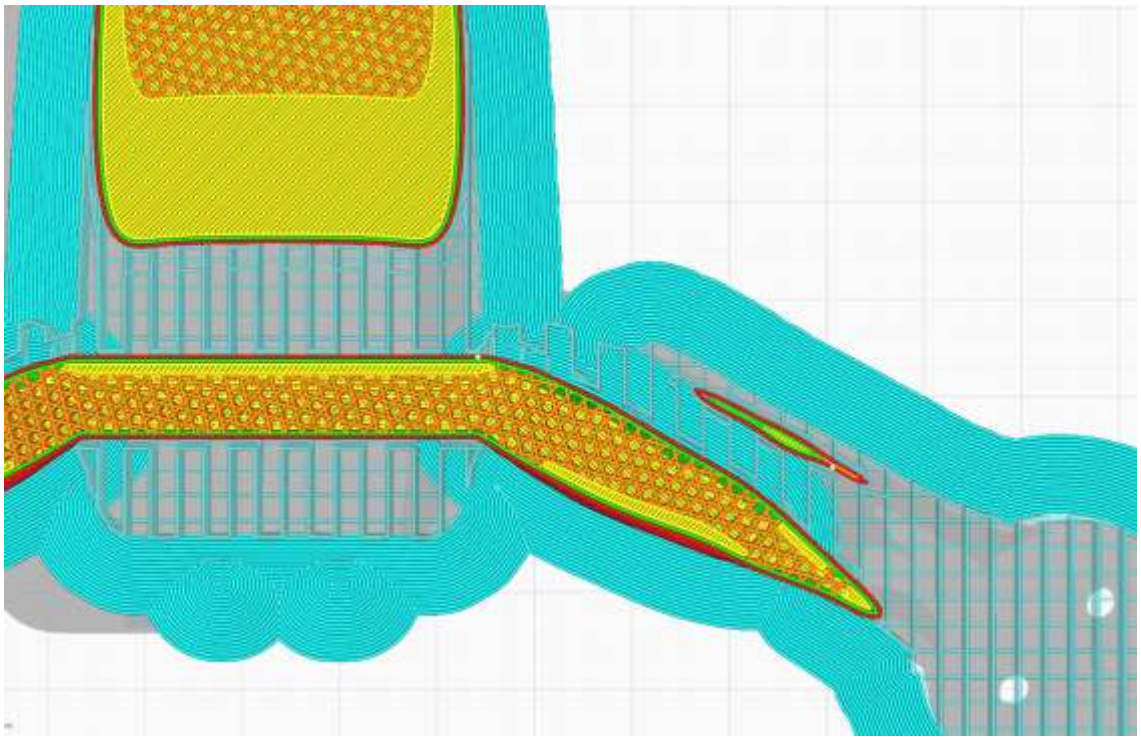
We will perform two printing simulations:

- Lower body filled with tri-hexagon type at 70% filling.
- Upper body filled with tri-hexagon type at 70% filling.

As printing parameters we configure the following

Printer configuration parameters	
FDM Technology	Cast deposition molding
Layer height	0.2 mm
Extrusion width	0.4 mm
Filament diameter	1.75 mm
Support enabled	Yes
Extruder 1 Temperature	250ºC
Fill pattern	Tri-hexagon
Fill density	0.8
Bed temperature	90ºC

In this snapshot we can see the profile of the supports and filling.



Costs Chassis 4 Body Lower				Total consumption kW
Average power consumption	0,12	[kW/h]		1,89
Average price kW/h in € 2021	0,253	€/kW		
Electricity cost €				0,47817
Print time [h]			15,75	
ABS volume consumed [cm^3]			93,33	
Meters ABS consumed diameter 1.75 mm			38,88	
ABS density [g/cm^3]	1,05			
Mass consumed ABS [g]	98,0	in kg		0,098
ABS Price	20	€/kg		
Cost in raw material	1,96	€		
Total	2,44	€		

Author: Carlos González Heredia. https://generativedesign.site

Costs Chassis 4 upper body				Total consumption kW
Average power consumption	0,12	[kW/h]		0,9804
Average price kW/h in € 2021	0,253	€/kW		
Electricity cost	€			0,2480412
Print time [h]			8,17	
ABS volume consumed [cm^3]			48,57	
Meters ABS consumed diameter 1.75 mm			19,36	
ABS density [g/cm^3]	1,05			
Final mass [g]	51,0	in kg		0,051
ABS Price	20	€/kg		
Cost in raw material	1,02	€		
Total	1,27	€		

Cost per print 3,71 €

Printing process performance = part mass/(part mass + support mass)

Yield = 109*0.8/(98+51) = 0.58 i.e. 41% of the material is consumed on media.

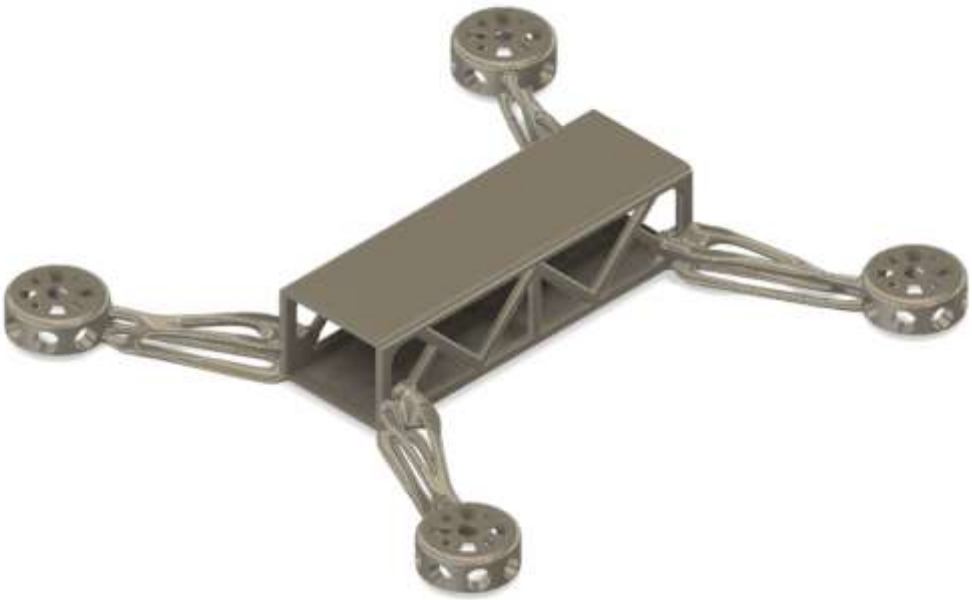
15. Conclusions

Throughout this work, four support structures, or chassis, of quadcopter drone have been developed. The objective to achieve is an aerobatic flight drone chassis of lower mass than 180 g, since, as a design base, we start from its functional dimensions of a commercial model of that weight

We are going to make a comparative analysis of the performance of the four solutions obtained.

Chassis 1

Chassis 2



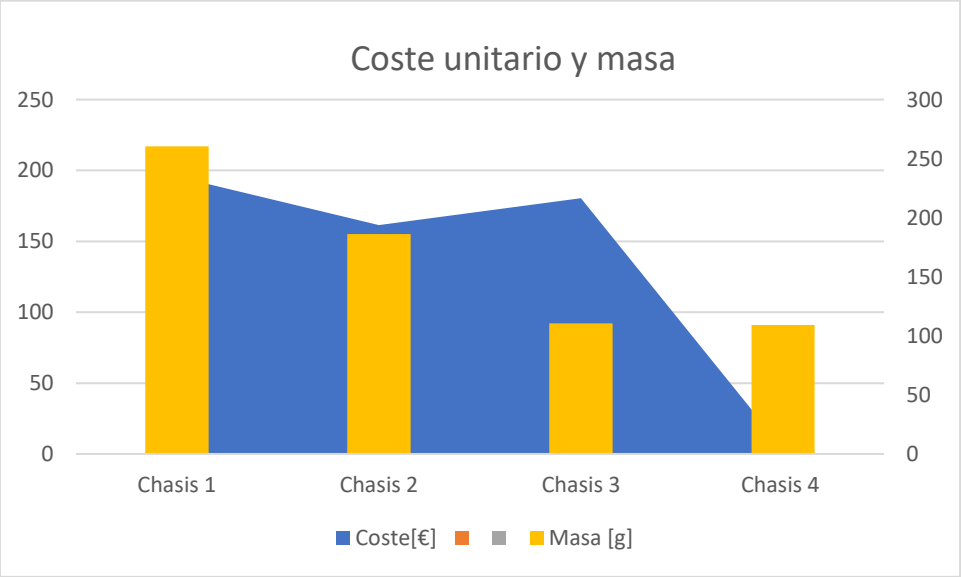
Chassis 3

Chassis 4

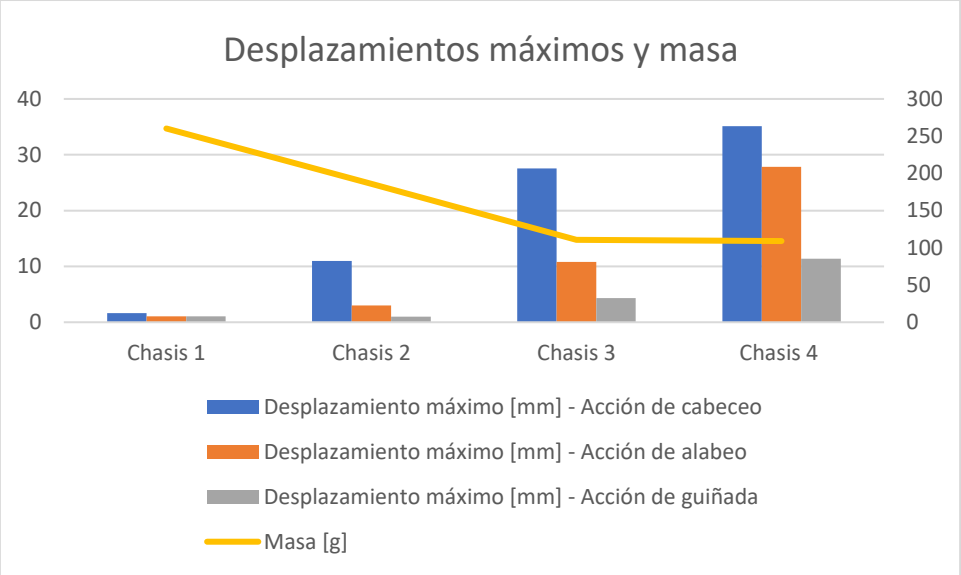
To have an overview of costs, manufacturing methods and materials we present the following table.

	Chassis 1	Chassis 2	Chassis 3	Chassis 4
Cost[€]	195,67	161,37	180,34	3,71
Mass [g]	260,3	186,18	110,55	109,1
Additive manufacturing performance	0,56	0,67	0,46	0,58
Raw material cost [€/Kg]	134	542,5	542,5	20
Manufacturing time [h]	260,31	186,19	110,56	109,11
Manufacturing method	DMLS	DMLS	DMLS	FDM
Material	AlSi10	Ti6Al4V	Ti6Al4V	ABS
Density [g/cm^2]	2,59	4,41	4,41	1,05
Volume piece [cm^3]	98,08	61,97	53,74	102,9

The first chassis consists of 2 pieces. The decision to place both for the same print, due to the high number of hours it needs, has made it necessary to place the chassis in an upright position adding a lot of support mass. The geometry in the form of a bathtub open upwards, if it had been arranged as the printing of chassis four, would have saved a lot of costs, since, in that simulation, the energy expenditure practically doubles that of the raw material. In other words, a bad manufacturing planning strategy has increased the final cost of the part above the other two, even when the price of the raw material is 4 times lower.



In this first graph where we compare the unit cost and the masses of the chassis it is evident the difference in costs due to the manufacturing method between the first 3 and the last.



	Chassis 1	Chassis 2	Chassis 3	Chassis 4
Maximum displacement [mm] - Pitch action	1,64	11	27,55	35,14
Maximum displacement [mm] - Warping action	1,06	3	10,83	27,86
Maximum displacement [mm] - Yaw action	1,05	1	4,35	11,37

If we compare the maximum displacements of the service stresses, it can be concluded that chassis 1 and 2 are oversized, note that the objective of this project will be to build chassis below 180 g.

For what has been said so far, chassis 3 and 4 are the ones that have some kind of value in terms of engineering design. Since it has been possible to reduce the mass considerably. If we compare these, the ABS model is 50 times cheaper than the titanium alloy model.

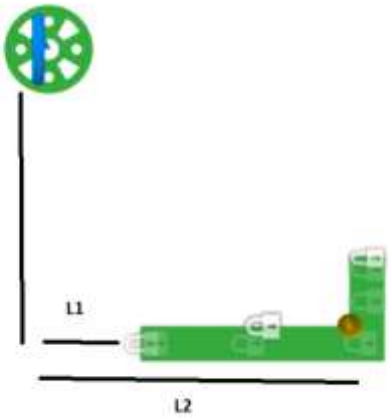
Generative design, as defined in previous chapters, is a recurrent algorithm that uses finite element structural simulation to obtain geometries optimized for specific problems. It generates a kind of bio-forms that resemble in a certain way the bones of vertebrate animals. Autodesk engineers are credited with the good work of approaching those geometries in such a limited number of iterations.

If you look at the solution of the arm of chassis 3, or solution 5 of study 3. They configure a hyperstatic communion bar structure optimized for the stresses with which it is generated. Undoubtedly, this type of tools means a paradigm shift in mechanical design, the synergy between the state of the art of structural analysis with cloud computing systems, "big data", makes it possible to obtain constructive solutions with minimal effort.

Solution 5, Studio 3, Iteration 15, Ti6Al4V

Most Autodesk tutorials use an initial shape, but if you look at the evolution of geometry with iterations, the initial shape is lost to the few iterations, The key to using this tool is in the choice of actions and constraints.

The reason that chassis 3 has such a pronounced longitudinal arrow for pitch solicitation is that a geometric constraint was imposed along the longitudinal section of the base parallelepiped.



The reader will wonder, what happens if we only impose restrictions in the central area of the drone body, as is logical, the structure in that case has to solve the flexo torsion of the arm to the center of the body of the drone, increasing the length of the torsion axis from L1 to L2 and being necessary to add mass around the body to resist it.

In the latter case, for the stresses and materials of the study the algorithm generates too much material in the area under the rotor and the solution geometries are not useful.

It should be noted that drone chassis manufacturers have been migrating the structural typology from elongated chassis plus arms to crosshead with arms that start from the same

point to solve the problem. The correct choice of arrangement of biaxial fabrics in the lamination of composite materials solves the problem of crosshead arrangement.

Finally, it shows a chassis built from the aforementioned restriction that we have not included in the project because it does not provide valid constructive solutions for the problem that concerns us. Aluminium 6061, 146 g

Bibliography

ZYGUŁA, K., NOSEK, B., PASIOWIEC, H. and SZYSIAK, N., 2018. Mechanical properties and microstructure of AlSi10Mg alloy obtained by casting and SLM technique. , vol. 104, pp. 462-472.