POLYTECHNIC OF TURIN

Bachelor of Mechanical Engineering

ENGINEERING DESIGN AND OPTIMISATION OF AN INDUSTRIAL WORKBENCH MECHANISM

Master Thesis

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ABSTRACT

Questa tesi affronta la riprogettazione e la reingegnerizzazione completa di un banco da lavoro industriale destinato alla preparazione e al servizio di cibi e bevande, con particolare attenzione all'ottimizzazione del suo meccanismo interno tramite la modellazione a deposizione fusa (FDM) nella manifattura additiva. Per raggiungere questo obiettivo è stato sviluppato un workflow additivo che comprende la riprogettazione dei componenti, l'assemblaggio e i relativi movimenti, la selezione dei materiali, l'anteprima di stampa e, infine, l'analisi statica FEM. Le nuove parti sono realizzate in polimero ABS, mentre alcuni componenti selezionati sono stati rielaborati per proporre potenziali soluzioni estetiche in legno. Il processo iterativo, supportato dalla modellazione CAD in SOLIDWORKS e dalla preparazione della stampa con Ultimaker Cura, consente un perfezionamento continuo e garantisce l'integrità funzionale del meccanismo. I risultati ottenuti evidenziano una riduzione del numero di componenti, una diminuzione del peso complessivo e una significativa semplificazione delle operazioni di assemblaggio. Il prototipo finale, realizzato con la stampante 3D LABZ di ITALDECO, dimostra come la manifattura additiva possa migliorare in modo decisivo la modularità, l'efficienza e l'adattabilità nella progettazione di arredi industriali.

ABSTRACT

This thesis discusses the comprehensive redesign and reengineering of an industrial workbench intended for the preparation and serving of food and beverages, with a focus on optimizing its internal mechanism using Fused Deposition Modelling (FDM) in additive manufacturing. To achieve this goal, an additive workflow is established, comprising component redesign, assembly and related motion, material selection, print preview, and finally, static FEM analysis. New parts are manufactured using ABS polymer, while selected components are reworked to showcase potential wooden aesthetic solutions. The iterative workflow, supported by CAD modelling in SOLIDWORKS and print preparation with Ultimaker Cura, enables continuous refinement and ensures the functional integrity of the mechanism. Results indicate a reduction in part count, a decrease in overall weight, and a significant simplification of assembly operations. The final prototype, fabricated with ITALDECO's LABZ 3D printer, demonstrates that additive manufacturing can decisively improve modularity, efficiency, and adaptability in industrial furniture design.

CHAPTER 1 INTRODUCTION

This thesis is bases on the redesign and engineering optimization of a workbench intended for beverage dispensing. The project was conceived by the company ITALDECO, based in Rome, with the aim of innovating the mechanical mechanism located inside the structure. Through collaboration between the University of Rome Tor Vergata and the Polytechnic of Turin, it was possible to act as intermediaries with the company and address an engineering design context.

The main objective is to redesign the components with an additive manufacturing approach, speed up assembly to increase productivity, and reduce assembly times while maintaining a good balance between aesthetics and the required functionalities. These requirements are of fundamental importance in a public and convivial context.

The first step involves evaluating and studying current Italian regulations. In the case considered, reference is made to the NTC 2018 standards, with particular attention to structural aspects affecting the design and relevant hygiene regulations.

The selected process is material extrusion (MEX-P/Tb also known as FDM), which is particularly suitable to produce large-sized components.

Starting from the initial model, the CAD files initially created using Inventor were redesigned in SolidWorks for further modification. The modifications followed the logic of 'additive for assembly' with the aim of reducing assembly times for the operator. Following the design analysis, a selection of polymeric materials was carried out, comparing four candidate materials. The process continued with 3D printing preparation using the Ultimaker Cura software, followed by a load analysis to best compare the theoretical model within a more realistic context.

The five case studies addressed were subsequently compared to identify critical issues and possible improvements. The discussion could be further extended by redesigning all components and including an analysis of environmental impact and costs.

The second chapter presents the case study, starting from the general characteristics of the industrial workbench under analysis, followed by a description of its main components and the bill of materials. Emphasis is placed on the internal mechanism, operated by a piston, which is the focus of the redesign process. Additional consideration is given to the assembly phases and the movement of the mechanism, as well as an overview of the relevant NTC 2018 regulations.

The third chapter is dedicated to the design criteria and methodologies adopted for Additive Manufacturing (Design for AM), with a focus on innovative aspects related to

FDM technology. This section includes references to scientific literature, guidelines for support structure insertion, and a brief overview of the main advantages and limitations of the technology. Details regarding the 3D printer used and the implementation of Ultimaker Cura slicing software are also provided.

Focuses on simulations and experimental tests, illustrating both the findings from 3D printing processes and those derived from static FEM analyses. A critical discussion of the collected data is offered to validate the design choices.

The fourth chapter presents the main results achieved through the redesign, with particular attention to efficiency indicators, material selection and diversification (with a focus on ABS and PA polymer), and most notably to the significant reduction in assembly operations made possible by the new design.

The concluding chapter summarizes the outcomes of the work, comparing the original and redesigned mechanisms, and discusses the main limitations of the study as well as potential improvements for future developments.

CHAPTER 2 ANALYSIS OF THE ORIGINAL CASE STUDY

In this chapter, we introduce the original case study, including its components. It focuses on the technical specifications and standards, the design and description of parts and, finally, a theoretical representation of motion and static analysis.

Standards and technical specifications

This thesis references two fundamental standards: UNI EN 16889:2017 and the Italian NTC 2018. UNI EN 16889:2017 is part of the European standards concerning professional worktops and counters, particularly for food-service environments. It is bases on primarily hygienic, safety, and performance requirements for worktops and surfaces. The essential aspects covered are [1]:

- Hygiene and cleanability
- Safety in use
- Surface performance
- Durability
- Customer information

Typical test methods include [1]:

- Scratch/abrasion resistance
- Resistance to liquids and staining
- Resistance to humid/dry heat
- Impact resistance
- Corrosion resistance (for stainless steel)

The technical specifications of UNI EN 16889:2017 are summarized below [1].

1. Dimensions and ergonomics

- Customer-side counter depth: 40–50 cm; total depth 110–130 cm

- Operator aisle behind the counter: ≥ 90–100 cm
- Heights: worktop 85–95 cm; customer ledge 105–115 cm (standing) or 75–76 cm (seated)

2. Services and safety

- Provision is required for water supply and drainage, electrical power, and ventilation for refrigeration units. Safety must be ensured against splashes and hot surfaces.

3. Hygiene

- Surfaces in food zones must be continuous and sealed.

4. Structural requirements

- As applicable to the project; global structural sizing is outside the direct scope of UNI EN 16889:2017.

5. Conformity and testing

- Residual deflection and maximum deflection are measured. Static, cyclic, and, where applicable, impact tests for glass are performed.

The scope of this standard does not cover global structural design; for that, reference is made to NTC 2018. The study presented in this thesis focuses solely on static analyses; other tests are not considered.

NTC 2018 sets out design rules for construction works. An industrial counter may fall into different categories depending on its function, permanence, supervision of the work area, interaction with the building, and associated risks. Design distinguishes between ULS (ultimate limit state: strength and stability) and SLS (serviceability limit state: comfort and functionality), combining loads with partial safety factors.[2]

Structures are classified into three categories, listed in a Table1.

Category	Intended use	Distributed load
A	Homes, residences, hotel rooms, private offices, residential corridors	$2.0 kN/m^2$
B	Offices, light archives, branch premises, school premises	$3.0 kN/m^2$
C	Moderate assembly areas, waiting rooms, libraries, museums, conference rooms	$4.0 kN/m^2$

Table1 - NTC Categories [2]

The counter examinate does not fit neatly into any one of the three categories; therefore, a balanced approach is required to avoid oversizing the system. For a public-service counter, reference is made to Category C, typical of crowded environments and areas open to the public. The analysed counter is more akin to a cantilevered shelf, with non-continuous use. Since the area is intended for the consumption of food and beverages, a uniformly distributed load of 2000 $N/m^2$is assumed, together with a concentrated load of 1500 N.

To correctly integrate the two standards, two phases are envisaged. The first phase concerns the Design defining size sections, substructures, anchors, and connections, ensuring ample safety margins against overturning and sliding. The second one is the validation phase in which prepares a test plan compliant with UNI EN 16889:2017 to verify, on sample and prototype: the resistance of the top to concentrated and distributed loads, stability under realistic pushing actions, and fatigue resistance of joints.

The combination of analytical verification and testing ensures that structural performance is properly assessed, and user safety is guaranteed.

Overall components

The original case study consists of numerous components, as shown in the CAD files. The complexity of the main assembly is evident in Figure1. The assembly can be divided into six sections:

1. External sheet metal
2. Internal sheet metal
3. Mechanical components
4. Lighting fixture
5. Motor block
6. Additional cover parts

Firstly, CAD files from Inventor are converts in SOLIDWOEKS with the purpose of knowing the measurements and the functions that compose all geometry. The Tables 2-3-4-5-6 -7show the components present for each section:

External sheet metal
Side panel DX
Side panel SX
Side panel 3mm

Table 2 - external sheet metal components

Internal sheet metal
Slotted sheet metal DX
Slotted sheet metal SX
Panel 748x91.5
Panel 748x105

Table 3 - internal sheet metal components

Lighting fixture
Lateral plate
Lateral plate
Channel plate
Ceiling Fixture with 90° tube 1484mm
Internal 90° tube, 1484mm
Tubolar 90°, 1484mm
Turboplex, 1484mm

Table 4 - lighting fixture components

Mechanics
Bolt
Bushing 30
Bushing 60
Black Bushing
Bearings
Staff tubol 1
Staff tubol 2
Tube 50x30
Horizontal tube
Tubes

Table 5 - components

Motor block
Motor block 17
Motor block 36
Tube block
Tube block
Evap c3f
Laminate
Thin sheet metal
Tub inx

Table 6 - motor block components

Cover parts			
1	124 Cap	18	Upper front
2	1500x150x14	19	Motor gear grille
3	Glass Shelf	20	Guides
4	Base 940x714	21	Stainless steel transformer plus
5	Base transformer	22	VSC side panel
6	Glass support	23	Shelf
7	Dropin 750, Internal floor		
8	Sides		
9	Lateral sides		
10	Side panel 714xh621		
11	Stainless Steel Transformer side		
12	Intermediate Side Panel 714xh621		
13	Transformer side		
14	Lining 940		
15	Glass front panel		
16	Lower front		
17	Sliding front		

Table 7 - cover parts

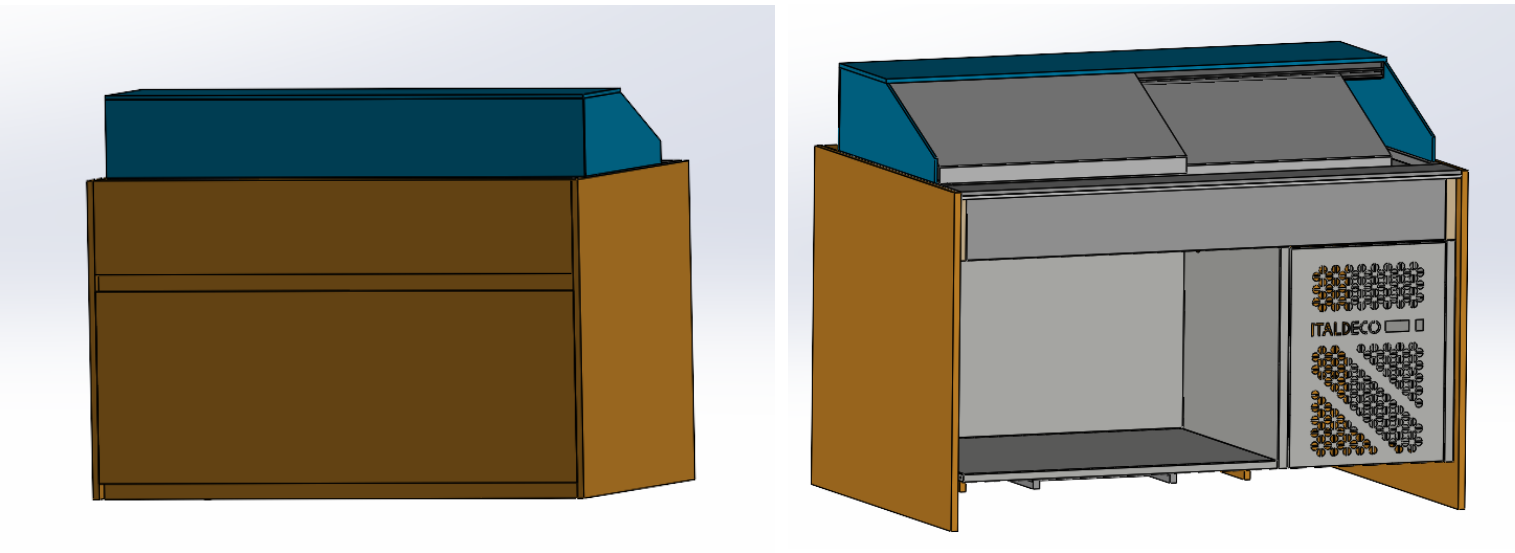


Figure 1- industrial workbench initial case

After describing the entire component, the focus shifts to an in-depth analysis of the internal mechanism under investigation.

Description of the initial internal mechanism

The internal mechanism consists of 20 components described in Table8.Each CAD files will be described below. Figures 2-3 show the bill of materials.

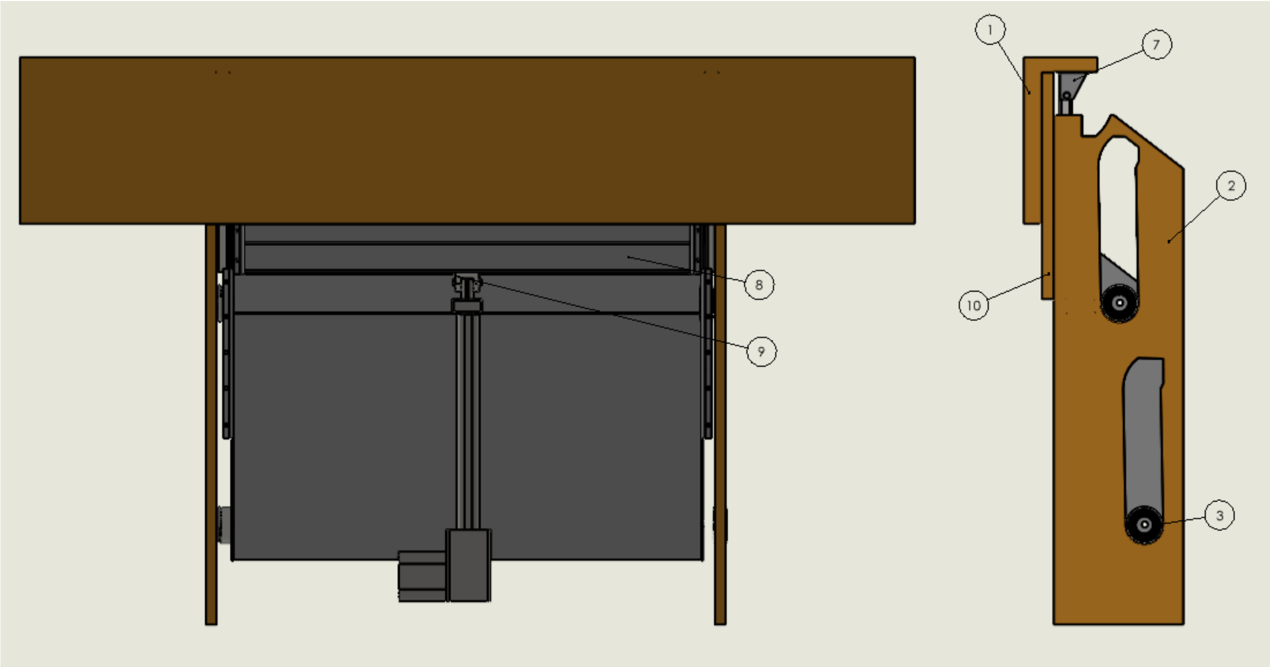


Figure 2 - bill of materials

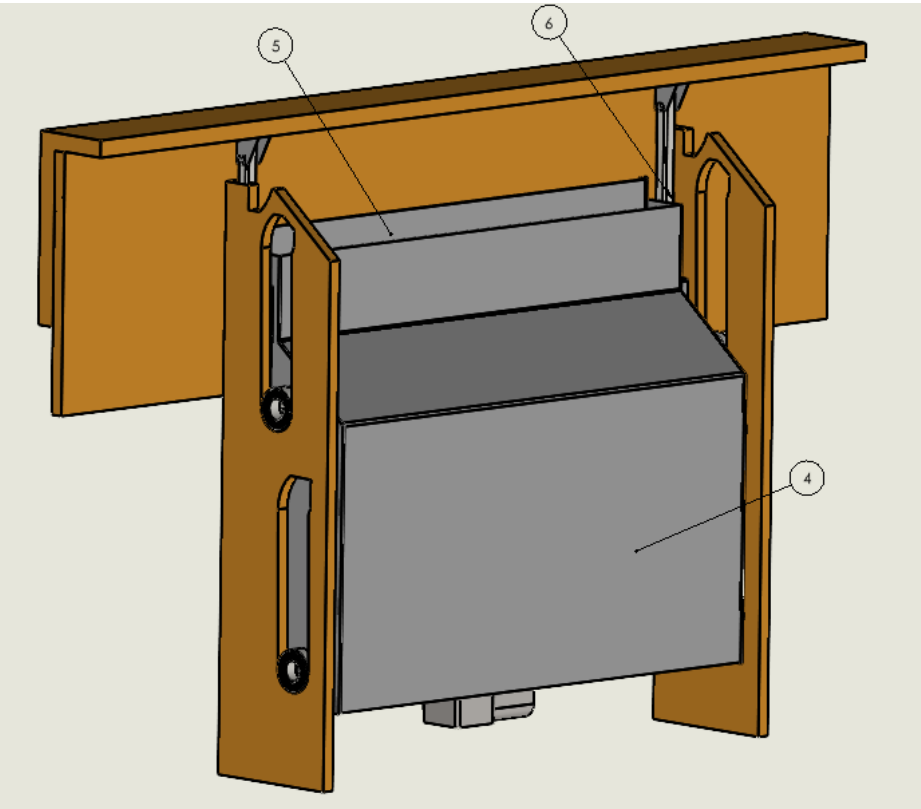


Figure 3 - bill of materials

Item	Parts	Assembly components	Quantity
1	Shelf		1
2	Side panels		2
3	Bearings	3	4
4	External sheet metal	3	1
5	Internal sheet metal	4	1
6	Tubes		2
7	Staff tubol		2
8	Shaft		1
9	U-bracket		1
10	Upper front panel		1

Table 8 - Baseline assembly

It is essential to look at any component to see the geometry.

The shelf's function is to support the applied load; it measures 1500 mm x 280 mm and has an L-shaped geometry.

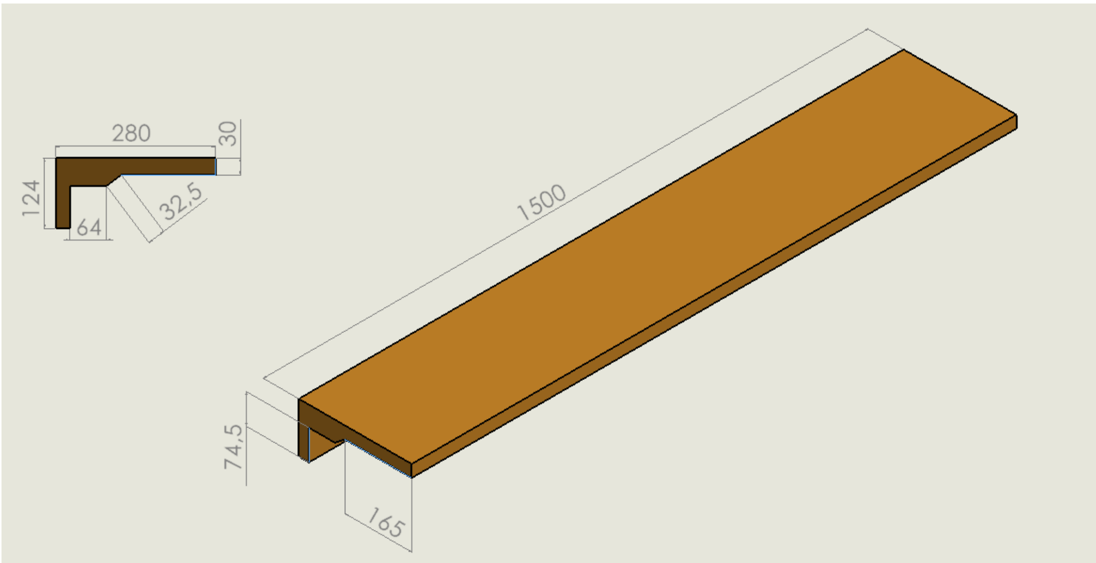


Figure 4 - shelf

The shelf is connected to two hinges called Staff Tubol that allow the tabletop to rotate. These hinges are fastened with two bolts to two tubular members. The tubes shown in Figure 6 are then connected to the main shaft. The hinges have a rectangular cross-section and are illustrated in Figure 5.

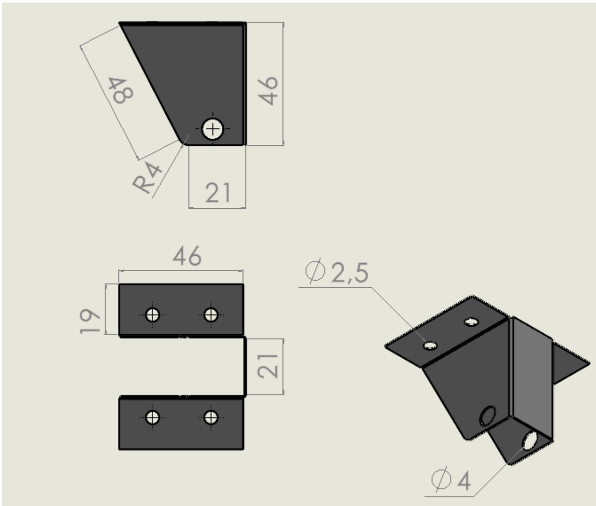


Figure 5 - staff tubol

Figure 6 - tubes

To connect the system to the mechanical piston, there is a connecting U-bracket, which is shown in Figure 7.

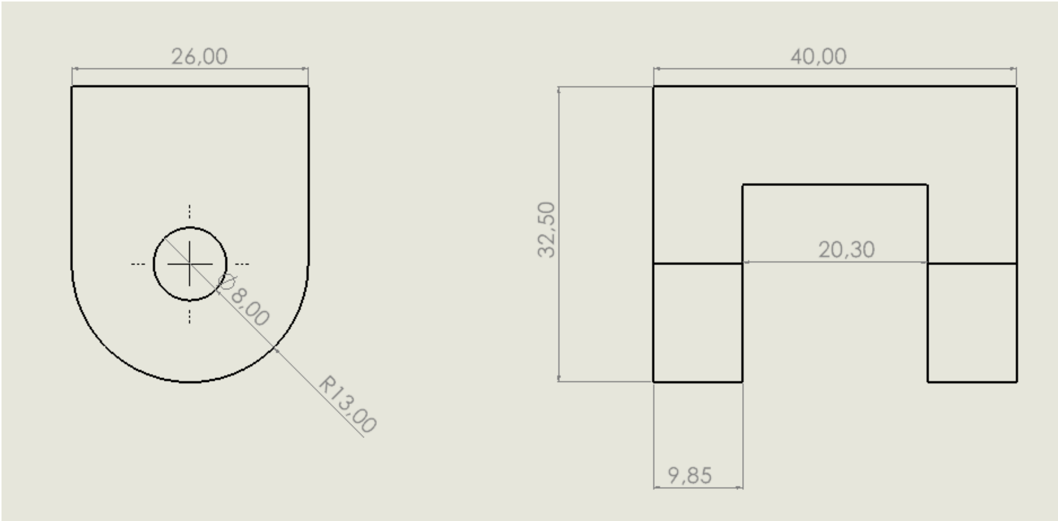


Figure 7 - U-bracket

There are also two sheet-metal assemblies: the outer sheet-metal assembly and the inner sheet-metal assembly. Each assembly consists of multiple parts. Figure 12 shows the inner sheet-metal assembly.

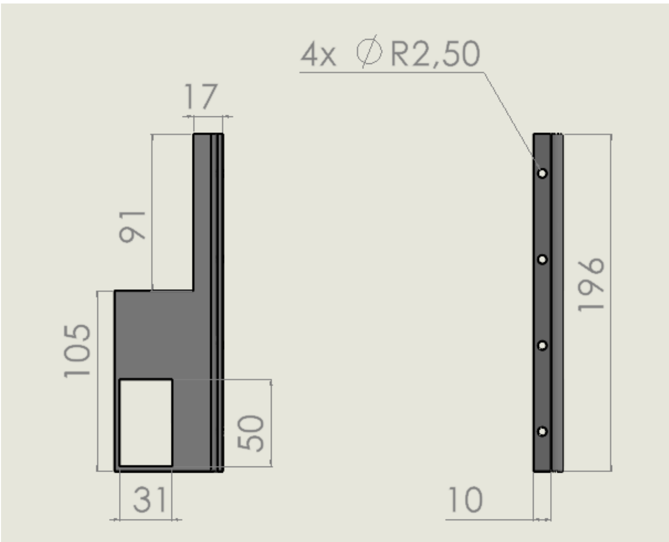


Figure 8 - slotted sheet metal DX

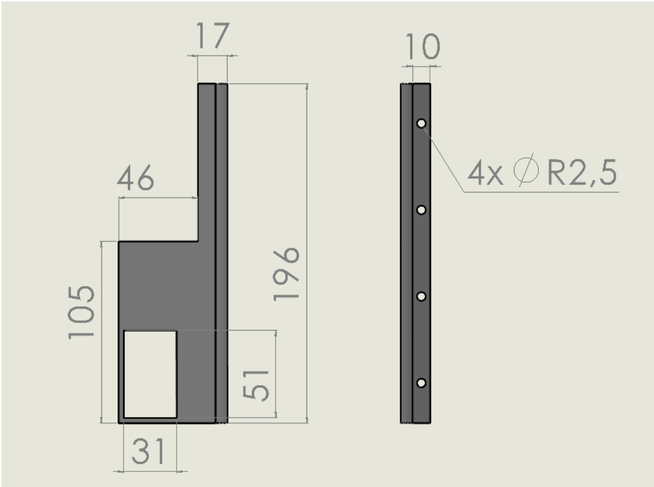


Figure 9 - slotted sheet metal

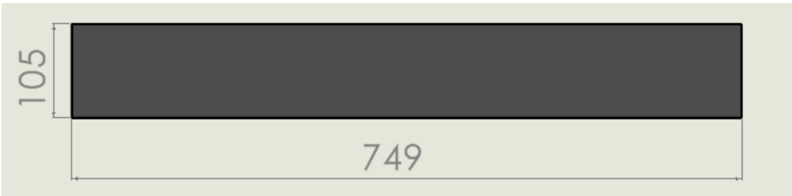


Figure 10 - panel 749.x105

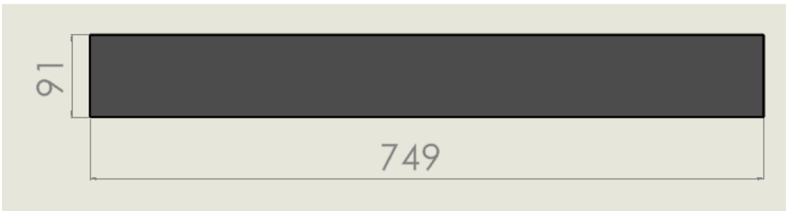


Figure 11 - panel 749x91.5

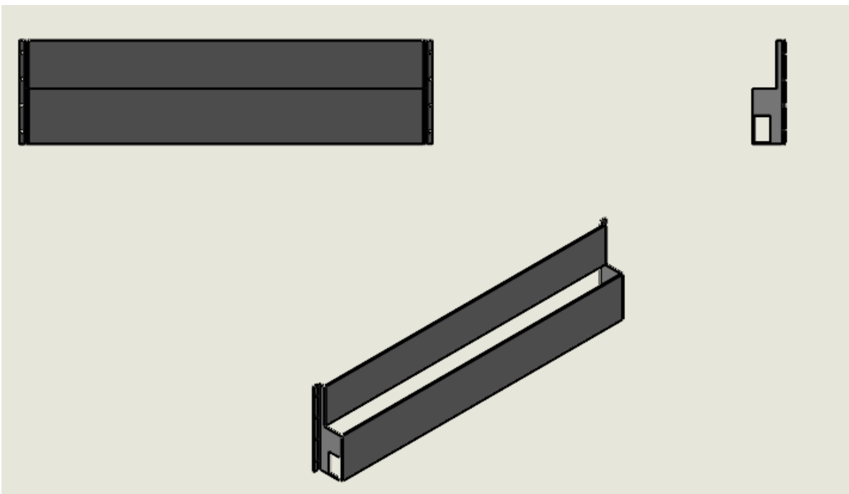


Figure 12 - internal sheet assembly

Figure 16 shows instead the components of the outer sheet-metal assembly.

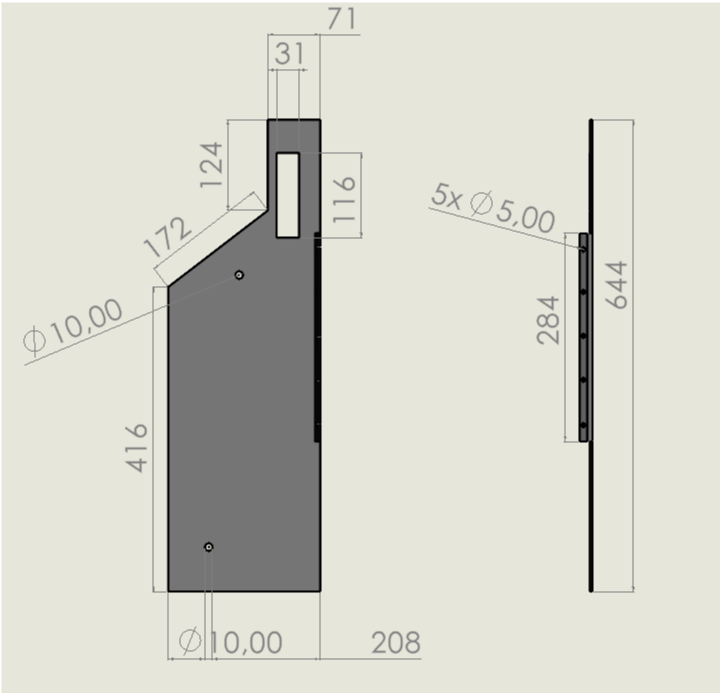


Figure 13 - side panel DX

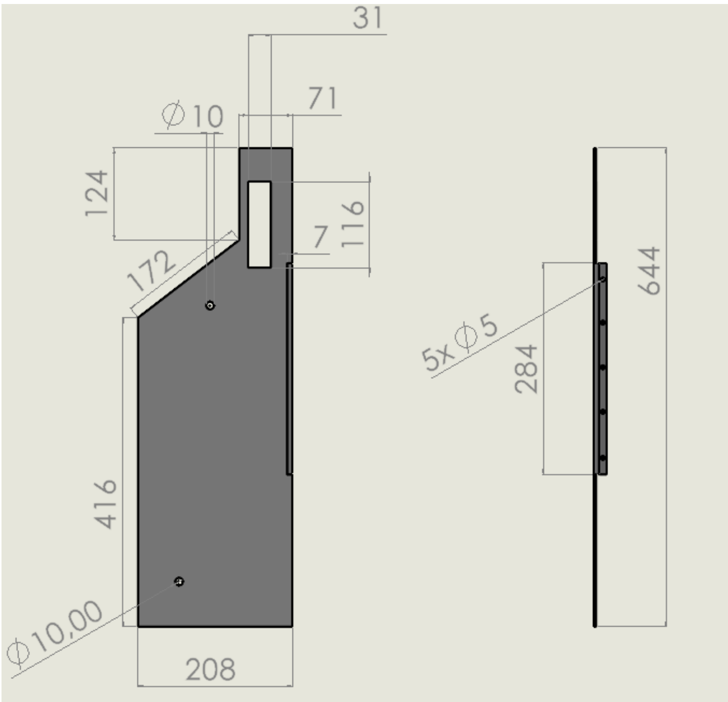


Figure 14 - side panel SX

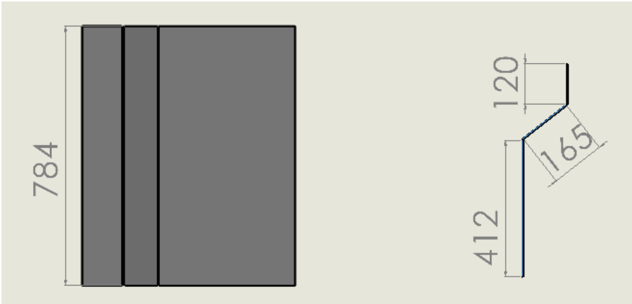


Figure 15 - side panel 3mm

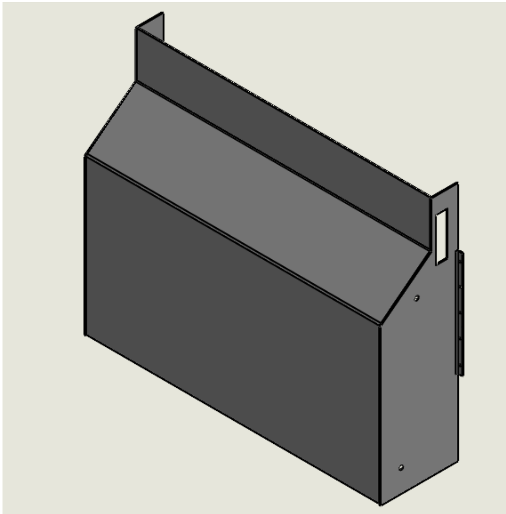


Figure 16 - external sheet assembly

In Figure 17, the side panels are shown, with the same geometry for both the right and left sides.

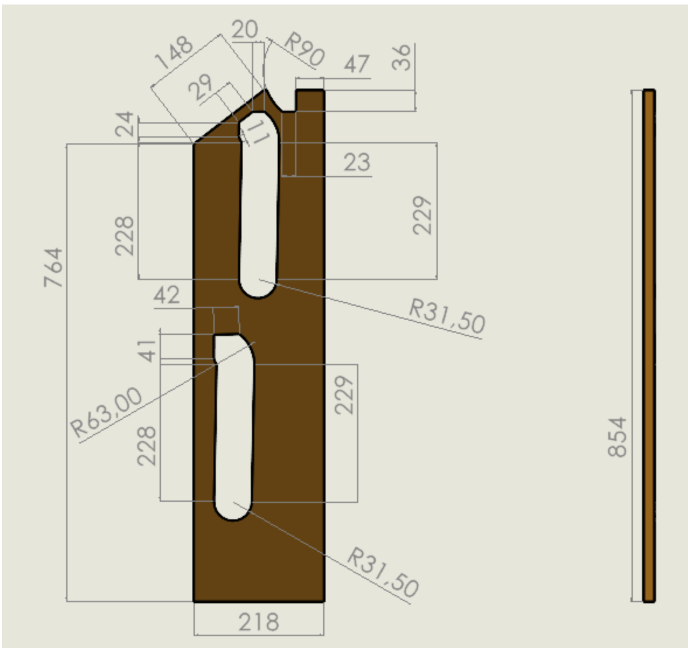


Figure 17 - side panels

The outer sheet metal slides along the side panels by means of bearings that serve only a sliding function.

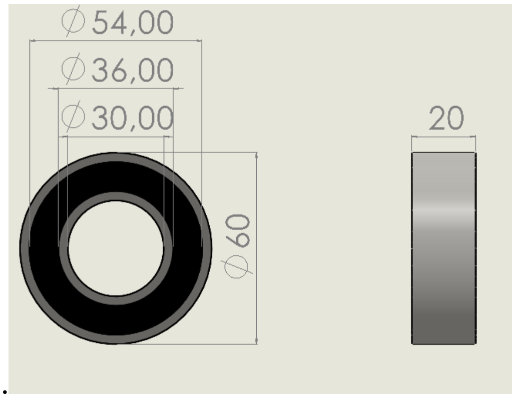


Figure 18 - bearings

SOLIDWORKS: 3D Modelling and Design for Additive Manufacturing

SOLIDWORKS is a 3D design software that was conceived in 1993 and released in 1995. Founded by Jon Hirschtick, the project aimed to design an easy-to-use, affordable, Windows-native parametric CAD system. With SOLIDWORKS, users can create 2D sketches, 3D solids, and surfaces, as well as import and export AutoCAD files and various geometries.[3] Developed by Dassault Systems, it has become a reference standard for the digitalization and virtualization of product development in manufacturing. The following are the most relevant actions.

- Sketching and 3D solid/surface modelling. In the 2D environment, you can create sketches that are constrained by geometric relations and dimensions, then convert them into solids or surfaces using extrusions, sweeps, lofts, and Boolean operations.
- Assembly design and management. Complex systems are constrained with mates to simulate motion and to run interference and clearance checks.
- Automated drawings and documentation. The software generates technical drawings, exploded views, and bills of materials to streamline project documentation.

- Integrated analysis and simulation. Built-in tools help optimize designs prior to manufacturing, including structural FEA and CFD analyses.

SOLIDWORKS is a valuable tool for additive workflows because it enables to:

1. Design for Additive Manufacturing (DfAM): The creation of complex geometries, internal lattice structures, fluid channels, and integrated systems that are difficult to achieve with conventional processes.
2. Printability verification: Tools support checks for minimum thickness, undercuts, overhangs, and enclosed volumes, and allow direct export of models to STL/OBJ for slicing.
3. CAD–CAM–AM workflow integration: SOLIDWORKS connects to slicing software and 3D printers via dedicated plug-ins or optimized exports, improving the handoff from digital model to physical part.

There are many advantages such as:

- A user-friendly graphic interface
- Extensive libraries of standard parts and commercial components, with a high degree of customization
- Advanced analysis, simulation, and documentation tools
- Broad compatibility with 3D-print export formats

Although the advantages, there also several limitations, including:

- Expensive licensing and restrictions for Educational/Student versions
- High-performance hardware required for large or complex assemblies
- Some advanced 3D printing tools are limited or require add-ons/extensions

Integrated Mechanical Design: Motion Analysis and Static Load Analysis

In integrated mechanical design, two types of simulation play a fundamental role: motion analysis and static load analysis, both widely supported by modern software tools.

Kinematic analysis makes it possible to simulate the behaviour of a mechanical system composed of multiple rigid bodies connected by appropriate constraints. The theoretical objectives are to determine:

- Displacements, velocities, and accelerations of each component over time
- Trajectories and relative motions among bodies
- Detection of collisions or unintended wear

The analysis requires defining geometric constraints, degrees of freedom, and initial conditions. It is based on the equations of rigid-body kinematics and dynamics. This approach evaluates the feasibility of mechanisms, optimizes motion sequences, and prevents assembly issues or undesired wear [4].

Structural analysis aims to determine the response of a structure subjected to external forces (static loads), evaluating effects on:

- Deformations and displacements
- Stresses and internal forces
- Safety factors and critical stress concentration zones

In theory, it applies the principles of static equilibrium of rigid bodies and mechanics of materials (Hooke's law in the elastic regime, failure criteria, etc.). The analysis is conducted using the Finite Element Method (FEM), which discretizes the model into a mesh of elements to compute the distribution of internal stresses [5].

These analyses are essential during the design phase because they represent the simulation of real product behaviour before physical realization. They reduce the need for physical prototypes, lowering development costs and time. They enable the selection of shapes, geometries, and materials based on safety, strength, and durability requirements.

Integrating analyses into digital design processes is a key step towards an engineering-driven approach that guides the development of reliable, efficient, and innovative solutions.

Assembly and Design Criticality Analysis

This section examines the assembly of the components that make up the original case study. Since there are around twenty parts and they are all theoretically disconnected from each other, the assembly operations should correspond to at least twenty steps. Clearly, this is demanding for an operator in terms of effort and time, and component adjustments are required.

To carry out the design studies, it was necessary to analyse the structural criticalities in detail. One of the issues identified concerns the bending of the sheet metal, which proves to be a challenging step considering that this operation is usually manual and therefore varies from operator to operator. Numerous auxiliary rework operations are required on the sheet metal for assembly, which also makes the assembly times excessive. By studying the case, it is evident that there are many components that could be reduced. Moreover, the cost of sheet metal is high, so it would be advisable to choose a more economical and eco-sustainable solution by using polymer material.

CHAPTER 3: DESIGN FOR AM

Overview of Applied Technologies

In this section, we introduce technical principles of design for additive manufacturing, focusing on the process, the machines involved, and the advantages and disadvantages of FDM.

In material extrusion technologies, a material is forced out through a nozzle under applied pressure. Given that the pressure remains constant, the extruded material maintains a consistent cross-sectional diameter and flow rate. After extrusion, the material is deposited on a substrate that moves at a controlled, constant speed, and the material must be in a semi-solid state to ensure precise placement. For effective construction, the newly extruded material must adhere properly to the previously deposited layers to form a cohesive, solid structure. This technology operates on a layer-by-layer manufacturing principle.

There are two principal approaches for achieving solidification in the extrusion process:

1. Thermal Solidification:

   The most common method involves controlling the material state via temperature. In conventional polymer extrusion processes, the extruder is typically mounted vertically on a plotting system, and the material is melted before being extruded. It subsequently solidifies upon cooling after deposition.[6]

2. Chemical Solidification:

   A replacement method utilizes a chemical change to induce solidification, which is typically applied to paste materials. Solidification in this case can be accomplished through different mechanisms, such as residual solvent evaporation, reaction with air (e.g., moisture cure), or by adding a curing agent.[6]

Both methods aim to ensure that the extruded material transitions from a flowable state to a solid state immediately after deposition, allowing for the reliable formation of three-dimensional structures.

There are several key features that are common to any extrusion-based system:

- Loading of material

  The chamber from which the material is extruded could be preloaded with material. The ideal approach is to pump the material, if it is liquid. Most materials are supplied as a solid, and the most suitable methods of supply are in powder form or in pellets. The chamber is the main location of the liquefaction process.

- Liquefaction of the material

  As mentioned before, the material solidifies following the extrusion because of the heat applied to the chamber. Heat transfer could be difficult if the chamber becomes larger.

- Application of pressure to move material through the nozzle
- Extrusion

  The diameter of the nozzle determines the minimum feature size that can be created and the shape and size of the extruded filament. In the picture below Figure19 it is possible to see the schematic system.

  After the extrusion process the material should remain with the same shape and size, however gravity and surface tension could change the shape. However, the effect of cooling could be creating a distortion.[6] This situation can be minimized by ensuring that the difference between the chamber temperature and the surrounding atmosphere is kept to a minimum.

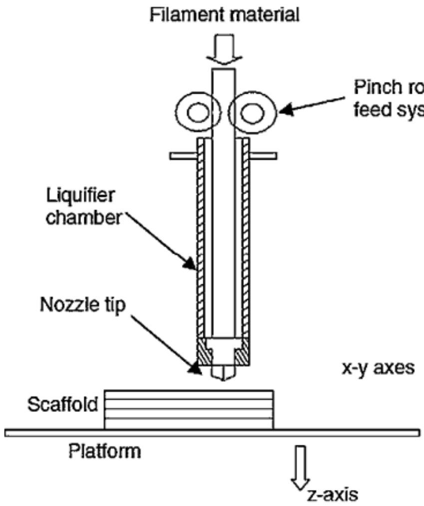


Figure 19 – extrusion [6]

- Plotting according to predefined path and in a controlled manner
  The plotting system allows movement in the horizontal plane and must be coordinated with the extrusion rate to ensure a smooth and consistent deposition. The appropriate mechanism involves two orthogonally mounted linear drive mechanisms, such as belt drives. The system must be reliable, permitting constant movement over many hours without any loss in calibration. The internal fill pattern can be seen as a coherent solid structure in the picture below Figure20.

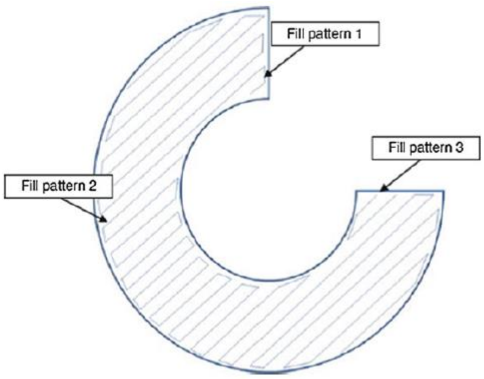


Figure 20 - internal fill pattern [6]

To correctly build a job, it is also necessary to use support structures, which can be of two types:

- Similar material supports

- Secondary material supports

  Support structures are important because it fixes complex geometrical features.

  If the extrusion system has only one chamber, the supports must be made using the same material as the part. It can be separated later. The temperature regulation is used to separate supports. It is possible improving the condition changing the layer separation distance when depositing the part material.[6] Otherwise, extrusion temperature or adjustment of the chamber when extruding supports might be a valid strategy. In all cases, support material will be difficult to separate from the part.

  The most powerful strategy consists of fabricate supports in a different material. To do is necessary to have a second extruder.

The technology was patented by Stratasys founder Scott Crump in 1992.[7] In the picture Figure 21 it is possible to see the nozzle and an example of machine.

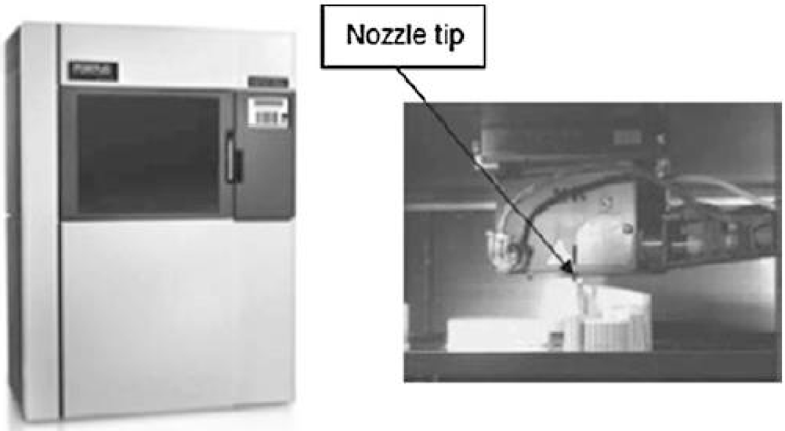


Figure 21 - Stratasys printer [7]

Parts made using FDM are the strongest for any polymer based additive manufacturing process due to the range of materials. There is a broad variety of machines, from low-cost, small-scale, minimal variable machines through to larger, more versatile and more sophisticated that are inevitably more expensive.

The most conventional material is the ABS plus material, which can be used on all current Stratasys FDM machines. The Table9 shows variations in properties for the ABS range of FDM materials:

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength (MPa)	22	37	36	34.8
Tensile modulus (MPa)	1,627	1,915	2,265	1,827
Elongation (%)	6	3.1	4	4.3
Flexural strength (MPa)	41	61	52	50
Flexural modulus (MPa)	1,834	1,820	2,198	1,863
IZOD impact (J/m^2)	106.78	101.4	96	123
Heat deflection at 66 psi (°C)	90	87	96	110
Heat deflection at 264 psi (°C)	76	73	82	96
Thermal expansion (in./in./F)	5.60E – 05	6.7E – 6	4.90E – 05	4.10E – 5
Specific gravity	1.05	1.08	1.04	1.2

Table 9 - ABS properties for FDM [8]

Although FDM machines are very successful there are several disadvantages using this technology, including build speed, accuracy and material density. All nozzles are circular so it's difficult to draw sharp external corners. The shape produced depends on the nozzle, acceleration and deceleration characteristics, and the viscoelastic behaviour of the material as it solidifies.

The speed of an FDM system is based on the plotting speed and on the feed rate. Feed rate is reliant on the capacity to supply the material and the rate at which the liquefier can melt the material. If the liquefier were modified to increase the material flow rate, it would result in an increase in mass. One method to improve the speed of motor drive systems is to reduce the corresponding friction. An important consideration is that when using FDM is to account for the anisotropic nature of a part's properties. Different layering strategies result in different strengths. One of the major limitations with extrusion-based systems relates to the diameter of the nozzle. The goal is to produce scaffolds that are as strong as possible but with as much porosity as possible [6]. Cells growing better if there is a huge porosity. Scaffolds with greater than 66% porosity are common. Usually scaffolds with a simple 0° and 90° orthogonal crossover pattern maybe sufficient. Figure 22 shows the possible patterns using a bio extrusion system.

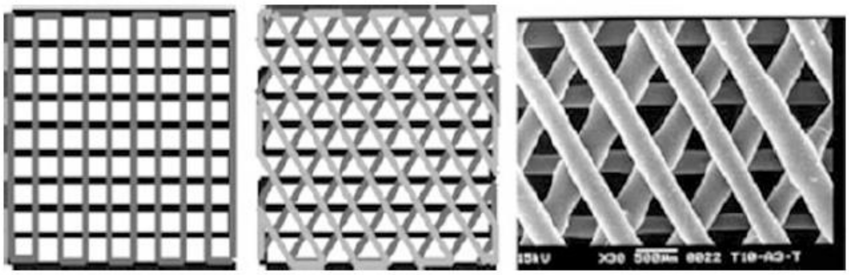


Figure 22 - scaffold architectures [6]

Other systems can be purchased only in China, until the expiration of Stratasys' patents. The most popular is available from the Beijing Yinhua company [7].

After the description of Stratasys machines and the commonly material, should be preface the technological innovations.

In Contour Crafting [9] (additive technology), components are built by overlapping two-dimensional layers. The use of thicker layers compromises geometric accuracy particularly in areas that are sloped or curved in the object. Contour crafting developed at Southern University in California represents an innovative breakthrough. It introduces the use of a scraping tool to ensure greater accuracy on the outer surface. In this way, good geometric fidelity is achieved even when using very thick layers. The flexibility of the finishing tool allows even the most complex surfaces to be accurately replicated. This technique allows for large-scale buildings by combining the technique with robotic assembly systems.[9]

Some 3D printing approaches do not rely on flat, stacked layers. Conventionally knows as Nonplanar systems [6].

Among these, Curved Laminated Object Manufacture (Curved LOM) is designed to use fibre-reinforced composite materials, such as carbon or Kevlar. To ensure proper structural strength, individual layers must precisely follow the shape of the object. The Curved LOM process requires very complex equipment, such as compliant robotic manipulators and high-power lasers. It is workable to use short fibres with resins in FDM processes, if fibre lengths and diameters do not cause nozzle clogging.

Positioning layers following the outer surface can refine surface strength.

Another application of FDM technology is the production of ceramic parts [10]. Following the extrusion, ceramic pastes solidify rapidly. The resulting parts are then fired in high-temperature kilns to fuse and densify the ceramic particles, achieving good properties and complex shapes typical of additive manufacturing. Most research on ceramics has been conducted at Rutgers University (USA) [10].

The FDM process is relatively simple, as demonstrated by two low-cost, easy-to-build systems [11]:

- Fab@Home is an initiative for accessible 3D printing: the printer's frame is made from laser-cut polymer sheets and assembled, while the extrusion system uses an air-pressurized syringe capable of depositing various materials at room temperature.
- RepRap is an open-source project born at the University of Bath (UK) that aims to create printers capable of replicating themselves, following certain theories on self-replicating machines. There are many variants of the project, usually with thermal extruders, but all based on the FDM principle.

Both projects have improved designs, developed software for greater precision, and enabled innovative applications. The simplification of printing technology has brought additive manufacturing to the attention of the media and the public.

Subsequent to the study of technological innovation observes the characteristics of LABZ.

In this thesis is inserting the data sheet of the printer used by ITALDECO shows in Figure 23.

Figure 23 - LAB Z [12]

The LAB Z series is configurable to specific application requirements, offering two available build sizes and support for one or two axes as well as one to four independent extruders. These types of printers are unique; they can perform mass production by obtaining structurally stronger objects without worrying about the position of the objects on the printing plate. The direct drive extruder with force multiplier allows the use of 1.75mm and 3mm filaments with nozzles from 0.15mm to 1.4mm and chambers with different volumes according to customer requirements [12]. Thanks to the quick couplings, the extruder change is very fast.

LAB Z printers are categorized as high-end industrial FDM systems, engineered for both rapid prototyping and continuous manufacturing environments.[12] Two primary models are:

- LAB Z 55 Work area 500x500x1000mm
- LAB Z 1010 Work area 1000x1000x1000mm

The print volumes unlike other FDM-FFF 3D printers are far above average. There are up to 4 extruders, several axes and print/mill head options, with the possibility to print in sequence and with different materials. These machines have a robust construction with aluminium body and Dibond panels and feature an advanced degree of automation, especially automatic calibration, axes-centred control, and recovery functions in case of power failure.

They are equipped with a combined additive/subtractive system with a milling cutter in addition to the extruder. The milling cutter features automatic tool change to improve the accuracy and finish of prints. [12]

As regards automation and control systems advanced kinematics with position control is introduced, making the printer up to 4 times faster than before. The system allows total control over movements so in the event of axes slippage, the system will instantly recover its nominal position to continue printing correctly. The system is supported by 3DPRN's proprietary software that is constantly updated. System speeds reach 400mm/sec while maximum accelerations reach 10,000mm/sec. [12] The advanced kinematics also include centesimal position control with optical/magnetic scales that help create more accurate objects. In addition to the advanced milling system, there is a reel weigher that monitors material availability, automatically pausing if the reel becomes blocked. A dimensional calibration procedure can be performed to increase the dimensional accuracy of prints.

The UPS management system is integrated. In the event of a power failure, work is interrupted and then resumed in hidden areas so that print quality is not compromised. Closed 3DPRN printers are characterised by a closed, insulated heated and controlled environment.

The print bed is divided into small, hidden areas so that objects are printed sequentially.

Among the various patents of the following printers are Print on Air, which allows for the printing of inclined or undercut surfaces without the aid of supports, and Vibrant Printing, which allows to produce objects with different types of knurled-type embossing. The variable pitch plane levelling procedure can be performed with both the 3DPRN-LOAD and the laser.

The worktop consists of a heated platen; you can choose between different powers and different surfaces depending on the types of materials you intend to use. The working environment is also heated; the maximum temperature must be 65°C and varies depending on the types of options installed [12]. Optionally, an air extractor with an active carbon filter can be fitted, which will intelligently activate to exchange the air inside the printer without cooling the environment itself or creating currents unsuitable for printing.

As far as supported materials are concerned, it is possible to use advanced materials for applications. In this case, there is advanced management of printing parameters with optimised software with the possibility of connection/upgrading. On the other hand, the target and applications concern the research laboratory to industrial production for large or multi-material parts, also useful for limited series thanks to area/sequential printing.

A comprehensive summary of machine features and supported materials can be found in Table10.

CARATTERISTICHE GENERALI	
Scocca	Alluminio, Pannelli dibond
Tecnologia	FDM-FFF
Piatto	Alluminio, Vetro, Policarbonato, Fibra di Carbonio, Ultem
Azionamenti	Hybrid Step Servo, Closed Loop
Asse 1-2	1-2 Estrusori, Mandrino
Tipo Estrusore	Acciaio (≤ 300°) Alluminio (≤ 500°)
Diametro filamento	1.75mm, 3mm
Ugello	Acciaio, Ottone
Diametro ugello	0.15mm, 0.25mm, 0.3mm, 0.4mm, 0.6mm, 0.8mm, 1.2mm, 1.4mm
3DPRNWARE	Software proprietario ottimizzato per la gestione delle stampanti 3DPRN
Area di lavoro	
LAB Z 55	500x500x1000 mm
LAB Z 1010	1000x1000x1000 mm

Table 10 - general specifications [12]

Design Methodology for Additive Manufacturing

Initially additive manufacturing techniques became useful for rapid prototyping processes. Now these techniques are ordinary used and there are now machines embedding these technologies for a large spectrum of applications. Taken new design theories and methodology area usually called Design for additive manufacturing (DFAM). Although techniques allow more freedom, they do have their specific limitations that must be considered. AM processes are uniquely characterized by the four capabilities [13]:

1. Shape complexity: due to the built strategy layer by layer.
2. Hierarchical complexity: features of any length scale can be integrated into a part's geometry
3. Material complexity
4. Functional complexity

To create engineered parts for AM there are simple regulations to respect. The regulations include part shape and dimensions, manufacturing orientation, etc. A German project named ''Direct Manufacturing Design Rule" (Adam & Zimmer, 2014; Zimmer & Adam, 2011) provided design rules (that are focused on geometry) for Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and FDM processes. In the same way Thomas (2009) developed design rules for SLM.

Kranz, Herzog and Emmelmann (2015) produced a structured database of basic design guidelines focused on Laser Additive Manufacturing of TiAl6V4 [13]. A list of recommendations or principles was also provided by Becker, Grzesiak and Henning (2005) to free designers' minds.

There are two main categories: DfAM for design assessment and design making. Design making can be divided into two sections: new design and re-design. The literature regarding design refers to three categories:[13]

- Conservation of part number: Topology optimization and design for multiscale structures

- Decrease of part number: Part consolidation
- Increase of part number

Figure 24 shows the classification of DfAM practices.

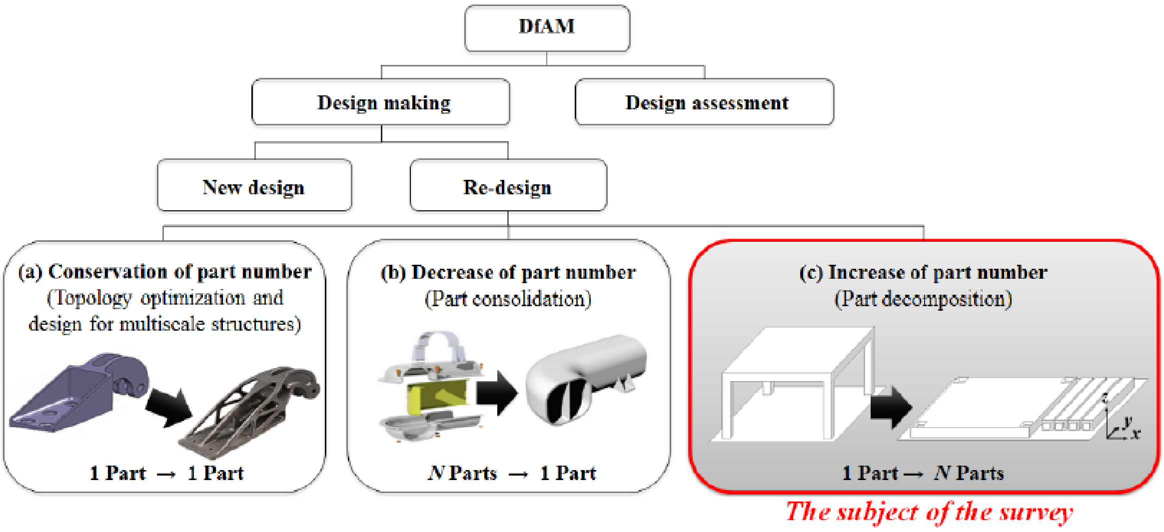


Figure 24 - DfAM classification [13]

Looking at the first group Figure (a) topology optimization and design for multiscale structures (lattice or cellular) is a re-design approach with the aim of part number conservation [13].

The two approaches provide the conservation of part number.

- Topology optimization is a numerical method that consists in optimizing matter distribution define boundaries and design space. This conceptual design born to improve aesthetics, performance and manufacturability. For instance, the aerospace and automotive industries have adopted it to minimize the part weight with the ultimate purpose of energy saving.
- Lattice structures as described by Gibson & Ashby (1997) are numerically generated truss-like structures. Lattice structures are typically incorporated at the detail design stage of a part's geometry. Their main advantages include a high strength to weight ratio, excellent energy absorption capabilities and effective thermal and acoustic

insulation properties. In addition, the bio-medical field has been applying these bio-structures made of lattice or cellular.

The second section concerning Figure (b) based on consolidation of multiple components into one single part known as Part Consolidation. The reduction makes it possible to save process time and cost. This strategy is a general design guideline in Design for Assembly, Design for Disassembly, Design for Manufacturability and Design for Manufacture and Assembly.

The third group in Figure (c) aims to partition an original object into several assemblies, Part Decomposition which results in an increase in the number of parts. This is the opposite concept of Part Consolidation, which emphasizes the role of post-processing for assembly. Part decomposition is useful for many reasons: printability, productivity, functionality, artistry and interchangeability.

Part decomposition also presents challenges regarding how to arrange and orient the parts within the printer's workspace (build volume), as well as the methods and sequences of final assembly. These aspects need to be planned from the early design stages, as shown in Figure25, since they affect both the printing process and post-processing.

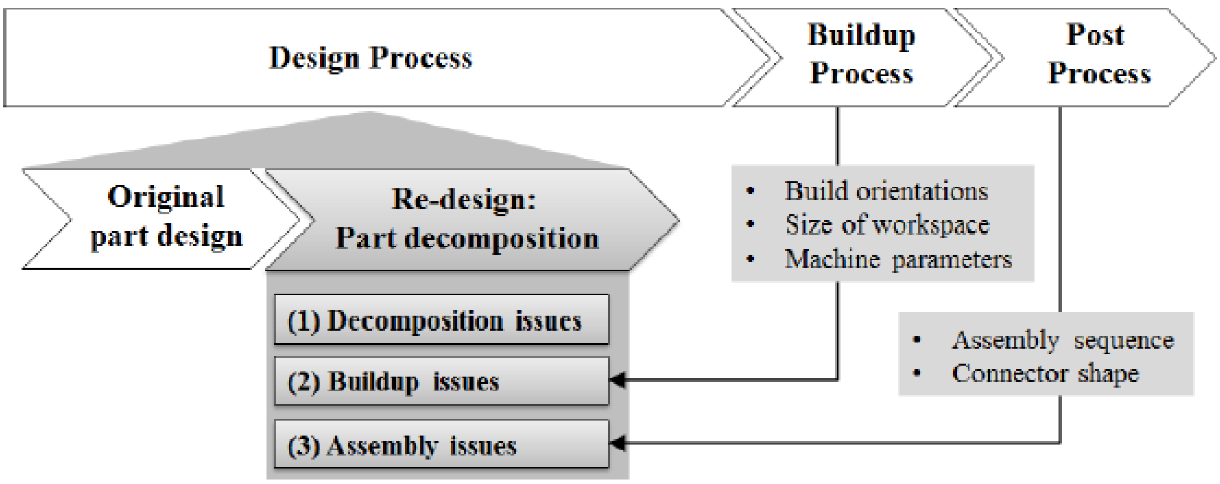


Figure 25 - Part decomposition [13]

The emphasis is on three major topics: decomposition, build volume and assembly issues. In Table 11, every single part is described.

-

Table 1. Keywords used to search part decomposition studies

Issues		Keywords: Main subject	Keywords: Application
Decomposition issue		Volume decomposition, object segmentation, model partition, cutting problems, slicing optimization, automatic subdivision, disintegrating object	Additive manufacturing, 3D printing, Rapid prototyping, Layered manufacturing
Buildup issue	Packing planning	Packing optimization, placement optimization, packing problems, layout planning, part nesting, volume optimization	
	Build orientation decision for multi-part	Orientation optimization for multiple parts, determining build orientations for multiple parts, build direction optimization for multiple parts	
Assembly issue		Design for Assembly, interlocking parts, puzzles, card boards, articulated models, folding objects, modular design, assembly-based design, assembly process planning	

Table 11 - part decomposition studies [13]

In this section describes design challenges for AM versus traditional manufacturing.

The introduction of additive manufacturing has revolutionized the approach to design, offering new geometric possibilities unattainable with conventional technologies. However, this revolution also brings new challenges and design constraints that require different perspectives compared to traditional methods.[14][15]

Geometric constraints and new opportunities can be realised. It is possible to create more complex geometries, internal channels, lattice structures, and gradients of material properties. Traditional technologies impose restrictions on shapes, internal cavities, and undercuts.[13][14][16]

New constraints: Additive manufacturing introduces new limitations, including:

- Build orientation: The positioning of the part on the build platform affects its properties and the quality of its surface finish.
- Support structures: Some AM technologies require the use of supports, which must subsequently be removed with precision and care.
- Size constraints: The maximum component size is limited by the build volume of the printer, which varies depending on the technology.

- Surface finish: The surfaces produced by AM techniques are often less smooth and more layered compared to those produced by traditional manufacturing.[14]
- Dimensional tolerances: Generally, AM offers lower precision than CNC machining or injection moulding. Post-processing is usually required to achieve tight tolerances.[15]

Due to mechanical properties another problematic is caused by anisotropy.
The mechanical properties of parts are often influenced by the build orientation, with reduced strength between layers.[13]. Another restriction concerned the range of materials. While continuously expanding, the range of materials available for AM is still limited compared to conventional manufacturing, and some materials may have inferior properties [14].

Costs, time, and efficiency are also relevant in AM production. Production using AM technologies is generally faster without the need for tooling but print times can be longer for large or complex parts. For small batch production, AM can be more cost-effective; however, for higher volumes, traditional manufacturing remains more competitive [14][15].

Additive technologies allow for a reduction in the number of components by consolidating more functions into a single part. This reduces assembly steps but requires a complete revision of traditional design logic [14].

The designer is thus required to approach the design process differently: not only by adopting new rules, but also by interpreting the project in a more integrated manner, taking advantage of the new freedoms while managing the new constraints.

The new AM-oriented design approach focuses on developing assemblies that are partially or entirely manufacturable through additive technologies. This methodology relies on two fundamental principles:

- Structuring the product architecture to make it suitable for additive manufacturing.
- Designing components with the aim of minimizing the amount of material used.

As stated by Ullman (2009), less than 20% of a component's volume is typically critical for its performance; most of the material is necessary only to connect functional interfaces. Through additive manufacturing, it becomes possible to design these connections in a sophisticated manner—linking critical points while still ensuring structural integrity and the correct transmission of functional flows.[14][15]

Three key elements are defined for each component:

1. Functional Interfaces (FI): Points where functional exchanges occur between the component and either the environment or other components.
2. Flows to be transmitted through the component: Including energy, material, or signals.
3. The available design space: The volume within which the component must be contained.

The process itself is divided into three main phases:

1. Functional Analysis: Identify all the flows involved, understand the functions the product must perform, and establish the relationships between the environment, the product, and individual components.
2. Definition of Control Structures: Ensure proper operation and verify that the component fits within the required dimensional constraints. Establish and connect the functional interfaces.

3. Component Geometry Design: Translate the control structures into actual 3D forms, considering the imposed constraints.

Functional Interfaces (FIs) can be classified into three main types:

- Non-contact interfaces: Used for aesthetic functions, gas or liquid sealing, dissipation, or fluid guiding.
- Handling interfaces: Allow the product to be used, moved, assembled, or maintained.
- Contact interfaces between parts: Necessary for fastening, positioning, load transmission, or guiding within assemblies.

Every product is characterized by specific functional flows—such as energy, material, or signals. These flows can either pass through or interact with a component. Depending on the specific function, a flow may traverse the component or simply interact with it at an interface. Consequently, the design process should focus primarily on those functional interfaces that are truly critical for the component's performance.[14][13].

The functional analysis of the product comprises the following steps[14]:

1. External Functional Analysis: Identifying the flows between the environment and the product and clarifying the interactions occurring between them.
2. Functional Decomposition: Breaking down the main function into basic sub-functions.
3. Product Architecture: Analysing the relationships between components as well as interactions with the external environment.

At the end of this phase, a clear representation of the product in terms of relationships, components, and functions is achieved.

In this stage, the constraints specific to additive manufacturing are established, including:

- Definition of Design Spaces: Identification of preliminary design volumes (such as cylinders, cubes, etc.), which are then positioned relative to one another.
- Functional Interfaces Emergence: Identification and localization of interfaces within the model—either between components or with the external environment. As interfaces are progressively defined, they guide the refinement of the product layout, component volumes, and their connections.[14][16]

All practical aspects that influence the additive manufacturing process of the assembly are considered, including:

    - Clearance Settings: Based on AM technology limitations (typically 0.2–0.5 mm), appropriate spaces are defined between moving surfaces (such as joints) to ensure both assimilability and functionality.
    - Print Configuration: Components are arranged within the printer build chamber in an optimal manner, with the goal of minimizing the use of support structures in critical areas.
    - Print Orientation: The orientation of each component impacts accuracy, surface finish, mechanical strength, and the presence of support materials in sensitive areas. The configuration should favour orientations that reduce potential issues, especially minimizing supports in critical connections.
    - Accessibility for Clearances: Unwanted material may remain within clearances. The design must provide access for post-processing cleaning, including the selection of suitable removal tools and, if necessary, modifications to component geometry.

Once the manufacturing approach and functionality are established, the next step involves detailed component geometry design in five stages [13][16]:

1. Design of Functional Interface Shapes
2. Determination of Interface Thickness and Definition of Functional Volumes
3. Development of Paths Connecting Functional Volumes, Ensuring Structural Continuity and Flow
4. Design of Connection Forms, Selecting the Most Appropriate Type (solid, lattice, hollow, etc.)
5. Edge Rounding to Minimize Stress Concentrations and Enhance Functional Performance

It is relevant also to show an example refers to real life. In the paragraph below it is possibly understanding a typical use of design for assembly in AM.

As a practical example, a vise for domestic function was designed and manufactured in steel using Selective Laser Melting (SLM). The process began with an analysis of the required functions and construction of the functional layout, followed by the definition of design volumes for each component. Clearance between moving surfaces was set to 0.2 mm. Subsequent steps involved searching for the optimal print configuration and orientation to minimize supports in critical areas, favouring easily removable powder over metallic supports. The design was then parametrically optimized through FEM simulations, reducing the initial mass from 1.57 kg to 0.71 kg while ensuring that stress remained below the material's yield strength [13][16]. In Figure 26 we represent the distribution of the Von Mises stress. Figure 27 shows the evolution of the case study.

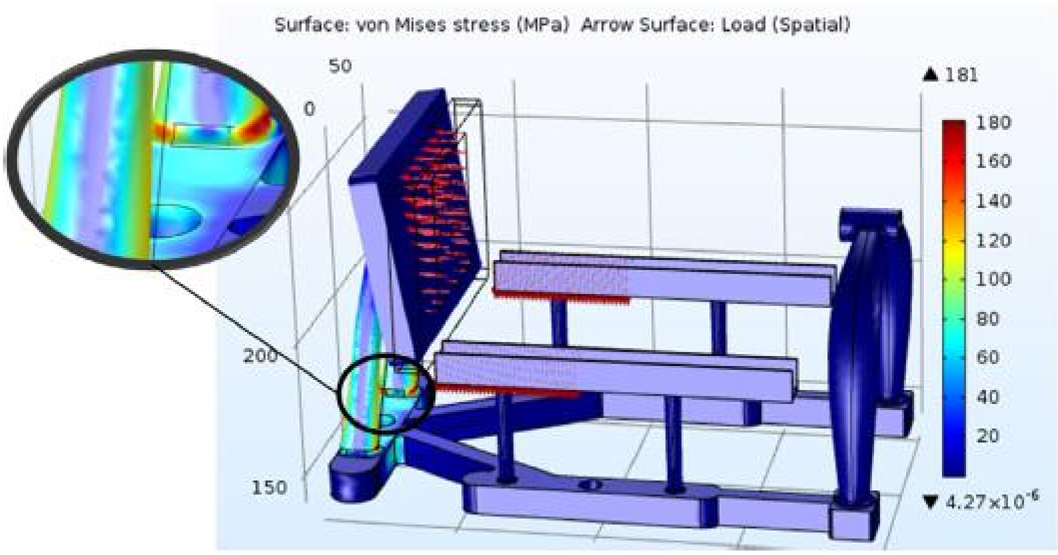


Figure 26 - domestic vise representation [13]

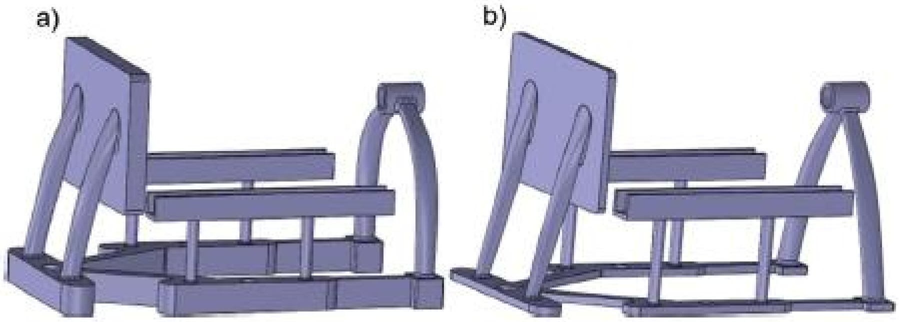


Figure 27 - case study evolution [13]

Design guidelines: Fused deposition modelling

This section is based on design guidelines of fused deposition modelling (FDM). Designing for FDM is an iterative process in which features will not always print as desired the first time. Producing parts is a combination of iterating through prototypes and designing for the process. Compared to Selective Laser Sintering (SLS) parts are very rigid. Moreover, the filament has a thickness of 0.254mm, some fine features may not resolve properly. It is essential to follow guidelines set to ensure that all features are properly solved. Support materials are required for certain features. Producing parts in FDM follow three steps [18]:

1. Pre-processing

Specific software provides slicing 3D CAD file into layers. The software converts data into machine code that determines tool paths for the machine to follow.

2. Production

Interest the real process, in which an extruder head extrudes liquefied plastic filament along the tool path layer by layer.

3. Post-processing

Remotion of support material dissolving it in water or breaking it off.

General Tolerances

- +/- 0.004 or +/- 0.002 per inch in the XY-direction [17]
- +/- 0.010 or +/- 0.002 per inch in the Z-direction [17]

• Part orientation depends on Xometry choice to maximize part quality

• Minimum resolvable feature size, including positive text features, is at least 0.035 (0.045 or greater is safest) [17]

• Theoretical maximum build volume of 24 x 36 x 36 [17]

• Nylon 12 parts with thicker geometries, flat or broad parts, and parts with uneven wall thicknesses will be prone to significant deviations or warp due to variable thermal shrinkage and stress [19].

Filament size limited wall thickness and features thinner than twice the filament's thickness usually does not print successfully. Walls that support structures must be at least 1.2-1.5mm thick for best results.[19] Walls design out of tolerance may not register or might print incorrectly.

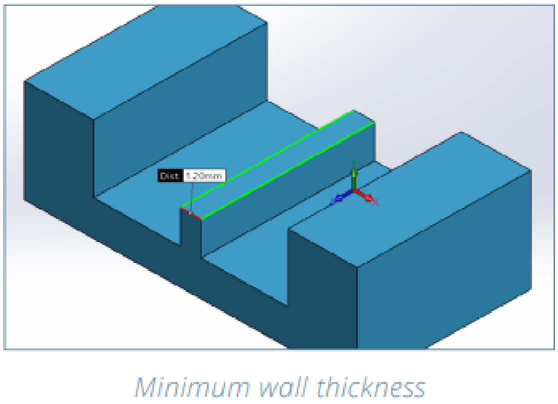


Figure 28 - Description of minimum wall thickness [17]

To retain a circular shape hole for FDM are drawn with a diameter greater than 1mm. A fundamental aspect is the orientation of holes and the resolution that tends to improve when printed parallel to xy-axes. To increase the accuracy of through holes, Xometry may drill out holes during post-processing.[17] Post processing drilling is only possible for solid infill parts.

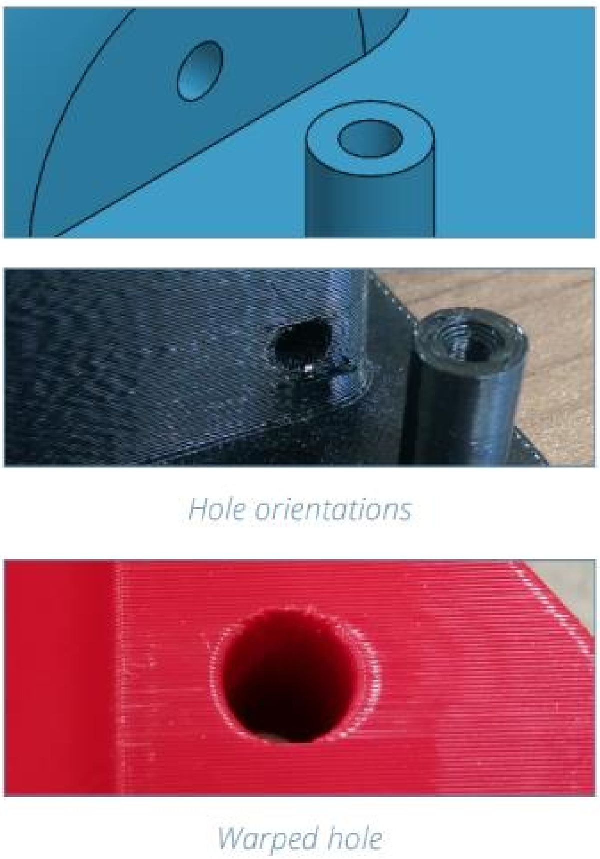


Figure 29 - hole descriptions [17]

Realise small details and texts is difficult to print in FDM because many small features do not register in the printing process when they are below certain tolerance. Text thickness must be at least 1mm to register properly, but 1.2-1.5mm is recommended to be legible and avoid unexpected errors. All text must also be oriented parallel to the xy-plane for best results.[17]

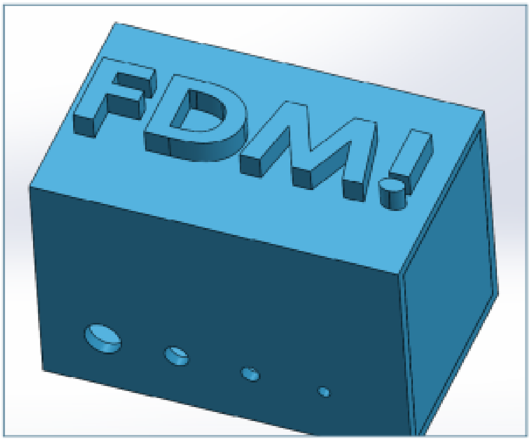


Figure 30 - details and text [17]

To ensure the remotion of supports gaps is maintain a width greater then 5mm.

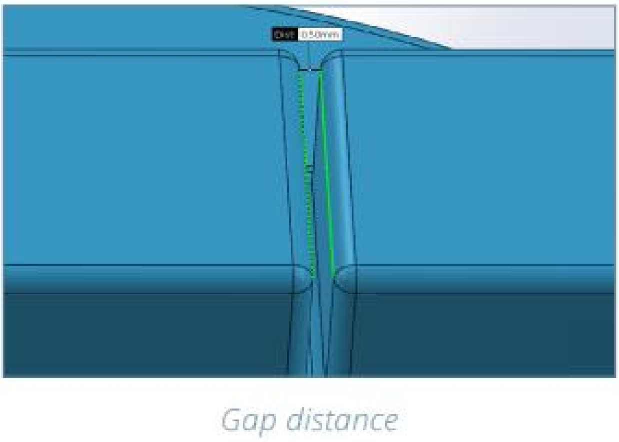


Figure 31 gap distance [17]

The size of the tab must be as large as possible depending on application and size of the overall part. Orienting tabs parallel to the xy-plane will also increase the strength of the tab and reduce the risk of breakage. [17]

In FDM tabs may be printed separately in the best orientation then inserted post-processing.

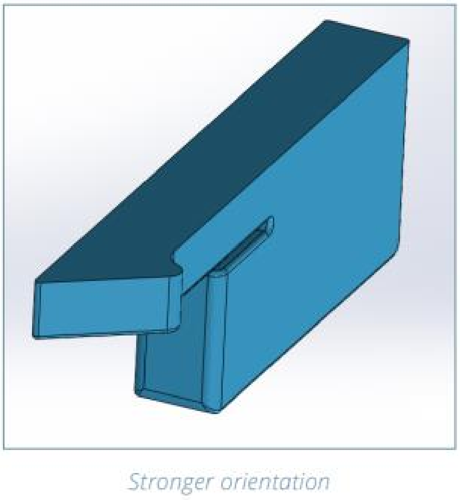


Figure 32 stronger orientation [17]

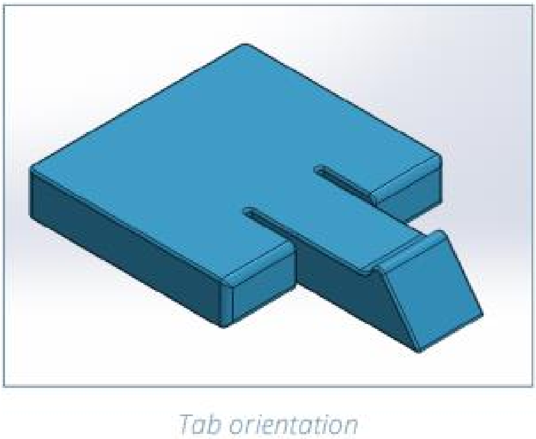


Figure 33 Tab orientation [17]

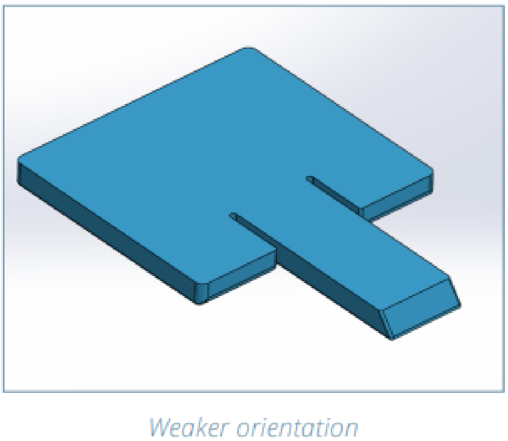


Figure 34 weaker orientation [17]

Introducing fillets in additive manufacturing process is important to reinforce fragile features. Fillets greatly increase structural rigidity, and help surfaces build naturally and avoid the need of support material. Overhang angle must be greater than 45 degrees from vertical, so adding a fillet will help the surface gradually grow and continually support itself.

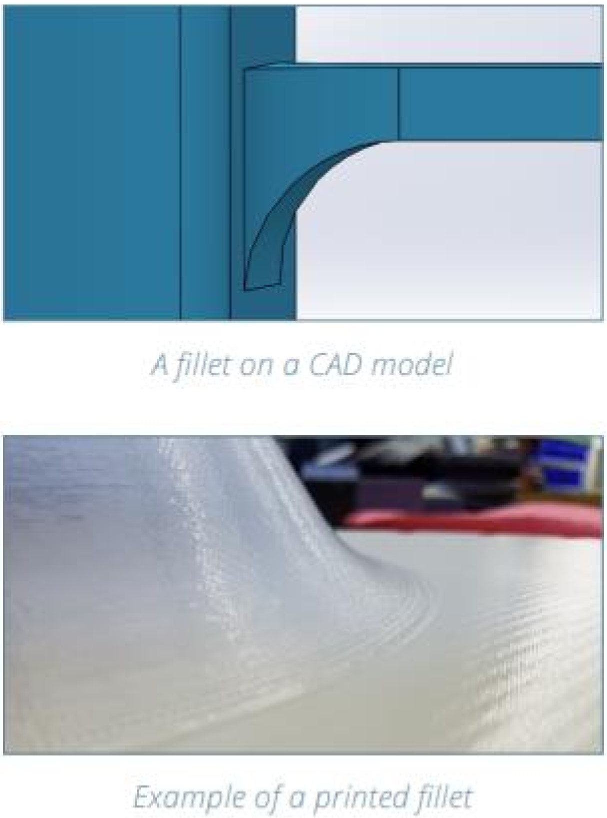


Figure 35 fillet on CAD and printed [17]

To increase the strength of support structures is possible adding ribs. Ribs aim is to distribute the force applied to a structure to a greater surface area. A safe minimum rib thickness to follow is 1.5mm to allow multiple layers of filament inside of each rib.

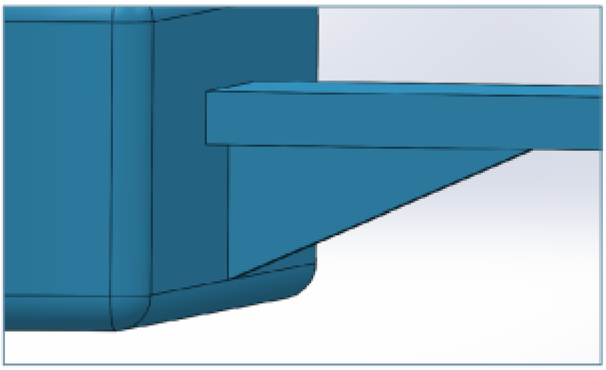


Figure 36 rib on a CAD model [17]

There are three different types of infill options:

- Ultralight: consisting of a single crosshatch pattern throughout the parts.
- Light: consisting of a double cross- hatch pattern throughout the part to increases some strength but keeps the price low.
- Solid: the standard, strongest option material is filled throughout the part.

Figure 37 ultralight infill [17]

A crucial part in FDM is the orientation of parts that has an enormous impact on its overall strength and appearance, especially for fine and concentric features. Many fine features are stronger when printed parallel to the xy-axes as well. Concentring features resolve best when layers print parallel to the xy-axes. Printing the part shown from the bottom up, vertical tabs are extremely weak and may break off between layers. Long surfaces will also save a lot of money and time if cross sections orient parallel to the xy-plane.

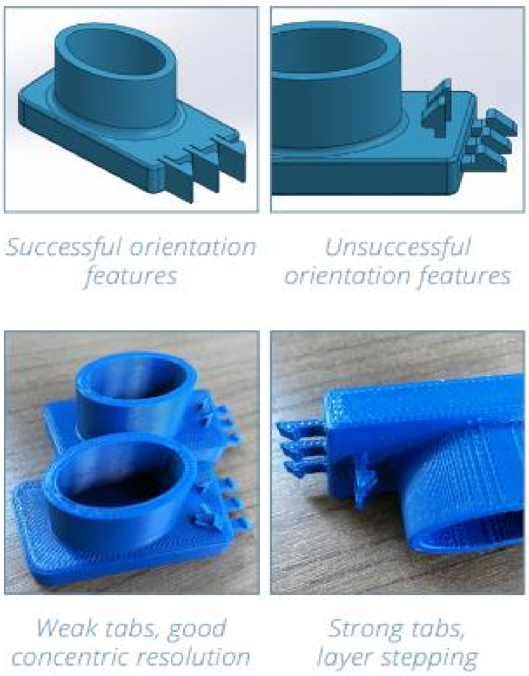


Figure 38 different types of orientation [17]

FDM technology tends to generate a rougher, more visibly layered surface finish than other manufacturing processes because of its method of formation by layer upon layer of plastic filament deposition. This "scaling" effect between layers is particularly noticeable on curved or poorly angled surfaces. To reduce this phenomenon, it may be useful to design components so that curved or sloped surfaces grow parallel to the printing plane, or to increase the angle or curvature of the surfaces themselves.

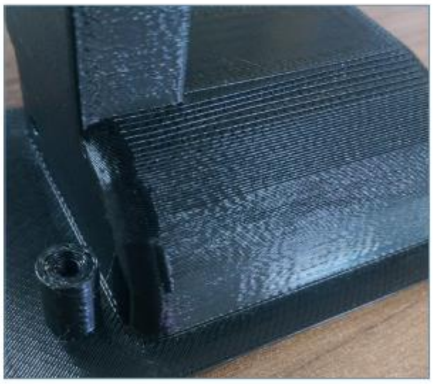


Figure 39 surface finish [17]

There are currently 16 different colour available in FDM depending on material to allow for tremendous customization for any part.

- ABS: strong and affordable, production-grade thermoplastic
- Ultem: most heat-resistant plastic, the strongest
- ASA: UV resistant, affordable, durable plastic
- Polycarbonate (PC): industrial thermoplastic, offers high tensile and flexural strength
- Nylon: used in traditional manufacturing, great impact strength
- PPSF: strong high-performance plastic, sterilizable

Many mechanical features can be applied to parts without risking structural integrity. Possible features include:

- Tapping
- Inserts
- Pins

Figure 40 - colour options [17]

Additive for Assembly: Potential, Limitations, and a Systemic Approach Part Consolidation

Additive manufacturing (AM) enables reduction in the number of components in an assembly by merging multiple functions into a single part. This strategy reduces assembly costs and lead times, minimizing potential assembly errors and weak points.[18]

By adopting this new design perspective, structures previously impossible to fabricate through traditional methods can now be realized such as mechanisms with built-in degrees of freedom, pre-assembled moving parts, and internal lattices [13]. AM also makes it possible to create both multi material and mono material devices with geometries specifically tailored to integrate mechanical, thermal, or optical functions. These technologies facilitate greater product customization, on-demand production, and the decentralization of manufacturing.[14][18]

Using AM technologies, we can find some limitations for example, systems generally offer lower accuracy and tighter tolerances compared to CNC machining or injection moulding. Clearances between moving parts require careful design and, often, post-processing [15]. Another limitation concerns the range of available materials, which remains narrower than with traditional manufacturing methods. Assembly size is further constrained by the build volume and the limits of part consolidation. post-processing challenges—especially the removal of powders, support structures, or unconsolidated materials from the gaps between moving elements—frequently necessitate specialized tools. Certain mating surfaces and complex geometries may be difficult to access or clean without thoughtful design adjustments.[18][19]

Some components, subject to frequent wear, replacement, or requiring specific materials, may still demand a traditional modular architecture. Additionally, mechanical anisotropy—i.e., differing strength along different print orientations—remains a functional limitation [16].

Three main categories can be identified where the logic of additive manufacturing is fully leveraged:

1. Monolithic Assemblies Printed in a Single Cycle: This includes mechanisms with multiple degrees of freedom, gears, hinges, and grippers.[18]
2. Self-Assembly Components: Components are designed with connections or joints that come together during or immediately after printing.[18]
3. Selective Integration: Only certain parts are consolidated, while others remain modular for maintenance, material, or upgrade purposes.[14][15]

Additive for assembly represents a real strategy to redesign product architectures, simplify assembly chains, and increase added value. However, it is crucial to adopt a systemic and informed approach—one that starts from the required function while recognizing the inherent limitations. Only this way can tangible progress be made in innovation, efficiency, and assembly-free design.[18][19]

Innovations Introducing Artificial Intelligence

Among recent innovations in additive manufacturing, artificial intelligence (AI) stands out as the most transformative. AI helps overcome many traditional limitations of AM by accelerating the development of new solutions, while improving quality, customization, and production efficiency.[16][18]

Design Optimization and Engineering Support Machine learning and deep learning algorithms can rapidly generate and evaluate complex, innovative geometries that are difficult to achieve using conventional approaches [13]. Neural network-based systems can suggest optimal solutions for part consolidation and functional integration, significantly reducing design time and iterations.[18]

Intelligent systems, combining computer vision and AI-driven data analysis, can proactively detect defects, dimensional deviations, and process anomalies. As a result, process parameters can be adjusted in real time to maintain high quality standards [16][19].

AI systems analyse historical data and operational behaviours to predict failures, minimize downtime, and optimize production assets. Some solutions can self-learn from print data, continually improving operational performance over time.[19]

Leveraging AI and data analytics, highly customized products can be manufactured. Design parameters are adapted based on user needs and operational conditions, enhancing production flexibility and supporting the transition toward more customer-centric manufacturing [13][18].

AI also supports the discovery of new materials and the optimization of process parameters through simulations. This broadens the range of AM applications and opens new opportunities in advanced sectors such as biomedical, aerospace, and automotive [16]. Adopting AI in additive manufacturing is emerging as a powerful driver of innovation, capable of revolutionizing the product lifecycle and business models. The synergy between AI and AM is set to enable smarter processes, higher-performing products, and new forms of human–machine interaction in the future.[18]

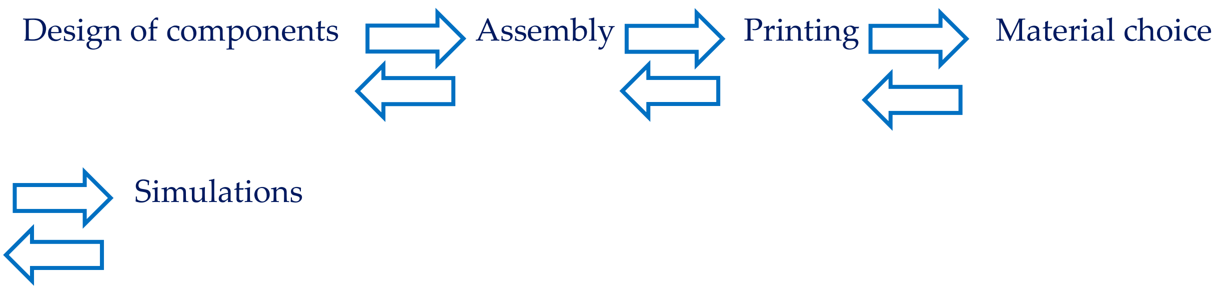
Additive Process Cycle – From Design to Production

Having explored the theoretical foundations underlying this study, the focus will now shift towards more practical and functional considerations. Attention will be given to the introduction and detailed examination of the additive manufacturing process cycle, highlighting its key phases and operational dynamics. A fundamental aspect in the development of this thesis is the additive process cycle, spanning from design structure to final production. The first step involves the design phase, where the original CAD files are adapted according to additive manufacturing principles. Each component of the internal mechanism is redesigned to maximize functionality and minimize weight. The image below shows the evolution of a selected component.

The second step focuses on assembly: the redesigned parts are assembled, and simulations are performed to optimize and minimize the necessary assembly operations. To further clarify the assembly process, a video demonstration is created.

The workflow continues with a print preview using Ultimaker Cura software. This is followed by a careful selection of materials, based on both application requirements and company availability. Finally, simulations are conducted to perform a static analysis of the assembled mechanism.

Representation of the Additive Process Cycle



To provide a clearer overview, the image depicts a component at various stages of its evolution. It can be observed how the initial sheet metal assembly Figure 41, originally consisting of three components, has been reduced to a single part, as shown in Figure 43. Through further iterations, the four bearings are also incorporated into the structure, as illustrated in the image below, resulting in the final integrated component.

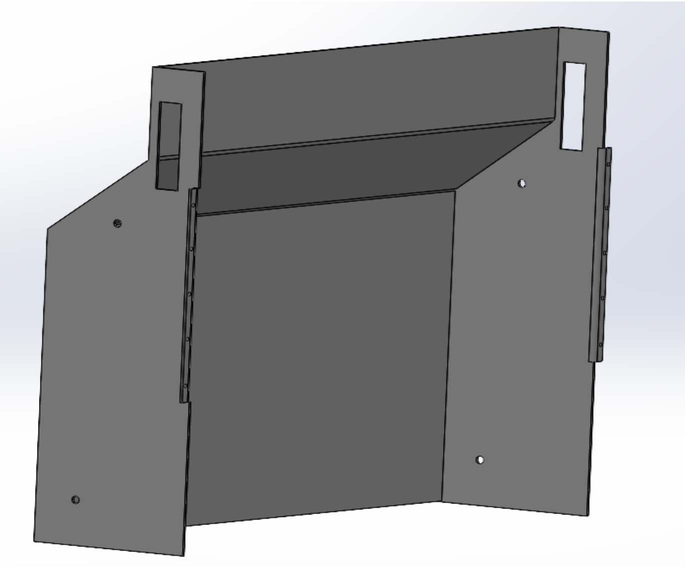


Figure 41 - external sheet metal

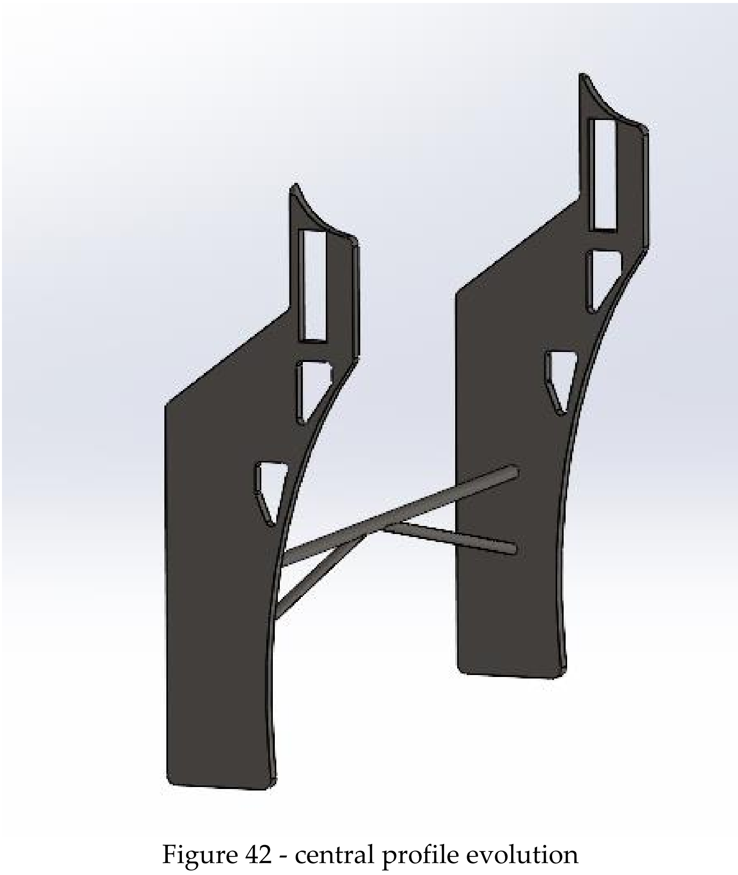


Figure 42 - central profile evolution

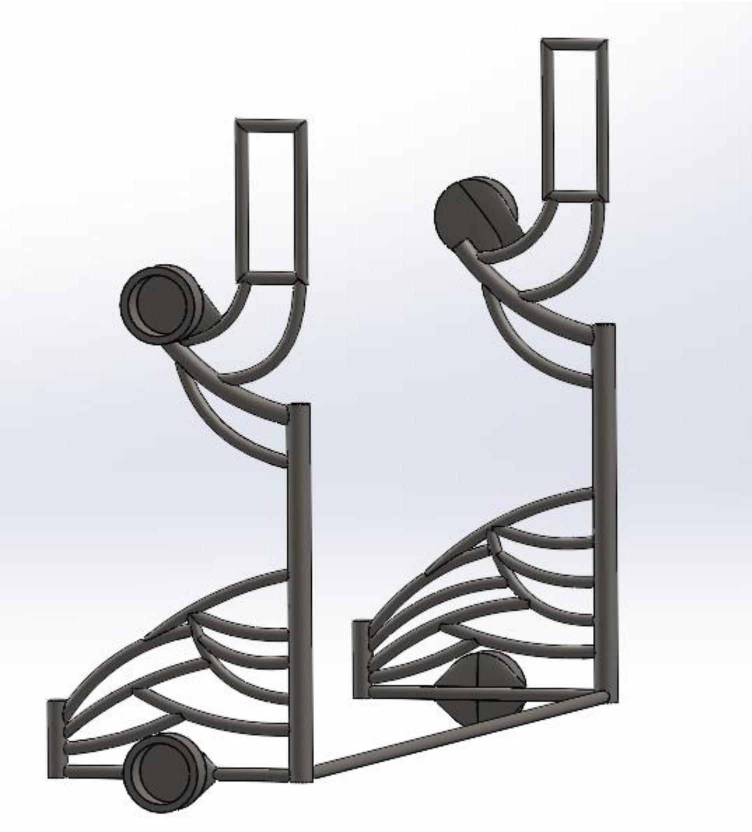


Figure 43 - central profile

File from CAD to STL

The CAD file generated with SOLIDWORKS is then converted into an STL file. The STL format converts the solid model into a mesh representation of the component. Before importing this file into Ultimaker Cura, it must be modified and repaired to ensure optimal print quality and correct support distribution.

Material Selection

Once the geometry is properly defined, the choice of material is carefully evaluated. To achieve a good balance between aesthetics and functionality, the materials for the assembled component are diversified. The external panels intended for decorative use are removable and can be changed based on personal taste; therefore, they remain in wood. Two wooden parts have also been designed: the shelf and the front panel.

As a first step, an initial screening was carried out by comparing four materials proposed by the company, listed below:

1. ABS

2. PC-PBT

3. PC-PBT + 20% carbon fibre

4. PA12 + 20% carbon fibre

The choice of material for FDM 3D printing of industrial technical components is not based solely on nominal mechanical performance; it must also consider processability factors, dimensional stability, behaviour under load, resistance to external agents, costs, and production reliability. This section compares four representative polymeric materials for advanced additive production—ABS, PC-PBT, PC-PBT reinforced with carbon fibre, and PA12 + 20% carbon fibre—analysing their characteristic properties, practical advantages, and usage limitations.

Acrylonitrile–Butadiene–Styrene (ABS)

ABS is one of the longest-standing polymers in technical 3D printing.

Characteristics:

- Ease of printing and post-processing: excellent melt flow, broad parameter windows, suitable for industrial post-processing (sanding, bonding, painting, acetone vapor smoothing).[6]
- Impact resilience: typical Charpy impact strength in the 10–30 kJ/m^2 range.
- Medium mechanical strength: elastic modulus around 2.0 GPa, tensile strength 40–55 MPa, flexural strength 70–90 MPa.[8]
- Heat deflection temperature (HDT): 82–96 °C at 0.45 MPa.[6]
- Density: 1.04–1.07 g/cm^3 [6][8]

However, ABS has limitations compared with more advanced engineering polymers:

- Limited thermal stability: continuous use above 80 °C can cause deformation.
- Intermediate stiffness and strength compared to fibre-reinforced materials.
- Sensitivity to UV radiation and certain chemicals.

PC-PBT (Polycarbonate / Polybutylene Terephthalate)

PC-PBT combines the stiffness, thermal stability, and chemical resistance of PBT with the mechanical properties and impact performance typical of polycarbonate.

- Higher mechanical strength than ABS:
  - Elastic modulus: 2.3–2.6 GPa
  - Flexural strength: 100–120 MPa
  - Tensile strength: 60–75 MPa
- Heat deflection temperature (HDT): 125–140 °C, practically double that of ABS.
- Density: ~1.25 g/cm³
- Excellent resistance to chemicals (especially fuels and organic solvents), low water absorption, and good dimensional stability.
- Better resilience and ductility than fibre-filled variants.[6][8]

In printing, PC-PBT is less easy to process than ABS (it shrinks, requires an enclosed, heated chamber and build plate, and can warp), but the resulting parts are much more robust in continuous service.

PC-PBT Carbon Fibre

Adding approximately 20% carbon fibre to PC-PBT raises the material to “super-polymer” levels for functional use:

- Typical flexural strength: 120–180 MPa
- Elastic modulus: 3.5–5.0 GPa
- Tensile strength: 85–110 MPa
- Heat deflection temperature (HDT): >140 °C
- Density: ~1.3 g/cm³
- Water absorption: negligible; excellent for harsh environments.[6][8]

These materials, however, exhibit increased brittleness (elongation at break typically below 3–5%) and are much more abrasive on printer nozzles (hardened nozzles are required). They demand greater care both in printing (pronounced shrinkage) and in post-processing (delicate surface fibres).

PA12 + 20% Carbon Fibre

PA12 with CF (CF20) is among the top materials for printing structural components:

- Elastic modulus: 6.0–7.0 GPa
- Flexural strength: 130–160 MPa
- Tensile strength: 75–105 MPa
- Heat deflection temperature (HDT): up to 180 °C
- Density: 1.10–1.20 g/cm³
- Water absorption: much lower than traditional PA6 and PA66.[6][8]

PA12+20% CF stands out for very high stiffness and dimensional stability, maintained even under constant loads (anti-creep), as well as high chemical and fatigue resistance. The main drawback is brittle behaviour: the material can crack suddenly under impact (elongation at break <4%). It is also highly abrasive and absorbs moisture during storage.

In Table 12, the main characteristics of the polymers are summarised

Property	ABS	PC-PBT	PC-PBT+20% CF	PA12+20%CF
Density (g/cm^3)	1,04-1,07	1,25	1,3	1,1
Elastic modulus (Gpa)	2,00	2,5	4	6,5
Flexural strength (MPa)	80	110	150	145
Elongation at break (%)	12-30	10-20	3-5	2-4
Heat deflection (°C)	85,00	135	145	180
Impact resilience	Alta	Alta	Media	Bassa
Shore D hardness	72,00	80	84	85

Table 12 - material properties

Theoretical comparison between PA12+20% and ABS

After comparing the four materials, experimental tests were conducted exclusively on PA and ABS for the following reasons:

1. Time and cost efficiency to ensure an adequate number of replicates and statistical robustness
2. Representativeness of the use case and data availability
3. Compatibility with the available equipment and process [6][8][12]

These materials are widely used: PA12+20% is stiff and easy to process for geometric and low-temperature functional validations, while ABS is tougher and more thermally stable for functional components. PC and PC-PBT-CF, on the other hand, require stricter processing conditions (higher nozzle and chamber temperatures, thorough drying, wear-resistant nozzles for fibre-filled versions). They also introduce anisotropy and variability related to fibre orientation and entail higher costs and setup overhead. For completeness, they have been included at the documentation level. If the application requirements include operation at elevated temperatures, repeated impacts, and higher chemical resistance, they can be considered in future iterations.

Static analysis

Static FEA analysis is a domain that verifies the strength of the component in an early design phase, simulating the real conditions to which it is subjected. The main steps required are : meshing of the component, application of the relevant constraints and loads, and final generation of results.

According to the reference standard NTC 2018, two static analyses (case 1 and 2) are typically performed for counters intended for public use. However, to better approximate actual operating conditions, three additional configurations (cases 3, 4, and 5) were also considered, selected to simulate more realistic scenarios.

The five examined cases are as follows:

1. Uniformly distributed load
2. Accidental concentrated load near a corner (a person leaning on it)
3. Linear weight of bottles (line load distributed over a narrow area)

4. Combined action of work area and appliance

5. Asymmetric load

For each case, the following sections are included:

- Load representation
- Von Mises stresses
- Resulting displacements
- Strains

The main objective of this phase is to compare the polymer materials PA12 + 20% Carbon Fibre and ABS to assess which of the two has better performance.

In this paper, components not subjected to stress were excluded, such as those intended solely for decorative purposes, including: the front panel and the side panels. In addition, the contribution of lateral support provided by the glass shelf located at the rear of the ledge is excluded from this analysis. The considerations made remain consistent across all five examined cases. Table 13 lists the components involved in the analysis.

Static analysis components
Central profile
Tubes
Hinges
Inner support
Shaft
Shelf

Table 13 – Static analysis components

In the Technical Standards for Construction (NTC 2018), paragraph 3.1.4 and Table 3.1.11 specify the accidental loads based on the use and intended purpose of buildings and structural elements. In the case considered, the component falls into category A structures intended for ordinary use and subject to exceptional crowding.

The following categories are identified from the standard:

Category	Intended use	Distributed load
A	Homes, residences, hotel rooms, private offices, residential corridors	$2.0kN/m^2$
B	Offices, light archives, branch premises, school premises	$3.0kN/m^2$
C	Moderate assembly areas, waiting rooms, libraries, museums, conference rooms	$4.0kN/m^2$

Table 14 - NTC 2018 Categories

The shelf in question has compact dimensions of 1.5 × 1.4 × 0.24 m. It is always supervised by staff and used exclusively in the evening hours as a support surface for aperitifs, with no possibility of access or foot traffic. Given its temporary intended use, the adopted data will comply with Category A of Table 3.1.11 of NTC 2018 (residential environments and similar). The approach considered ensure adequate safety levels for the intended use, without resulting in unjustified over-dimensioning for the operational context.

In Figure 44, the finite element discretization of the assembled model for the static analysis is shown. The mesh subdivides the continuous model into triangular elements, producing a set of finite elements across which quantities such as stresses and displacements are computed.

The mesh is denser in the areas of greater structural interest, where high stresses are expected. In this case, this is clearly visible around the four lateral bearings that were integrated into the central profile during the design phase. In less stressed regions or where the geometry is simpler, a coarser mesh was used, with the dual goal of keeping simulation times in check and reducing the computational load. The component that required the most attention was the central profile, due to the presence of intersections created with dedicated sweep and loft features, and it also exhibited some inverted normals.

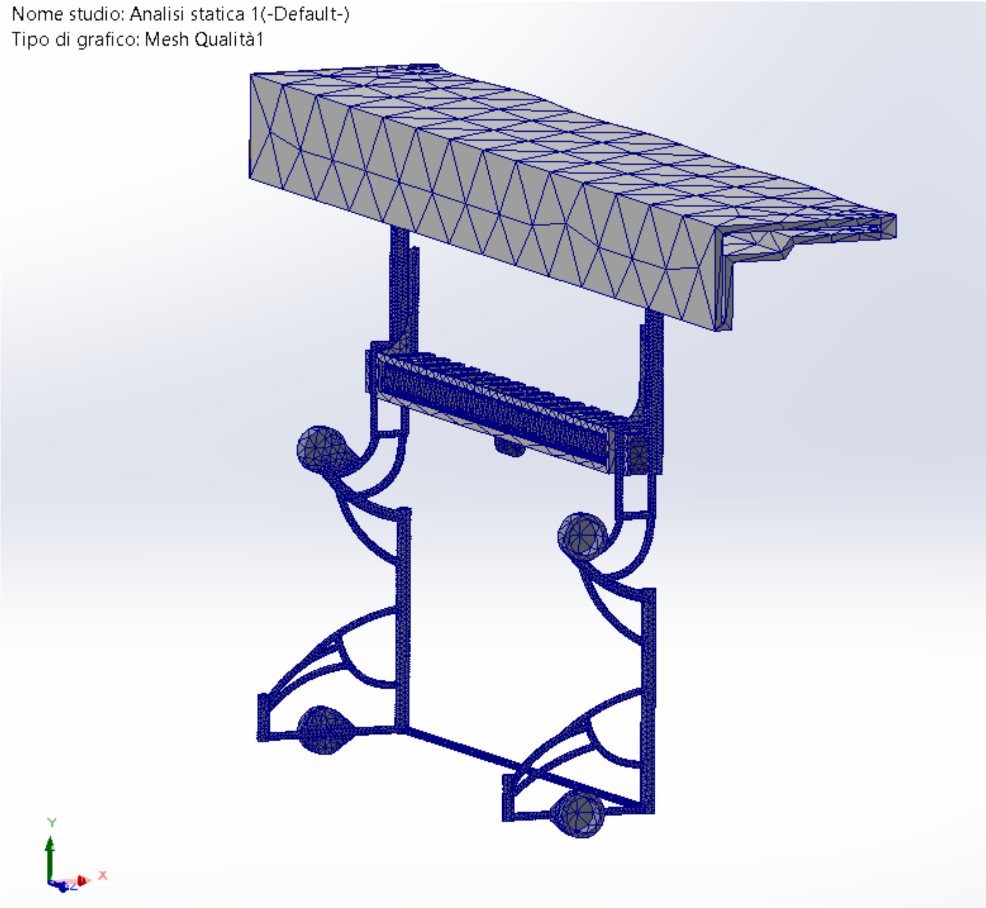


Figure 44 - mesh preparation

In this section, we present the components made from both steel and polymer shows in Table 15.

Steel components	Polymer components
Staff tubol	Central profile
Shaft	Tubolars
	Inner support

Table 15- Classification of components

For the metallic parts, we use annealed 4340 steel, chosen for its good machinability and toughness for the required strength level.

- Strength (annealed 4340): the typical yield strength is on the order of $\sigma_y \approx 400 - 600\ MPa$ with $\sigma_y = 500 MPa$ (to be confirmed with the specific supply and cross-section).

- Design criterion: it is essential not to exceed the material's yield strength to avoid permanent plastic deformation and the risk of failure in service.
- Safety factor: as noted previously, adopt a factor n (1.5-2), designing so that

  $\sigma_{max} \le \sigma_y / n$
- Conservative material choice: to remain on the safe side, a steel with relatively high yield strength was selected, increasing the margin with respect to service loads and reducing the likelihood of initiating plastic deformation.

Application of Constraints

For the purposes of the static analysis, it is appropriate to model the hinge as a "fix" constraint, locking translations. A second "fix" constraint is then applied near the connection between the shaft and the piston. Using other, stiffer constraint types—such as introducing a linear guide—would over constrain the system. The constraints are kept constant across all examined cases.

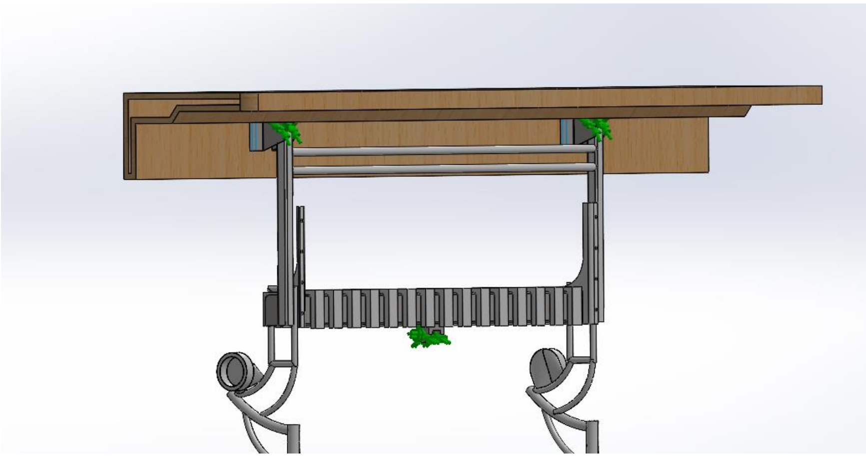


Figure 45 - constraints

Application of Load

The final step before performing the static analysis concerns the application of the load, which varies depending on the selected configuration. Table 16 summarizes the applied load, its magnitude, and its type.

Cases	Load types	Intensity
1	Uniformly distributed load	2000N/m^2
2	Accidental concentrated load at a corner	1500 N
3	Pressure load from a row of bottles	1667 N/m^2
4	Combined action of work area and appliance	280N
5	Asymmetric load	2000 N/m^2

Table 16 - Load types

Case 1: Uniformly Distributed Load

Load representation

In Case 1, a uniformly distributed pressure load is assumed over the entire surface. The applied operational distributed load includes the weight of objects and equipment required to carry out the task.

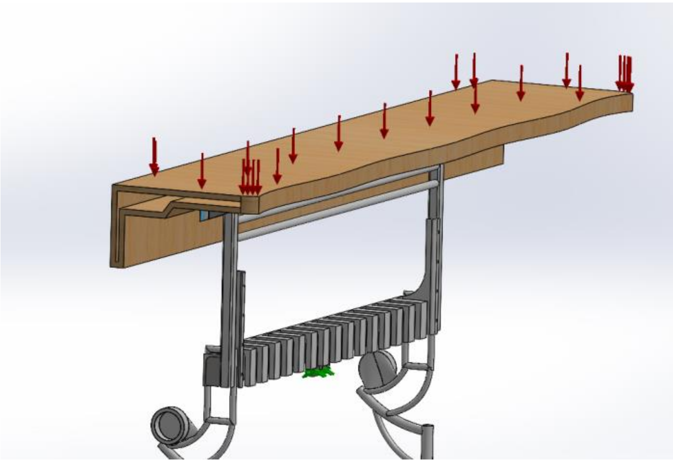


Figure 46 - uniformly distributed load

Case 2: accidental concentrated load at a corner

Load representation

For this simulation, an external force of 1500 N was applied at an unfavourable point on the surface—specifically along an edge—to obtain the most severe stress condition.

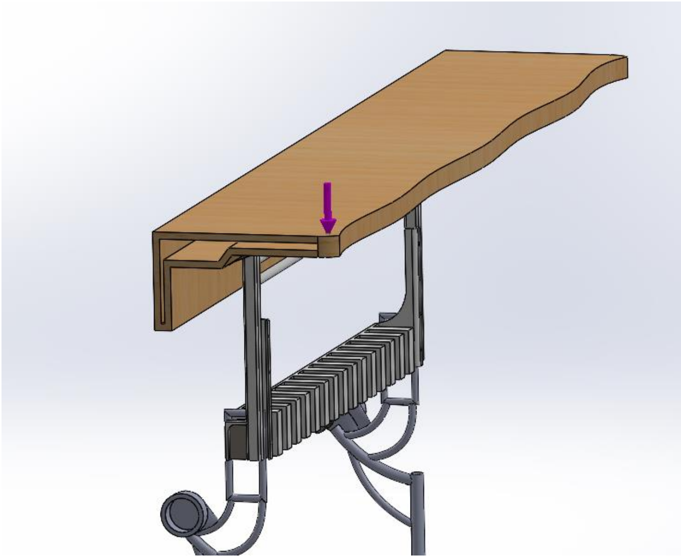


Figure 47 - accidental concentrated load at a corner

Case 3: weight of a row of bottles

Having completed the code-based cases, we now examine the following application cases, which involve conservative estimates performed numerically. The third case concerns a row of bottles arranged at the far end of the shelf. We consider a full bottle (wine, spirits:1.5kg). Assuming bottles are placed side by side along one meter, there will be 12–13 bottles, corresponding to approximately 18–20 kg/m; rounding up to20kg/m.

Considering the shelf depth of 0.12 m and assuming the bottles are placed on the half opposite the hinges, the following pressure is obtained:

$$P = \frac{F}{\frac{Area}{2}} = \frac{200}{0.12} = \frac{1667N}{m^2}$$

Load representation

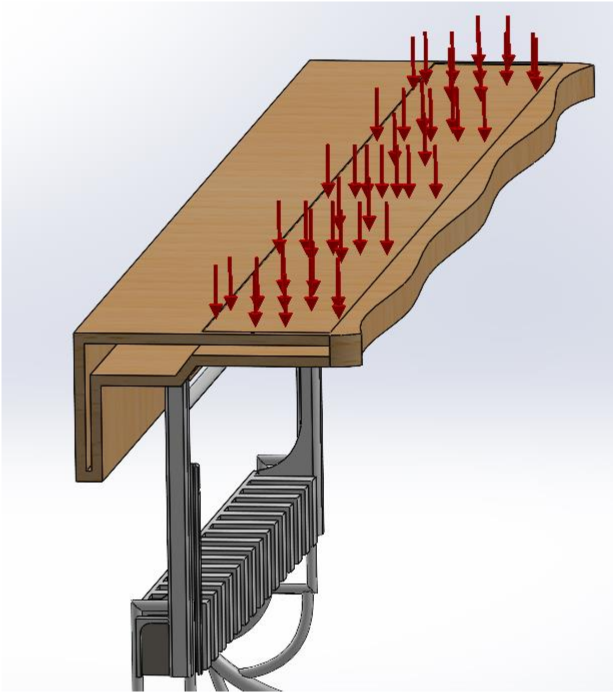


Figure 48 - weight of a row of bottles

Case 4: combined action of work area and appliance

Unlike the previous cases, we now consider the presence of an operator using a citrus juicer Calculations are performed to theoretically estimate the forces to be applied in the model. The resultant force is given by the weight of the juicer $F_1$and the force applied by the operator F_2 The data use is reported in Table 17:

m	juicer mass	3kg
F_2	force exerted by the operator	250N
A	juicer area	5000mm^2

Table 17 - parameters

$$F_1 = m \cdot g = 3 \cdot 9{,}81 = 30N$$

$$F_{TOT} = F_1 + F_2 = 280N$$

It is assumed that the juicer has a rectangular footprint of 50×100 mm. In terms of pressure applied over the area, we obtain:

$$P = \frac{F_{TOT}}{A} = 0.056N/mm^2$$

Load Representation

In Figure 47, the area of the juicer is shown positioned at the centre of the shelf, if the operator works near the centre of the countertop.

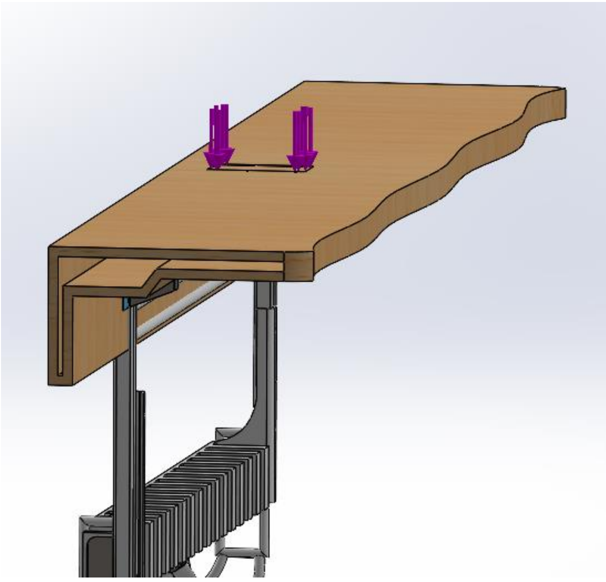


Figure 49 - combined action of work area and appliance

Case 5: asymmetric load

The following partially applied load configuration is of technical interest because it highlights an asymmetric distribution of loads. In this case, bending moments and concentrated stresses are generated that are higher than in the case of a uniformly distributed load over the entire surface. It helps to understand a real-world scenario in which loads are not uniformly distributed. As shown in Figure 50, an area approximately equal to half the surface is defined while keeping the total load unchanged, thereby further increasing the demand on the component.

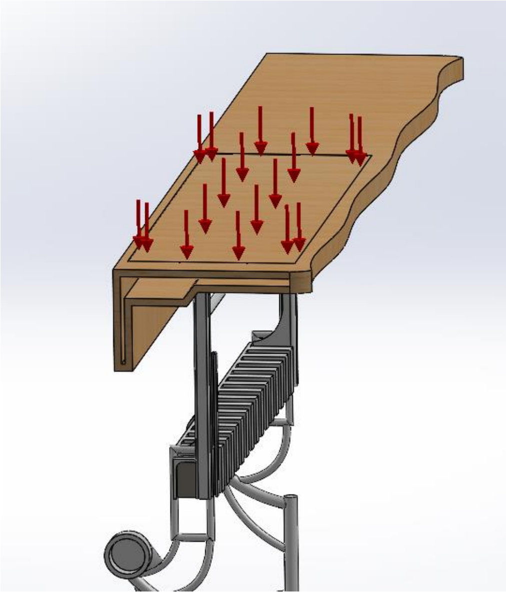


Figure 50 - asymmetric load

Print Preview: Ultimaker Cura

Within the following section, the Ultimaker Cura software is introduced, which is accustomed to generating a print preview. This software for 3D printing, is especially used for FDM/FFF printers. Before proceeding with the actual print using the machine, simulations are performed by adjusting process parameters to assess whether the redesigned components can be manufactured.

Figure 51 - printing preparation

Cura allows you to view every layer, the extruder path, and support structures. It also permits to check:

- Layers and infill
- Automatic supports
- Estimated time and material

The first step requires converting the 3D model—typically an STL file—into hundreds or thousands of horizontal layers called slices. Each slice represents the path that the extruder will follow to print a single layer of material.

The software processes and calculates all the printer movements (X, Y, Z axes, temperature, extruder, fan, etc.) and creates a G-code file.

Through visual simulation, it is possible to preview how the model will be printed. You can view the generation of the layers, extruder movements, infill, perimeters, supports, etc. The simulation contributes to understand the timing, the material usage, and the possible errors or defects before the real printing.

Ultimaker Cura enables to choose different type of parameters depending on your experience. It is possible to modify numerous print parameters, including:

- Layer height
- Extruder and build plate temperature
- Print speed
- Infill density and pattern
- Type and position of print supports

Supports are structures needed to print overhangs or suspended parts. You can adjust their pattern (linear, zigzag, grid), distance from the model, and ease of removal.

The simulation shows how these supports will be generated and how they will impact the print outcome and print time.

At the project start, Cura provides you to select the specific 3D printer intend to use. This ensures you work within the correct print area. Using a reference system, you can evaluate the positioning of the object in the most favourable area of the print bed

The choice of printer can affect slicing, print times, precision, and general settings. Printer selection determines:

- The available print profiles (preset parameters specific to that printer)
- The maximum printable dimensions (build area and height)
- Material compatibility
- Some advanced options

For this purpose, the parameters employed to achieve the modelling of the supports are defined. Given the complexity of the geometry, the profile used is "Extra Coarse" with a 0.6 mm nozzle, so that the print would be faster.

Parameters	
Layer height	0.48 mm
Line width	1.0 mm
Outer wall line width	0.95 mm
Top thickness	2 mm
Bottom thickness	1.5 mm
Infill density	8%
Printing temperature	255 °C
Inner wall speed	45mm/s
Travel speed	160mm/s
Outer wall accelaration	700mm/s^2
Inner wall acceleration	1200mm/s^2
Top/Bottom acceleraton	400mm/s^2
Travel acceleration	2500mm/s^2
Support pattern	lines
support density	8.5%
brim width	4mm

Table 18- print parameters

- Layer High (0.48–0.6) mm

    - 0.48 mm provides better surface quality and higher detail than 0.6 mm but increases print time.
    - Both are consistent choices; 0.48 mm maximizes quality; 0.6 mm maximizes productivity.
- Line Width 1.0 mm and Outer Wall 0.95 mm
    - Consistent with a large nozzle (typically 0.8–1.0 mm).
    - A slightly narrower outer wall (0.95) helps the exterior finish while maintaining good inter-line adhesion.
- Top/Bottom Thickness (2 mm / 1.5 mm)
    - Suitable values for "tall" layers: ensure proper top closure without translucency.
    - With 0.6 mm layers, 2 mm corresponds to approximately 3–4 layers.
- Infill Density 8.5%
    - Low; geared toward saving material/time and for non-structural parts.
- Printing Temperature 255 °C
    - Typical for materials like filled PETG or certain copolymers/ABS.
- Speeds and Accelerations
    - Inner Wall Speed 45 mm/s is conservative for quality; Travel 160 mm/s speeds up non-print moves.
    - Accelerations: 700 (outer), 1200 (inner), 400 (top/bottom), 2500 (travel) are balanced to reduce ringing on outer walls while keeping high throughput on travel moves.
- Supports

The software can automatically generate supports.

- The overhang angle is set to 45°,
- Support Pattern: lines, and Density 8.5% yield easy-to-remove supports suitable for surfaces that are not ultra-critical.
- Build Plate adhesion: brim, with a Brim width of 4 mm provides good protection against warping, especially with hotter materials.

Finally, in figure 52 is possible to see the preview printing. The time necessary to print the assembly is 2 days 23 hours. Thanks to the use of additive manufacturing technologies, the replacement of certain steel components with ABS parts, and design optimization, the weight decreased from 12.477 kg to 2.559kg resulting in a reduction of 9.918 kg (about 79.5% less).

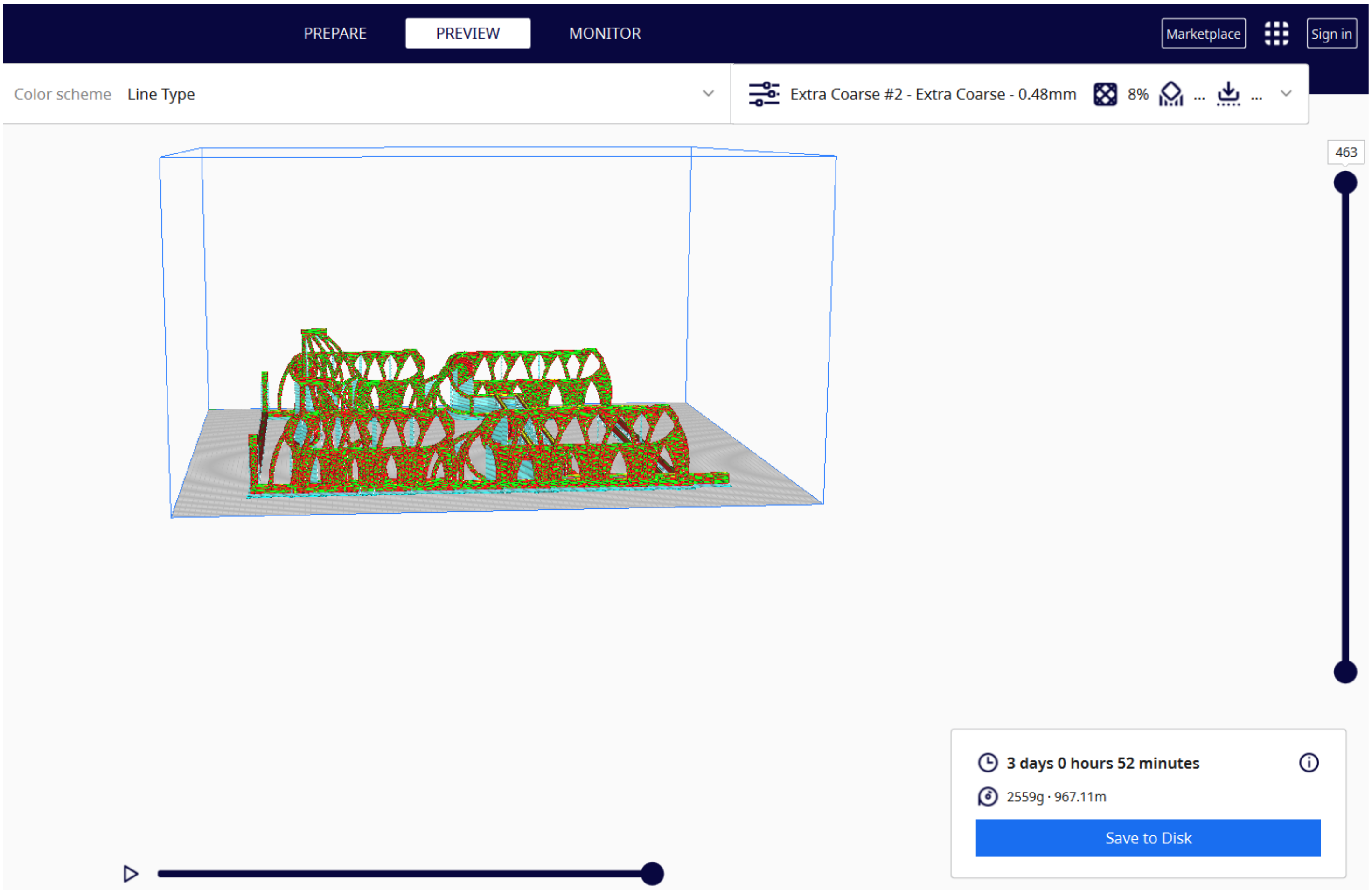


Figure 52 - print preview

CHAPTER 4 RESULTS

Redesigned Internal Mechanism

Following the iterative design process, a final component was defined in accordance with the theoretical framework. The "new" components are presented in a Table 19. For completeness, the upper front panel and the shelf were also modified, even though they are not involved in the static analysis as they are wooden components.

Item	Parts	Quantity
1	Shelf	1
2	Side support	1
3	Central profile	1
4	Tube	1
5	Inner support	1
6	Staff tubol	2
7	Shaft	1
8	Upper front panel	1

Table 19 – new parts

Figure 53 - new internal mechanism

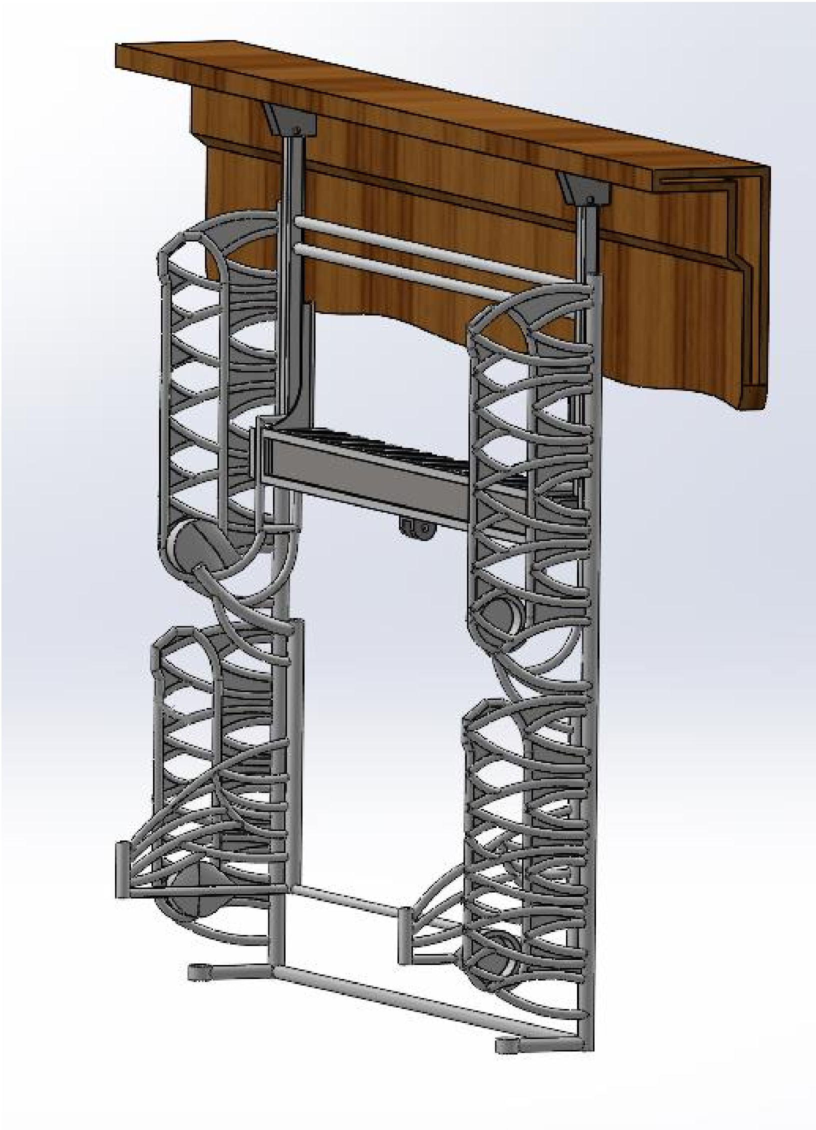


Figure 54 - new internal mechanism

In the following section, the components that were redesigned are listed, evaluating how they were modified to improve the assembly. Figure 55 shows the shelf, which was suitably hollowed out to lighten the component.

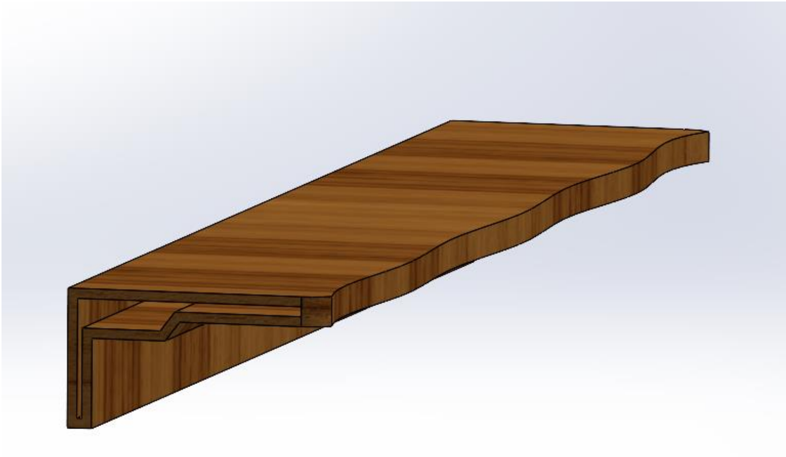


Figure 55 - shelf

The central profile is created by integrating into the model the four side bearings, which previously were four separate, outdated entities. The trusses are arranged vertically and interlaced to provide greater strength to the structure.

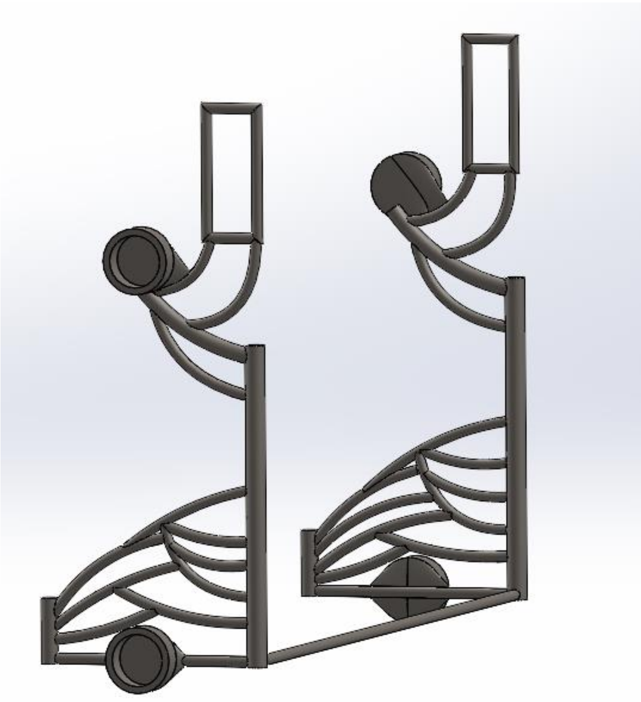


Figure 56 - central profile

The side support results from the union of the two lateral side plates, which were connected to each other and feature two vertical guides that allow the bearings to slide. This element primarily serves a structural support function and makes it easier for the central profile to slide.

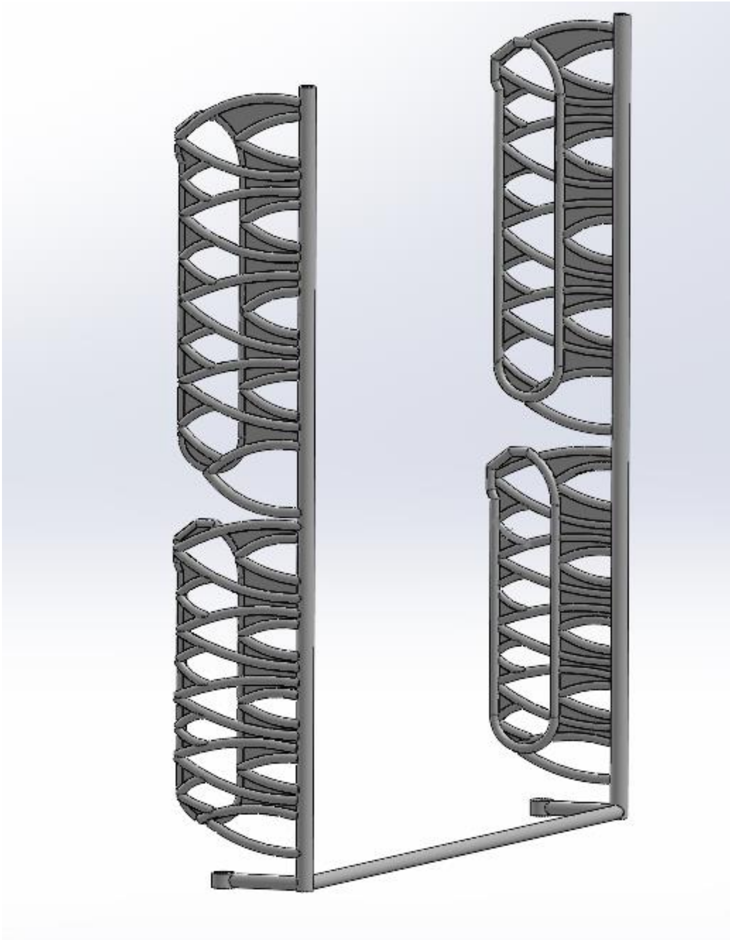


Figure 57- side support

The tubes, previously two separate components, were unified; their geometry was not changed significantly—indeed, the rectangular structure was retained and then extruded. To provide greater support to the structure, the tubes were joined horizontally with two bars.

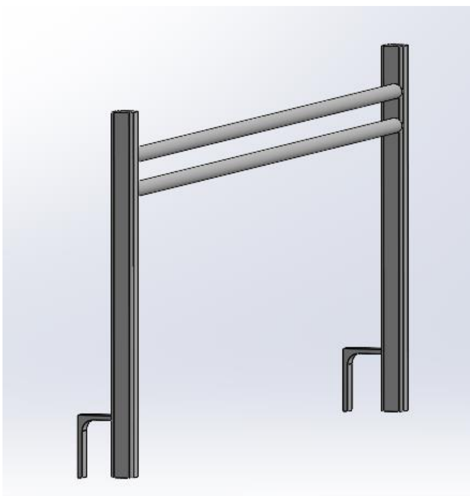


Figure 58- tube

The internal support was also lightened in weight, and pillars were added at approximately 20 mm to create small bridges to facilitate printing and reduce supports.

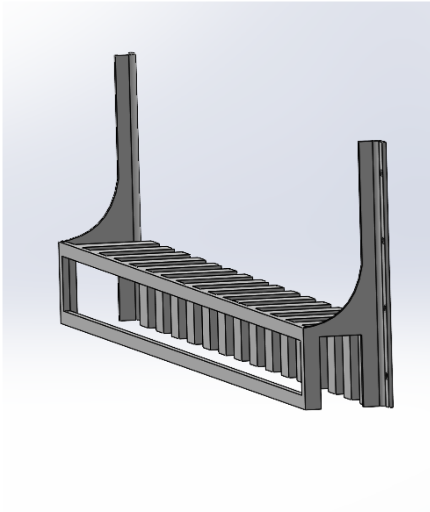


Figure 59 - inner support

The staff tubol serve as the component's hinges. They were slightly refined.

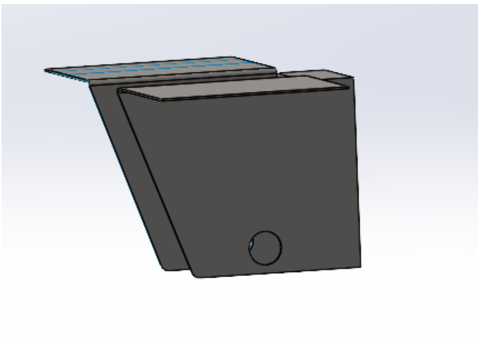


Figure 60 - staff tubol

Similarly, the shaft did not undergo changes, since it must be connected to the piston assembly. The only modification made was to integrate the connecting clevis with the shaft to further reduce the number of components.

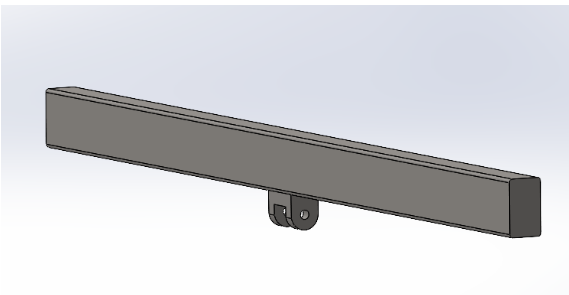


Figure 61- shaft

Comparative Results: ABS and PA12 + 20% CF

Case 1

Von Mises stresses

We proceed with the evaluation of the von Mises stresses for both materials. The most highly loaded areas are the two hinges (staff tubol), which are made of steel. It is necessary that the maximum stresses do not exceed the allowable stress of the steel under consideration.

To observe the stress peaks and better assess the distribution, a range between 10 MPa and 40 MPa is displayed. It is concluded that the remaining part of the structure is not subjected to stresses that could compromise its operation, as all other regions lie in the blue band, which is characterized by low stress.

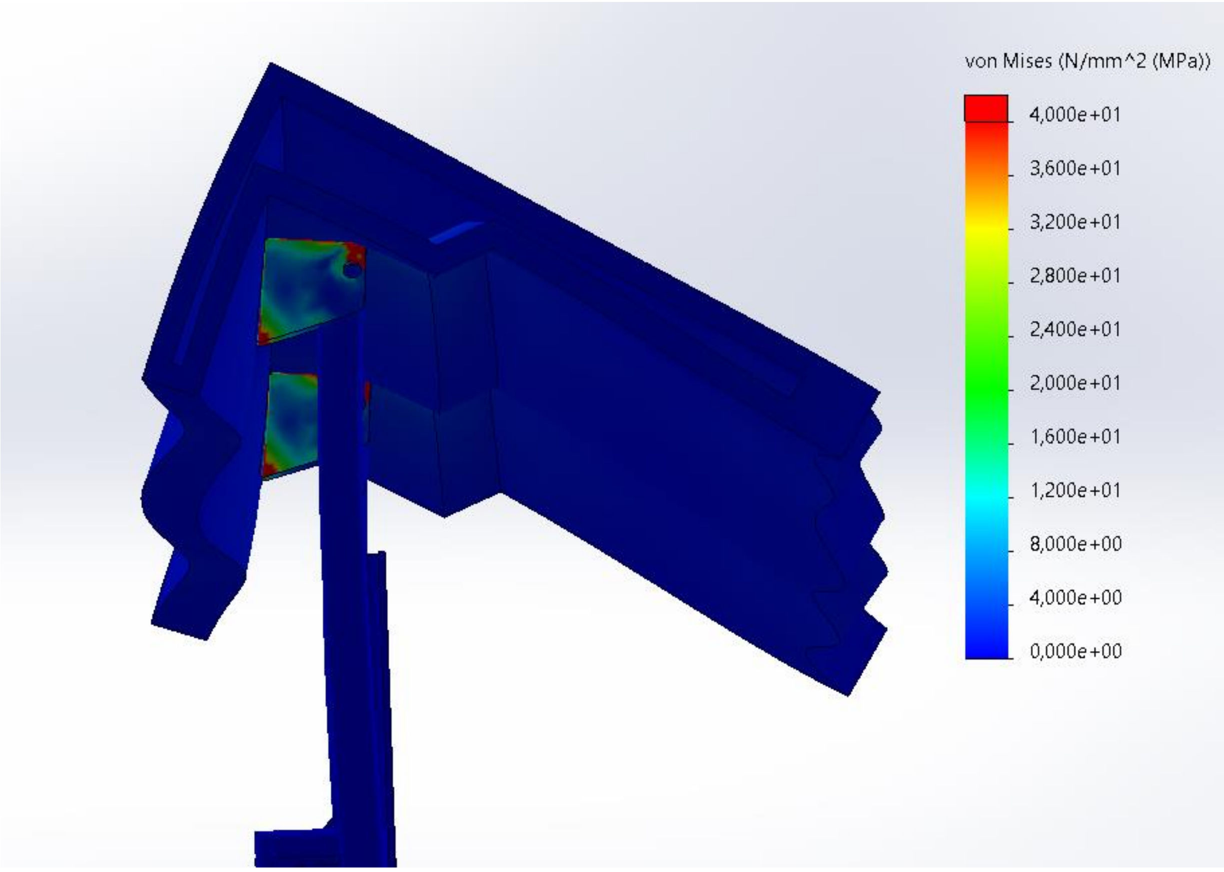


Figure 62 - Von Mises stresses ABS [MPa]

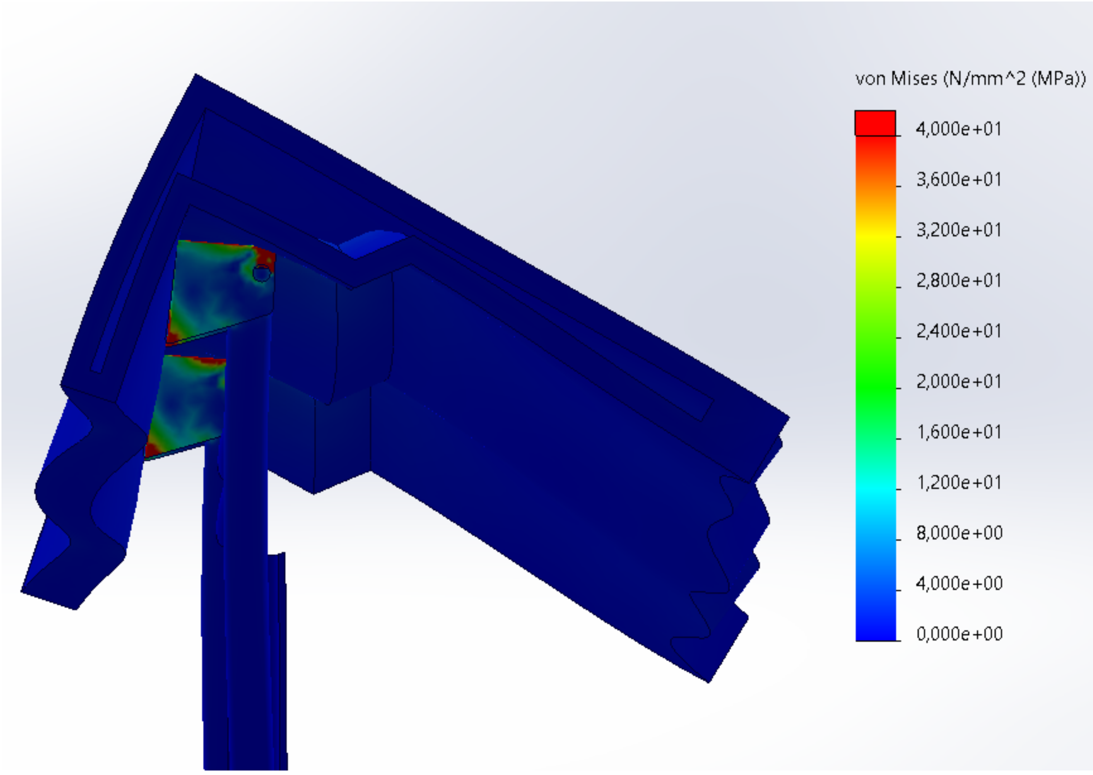


Figure 63 - Von Mises stresses PA12+20%CF [MPa]

Assessment of Maximum Stresses

During the analysis, maximum stress values on the structure were obtained through finite element simulation. For a more realistic evaluation, the significant maximum stress was defined as the highest value extended over an area comprising at least six surrounding elements, excluding any isolated peaks. This type of approach was adopted to avoid numerical anomalies.

The stress map is examined by focusing on the "hot zone" using the Probe tool. The resulting values are shown in Figure 64-65.

The nodes considered are reported in the Table 20-21.

Stresses applied to the nodes [MPa]	
NODE 969	126
NODE 1273	43
NODE 1402	191
NODE 924	171
NODE 1416	65
NODE 979	64

Table 20 - Stresses applied to the nodes ABS

Stresses applied to the nodes [MPa]	
NODE 1402	190
NODE 862	159
NODE 2426	333
NODE 1419	213
NODE 1264	238
NODE 924	170

Table 21 - Stresses applied to the nodes PA12+20%CF

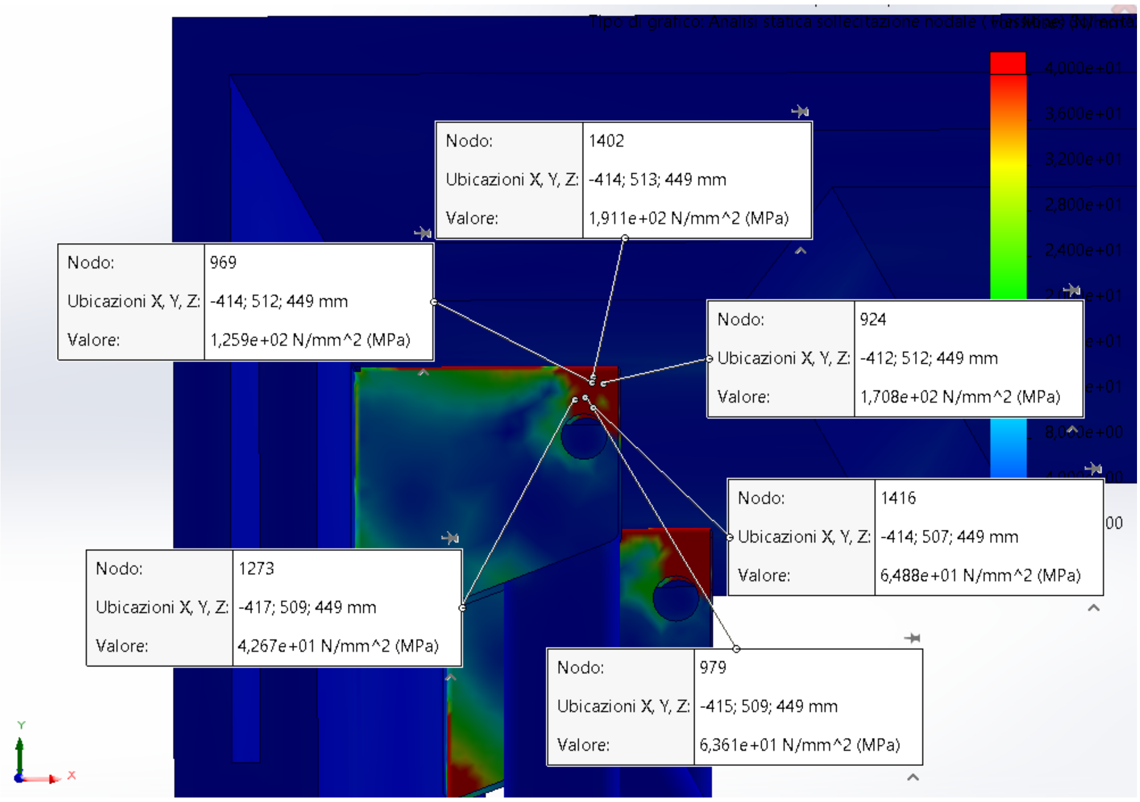


Figure 64 - maximum stresses ABS [MPa]

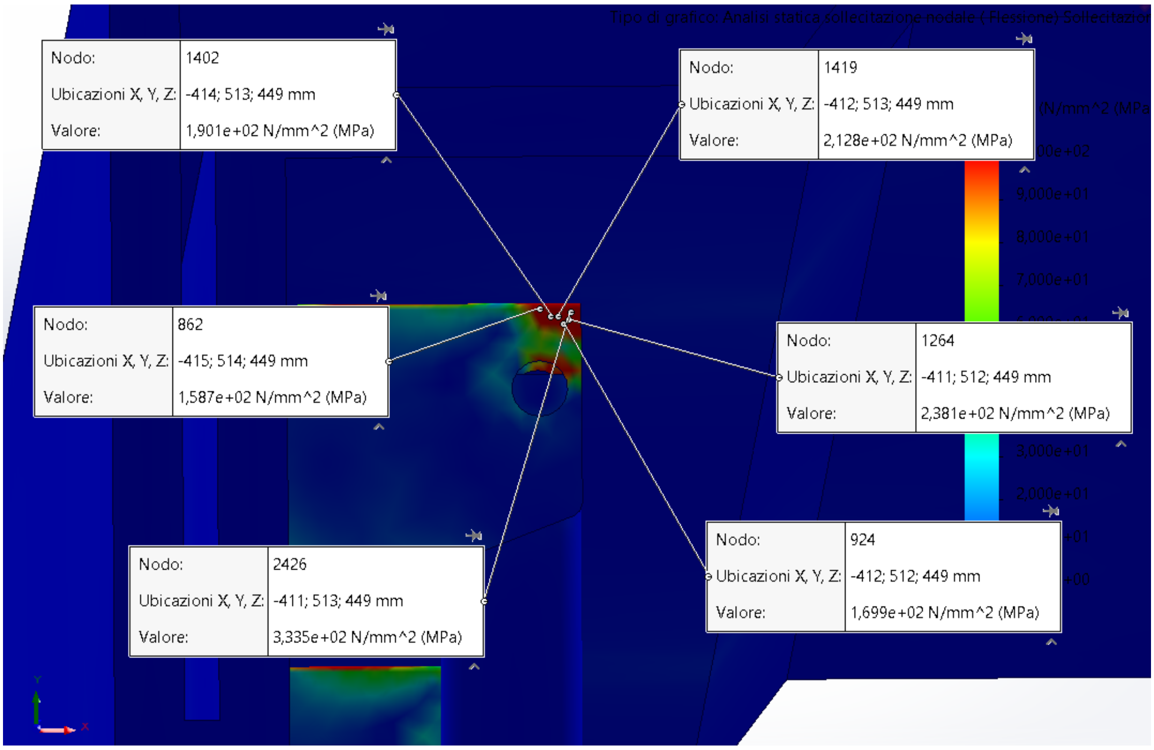


Figure 65 - maximum stresses PA12+20%CF [MPa]

Displacement: URES

We evaluate the URES, which corresponds to the maximum resultant of displacements in the three principal directions. Since the analysed case study does not fully fall into a defined category, there is no single prescriptive value in the NTC for this type of component.

For ordinary-use cantilever shelves, a maximum value is commonly adopted:

$$\Delta_{max} \leq L/150 - L/180$$

For elements with aesthetic requirements or coupled with sensitive finishes:

$$\Delta_{max} \leq L/250$$

L denotes the shelf length, equal to 1500mm. Considering the non-continuous use and supervision by an operator, L/150 is adopted as the design criterion:

$$\Delta_{max,amm} \leq \frac{1500}{150} = 10mm$$

In both cases, the condition is satisfied.

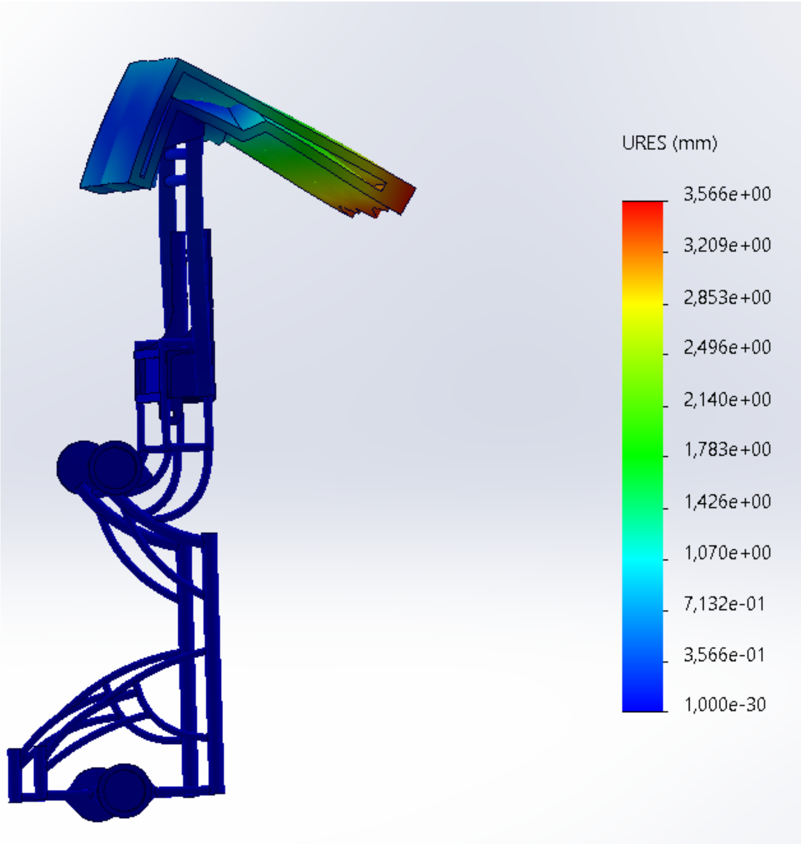


Figure 66 - URES ABS [mm]

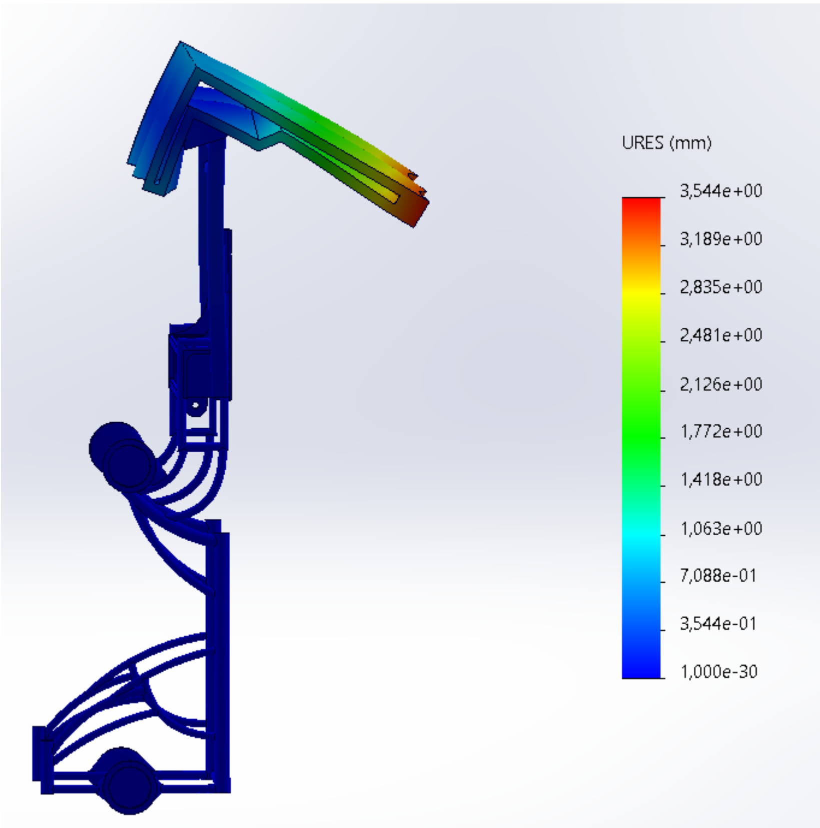


Figure 67 - URES PA 12+20%CF [mm]

Strains

By simulating realistic boundary and loading conditions, the maximum strain observed was found to be less than 2%. Considering that PA12+20% CF and ABS have an elongation at break of approximately 5%, it is evident that the calculated strain is well below the material limit and falls within the elastic range. This result indicates that the structure can effectively withstand the applied loads without risk of permanent deformation or failure. Finally, the design configuration is safe and suitable for the intended use, ensuring a high safety margin with respect to the material limits.

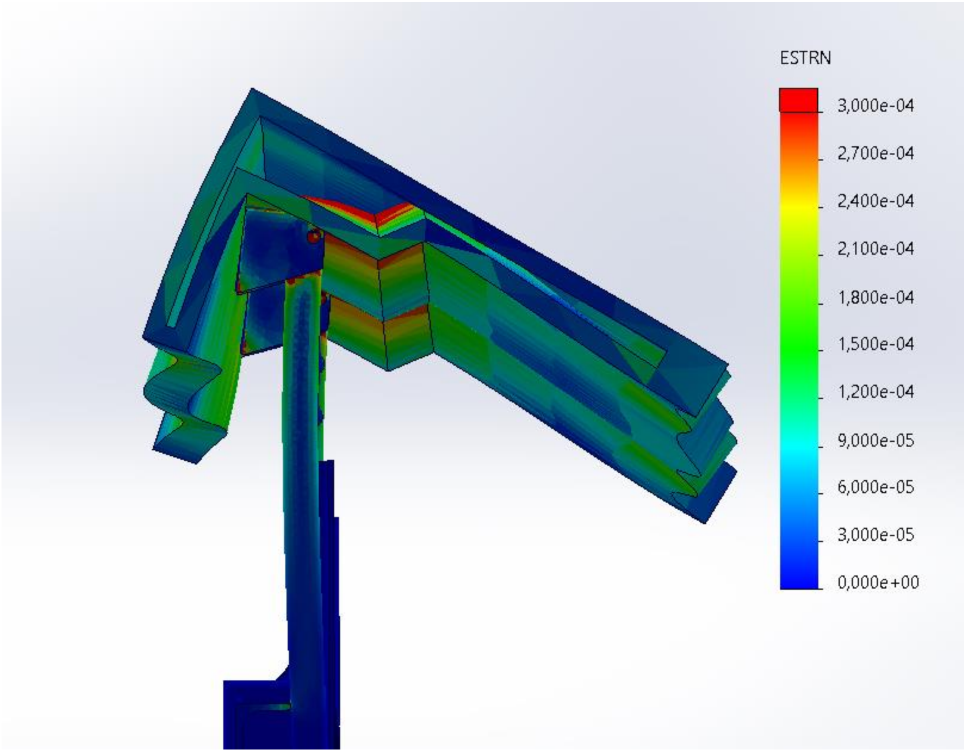


Figure 68 - strain ABS

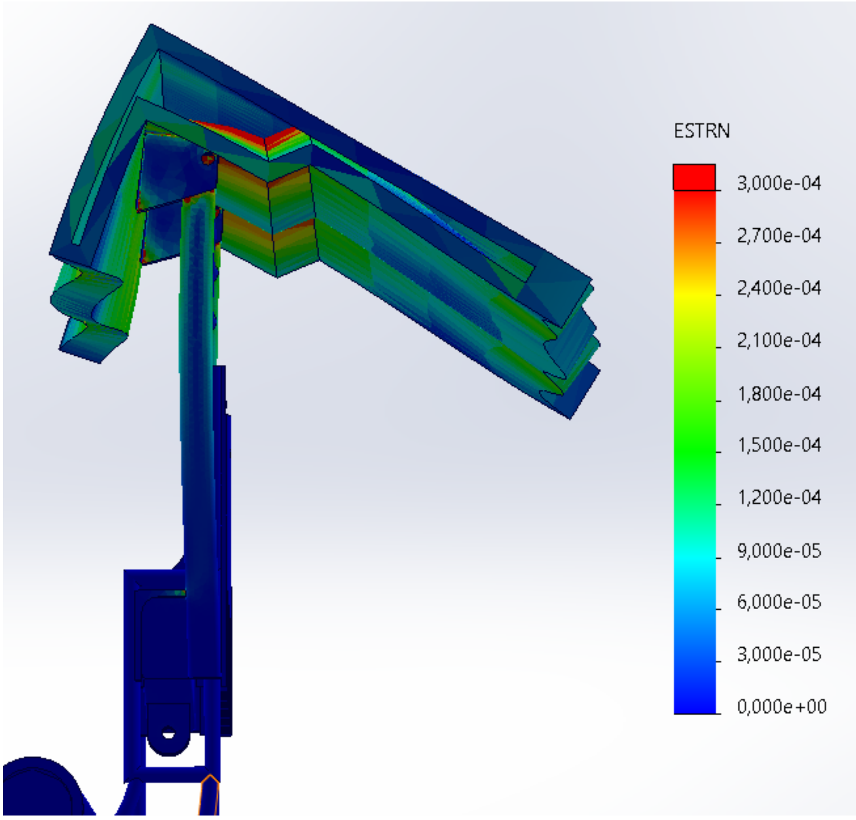


Figure 69 - strain PA12+20%CF

Case 2: accidental concentrated load at a corner

Von Mises stresses

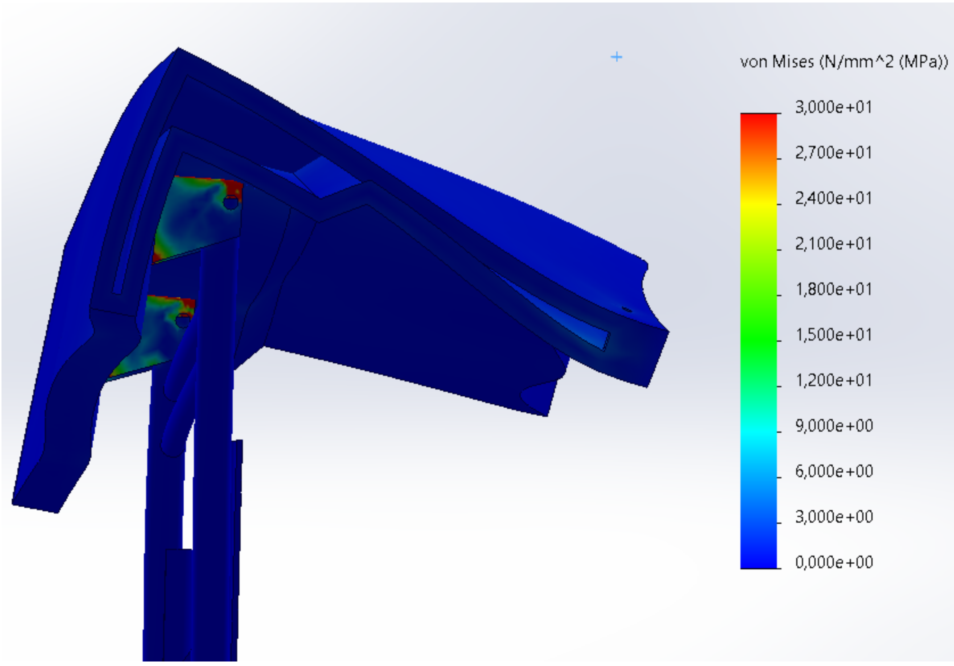


Figure 70 - Von Mises stresses ABS [MPa]

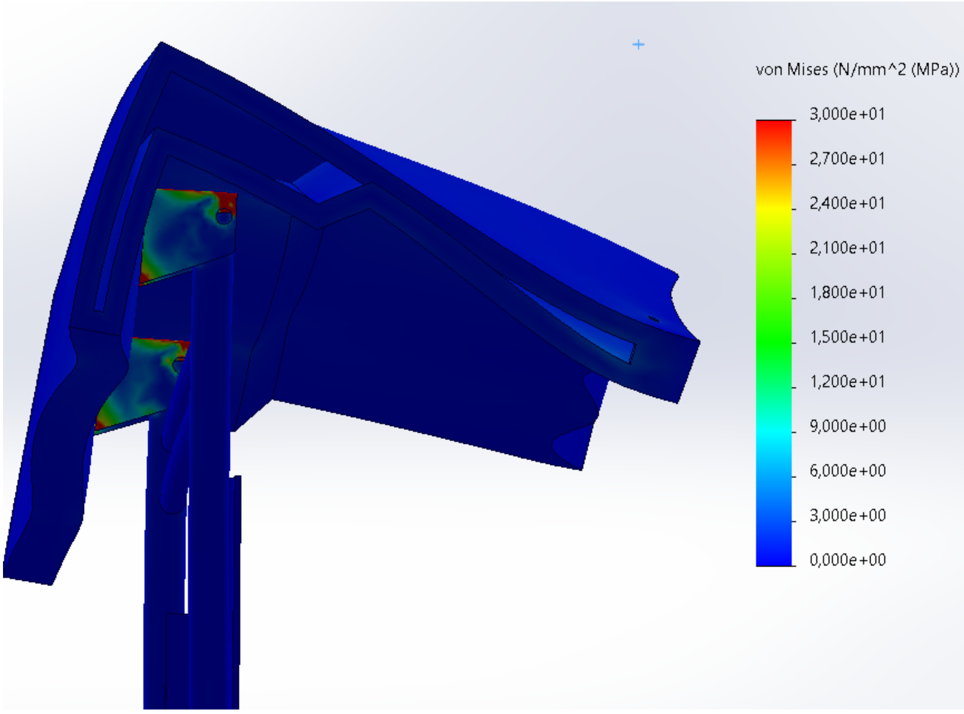


Figure 71 - Von Mises stresses PA12+20%CF [MPa]

Assessment of Maximum Stresses

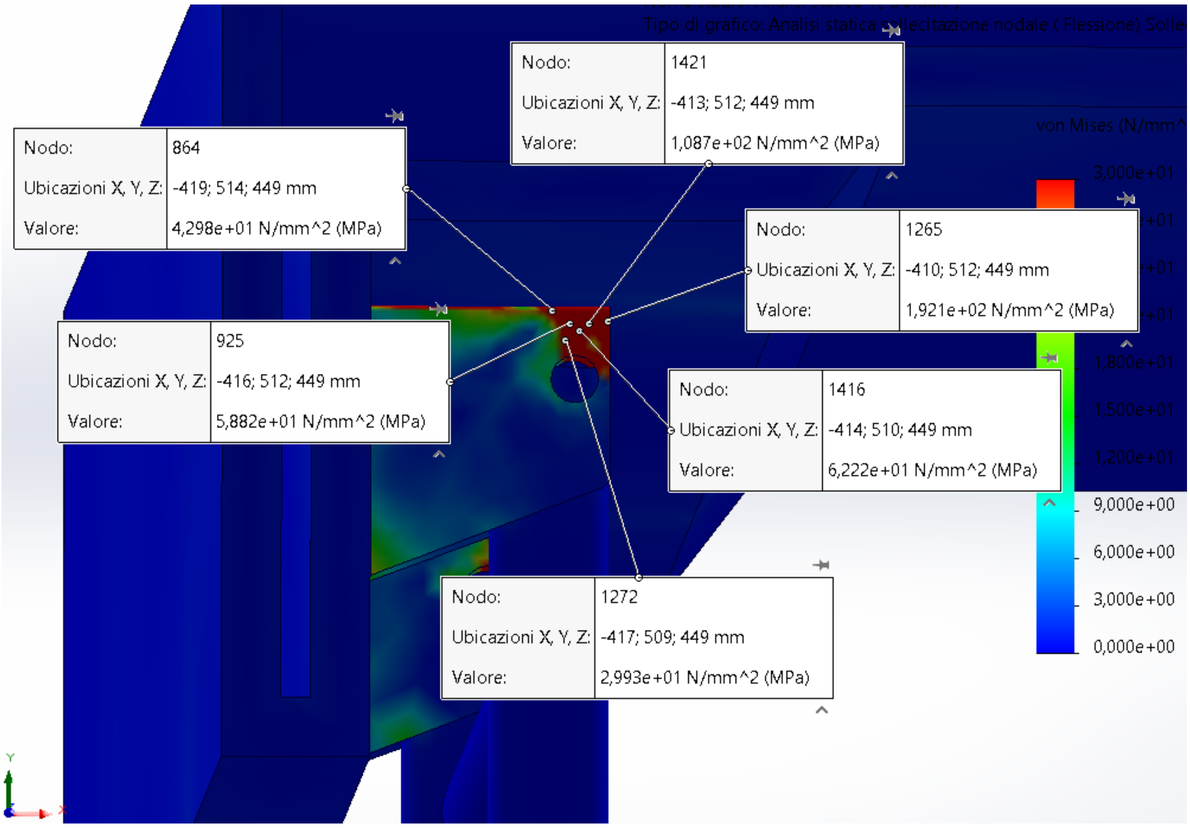


Figure 72 - maximum stresses ABS [MPa]

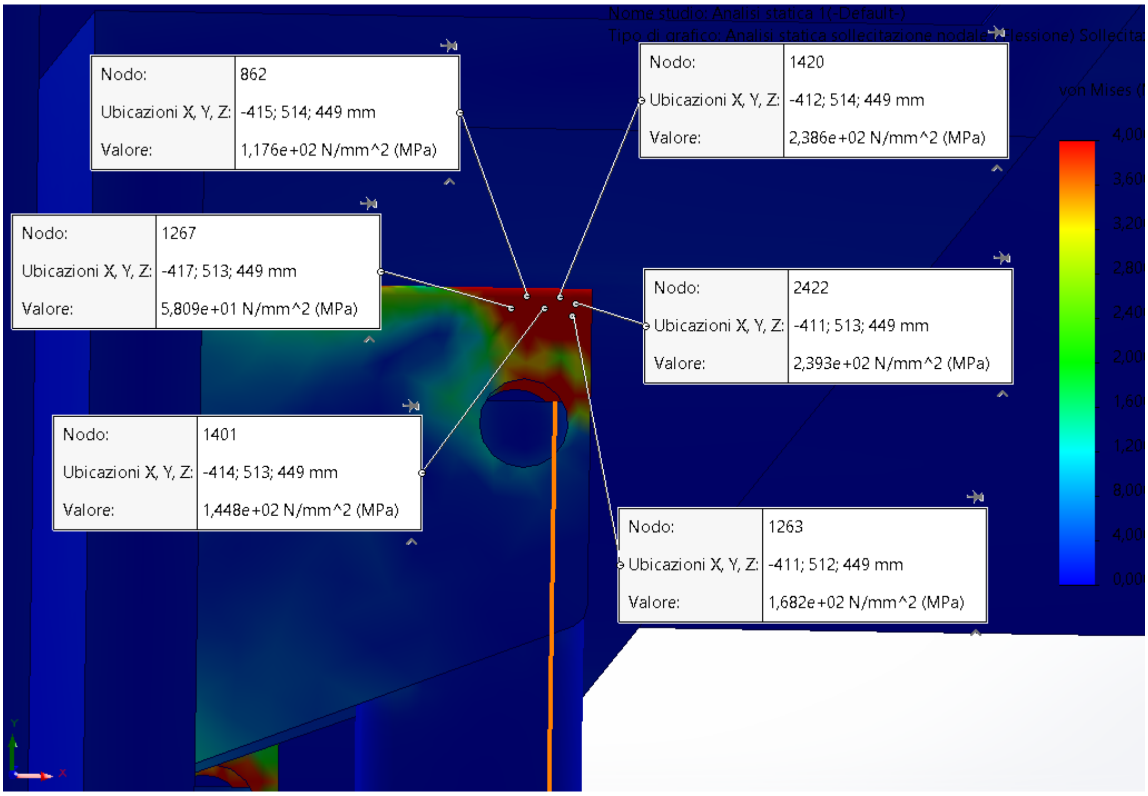


Figure 73 - PA12+20%CF [MPa]

Displacement URES

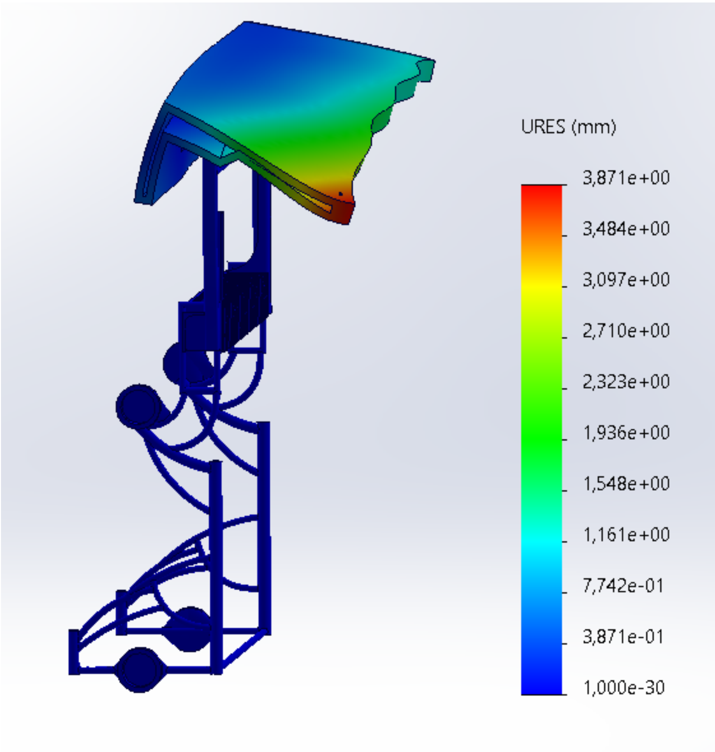


Figure 74 - URES ABS [mm]

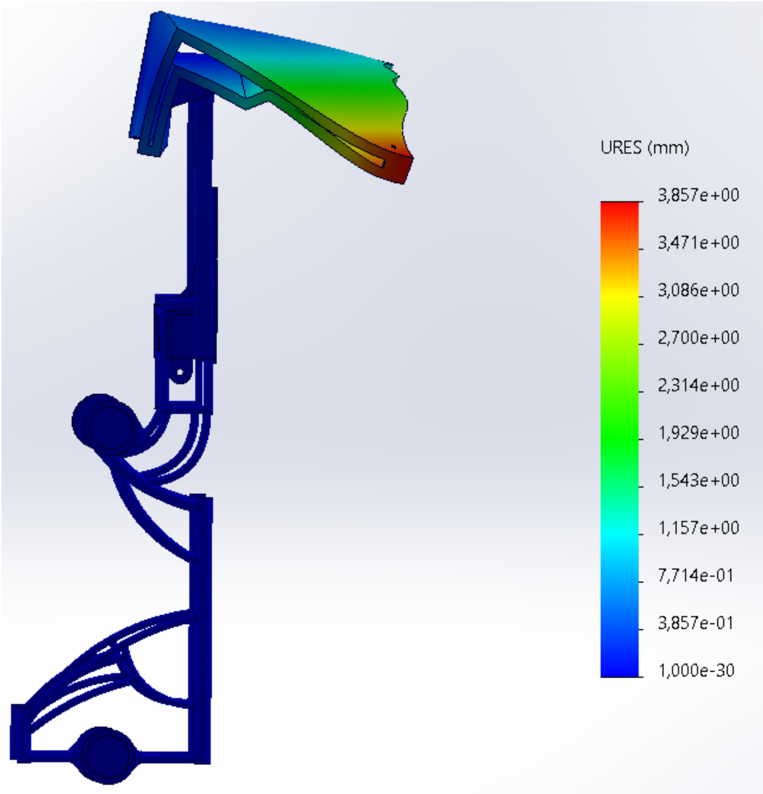


Figure 75 - URES PA12+20%CF [mm]

Strain

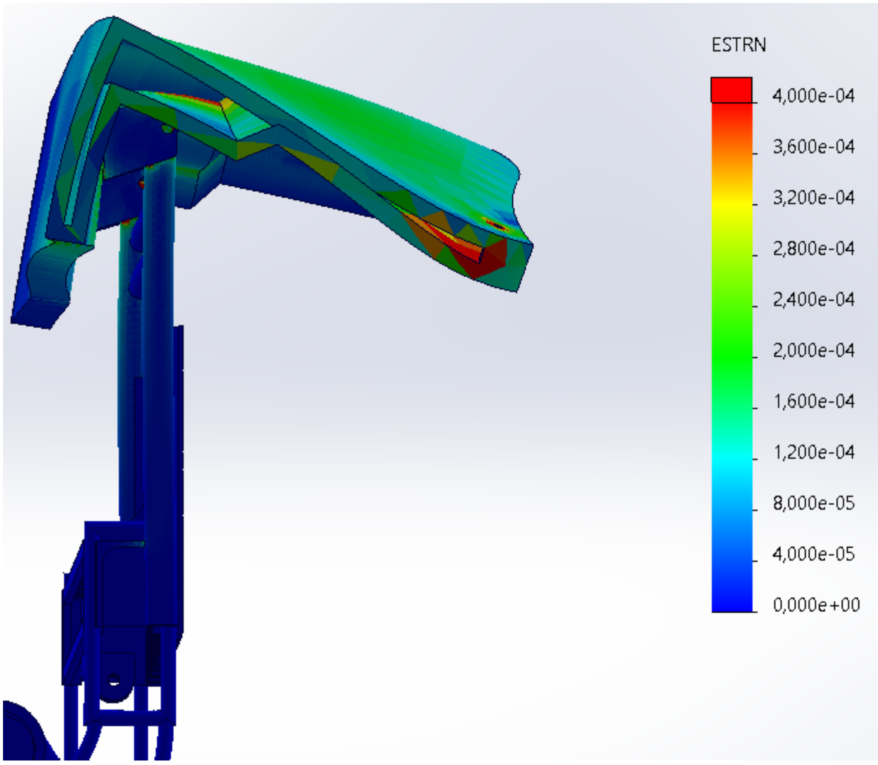


Figure 76 - strain ABS

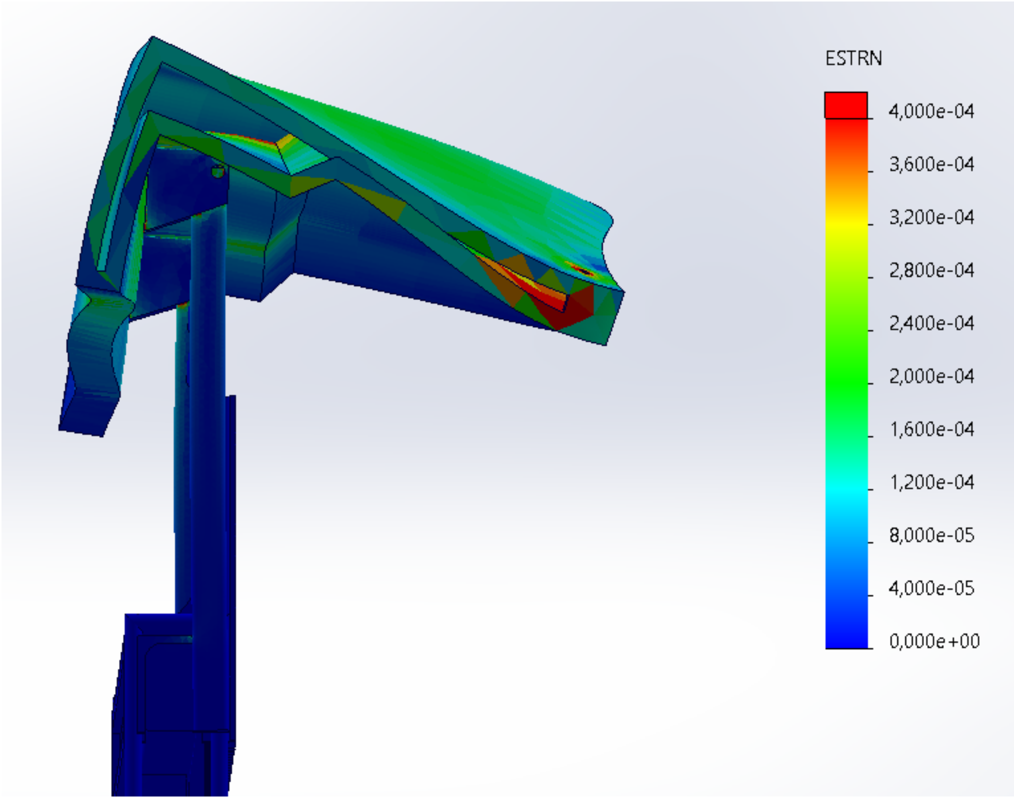


Figure 77 - strain PA12+20%CF

Case 3: weight of a row of bottles

Von Mises stresses

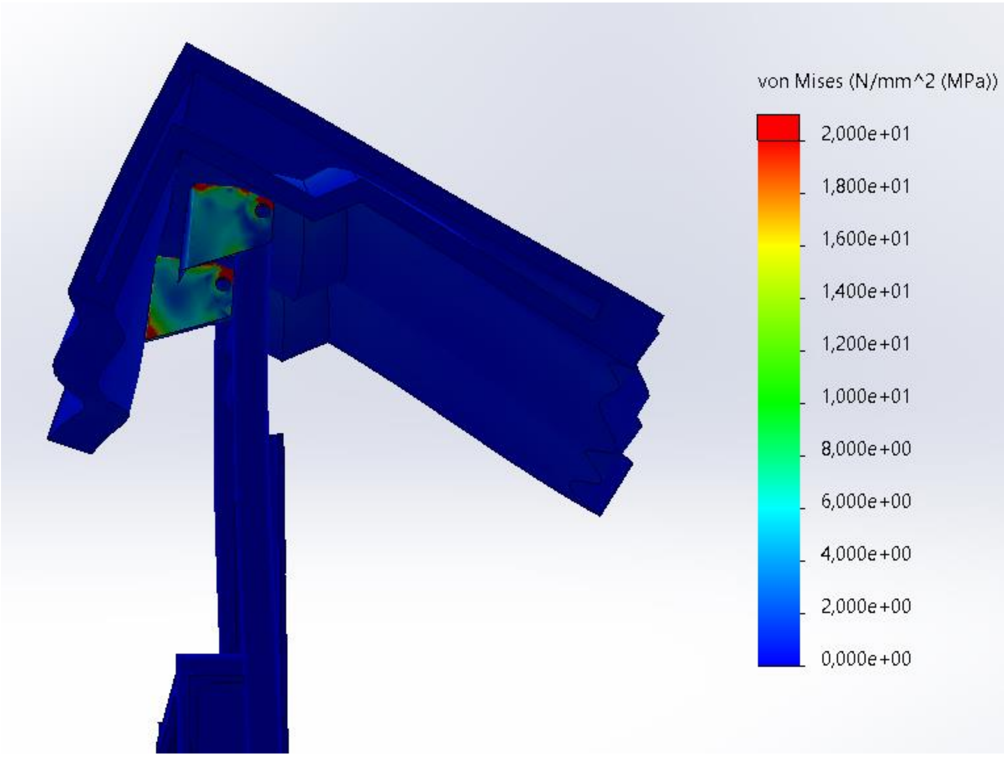


Figure 78 - Von Mises stresses ABS [MPa]

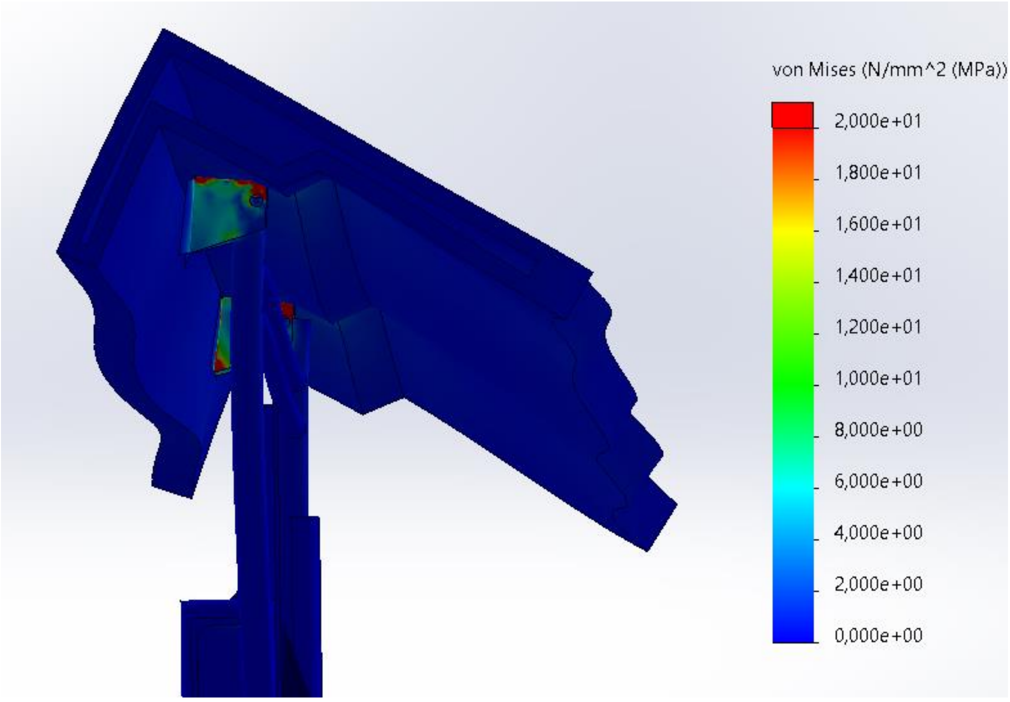


Figure 79 - Von Mises stresses PA12+20%CF [MPa]

Assessment of Maximum Stresses

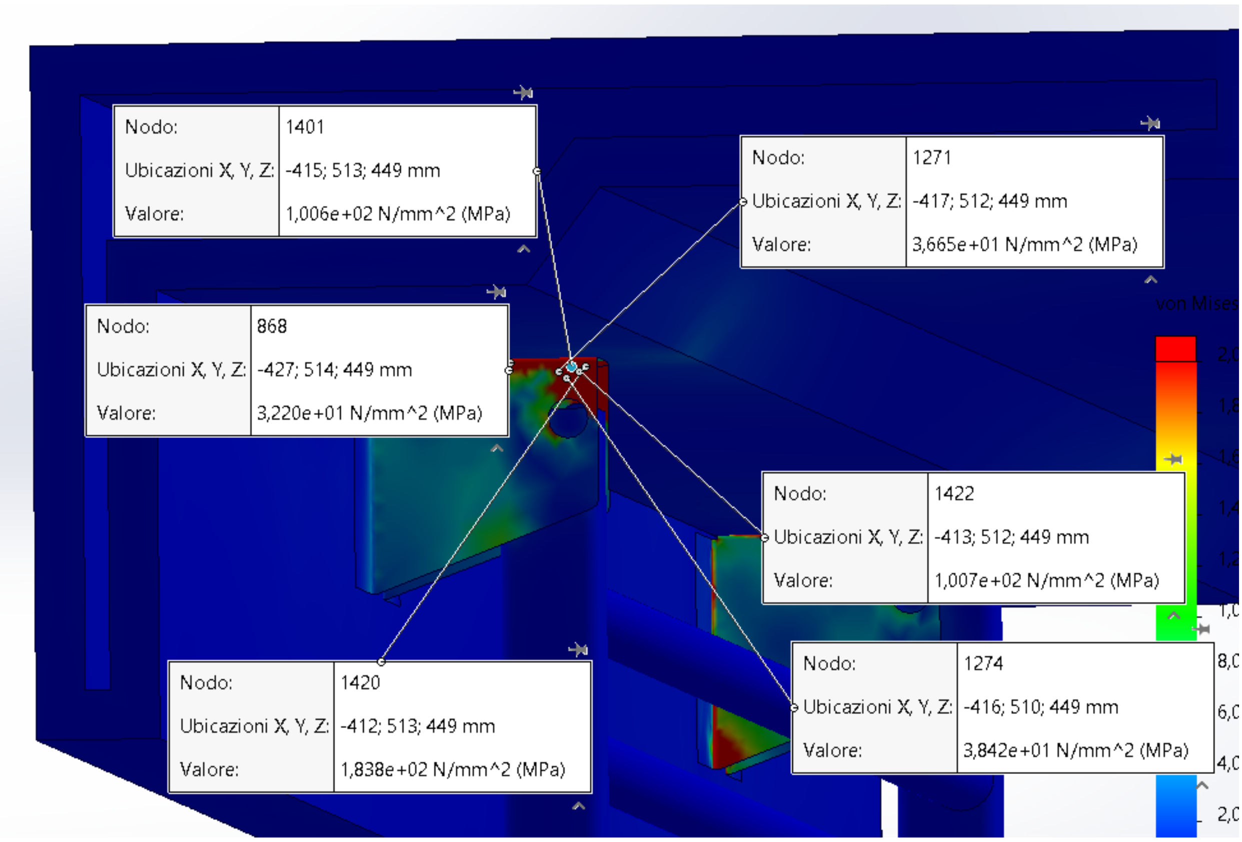


Figure 80 - maximum stresses ABS [MPa]

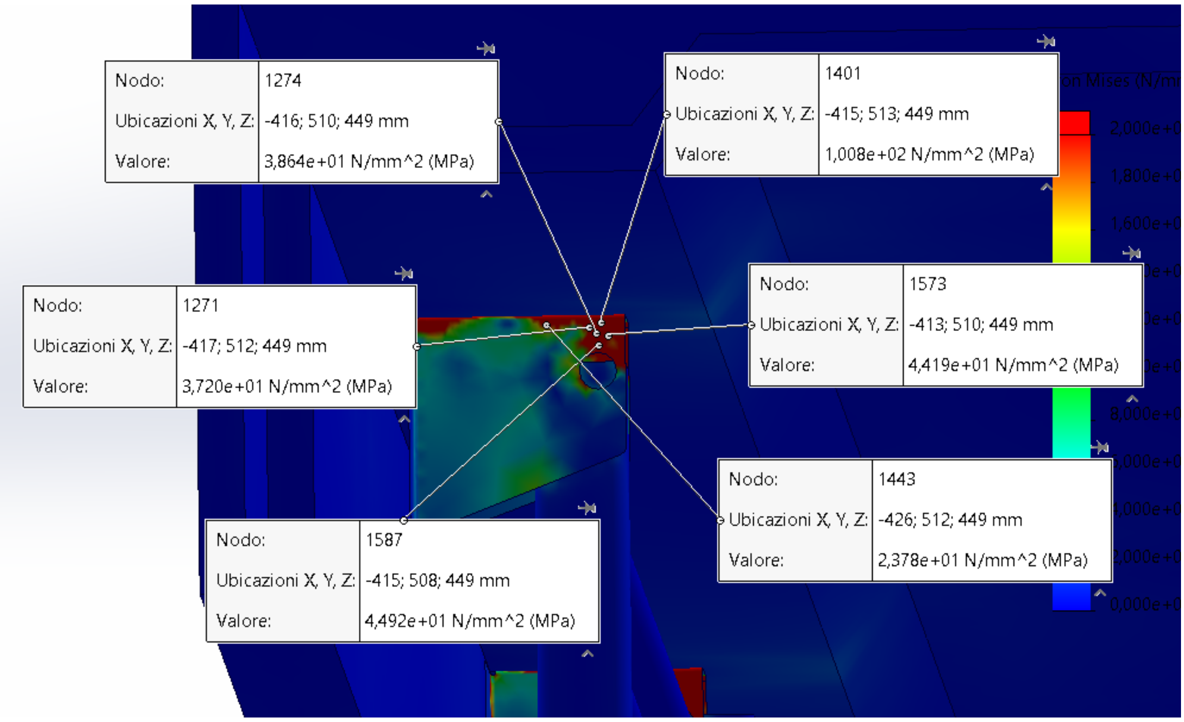


Figure 81 - maximum stresses PA12+20%CF [MPa]

Displacement URES

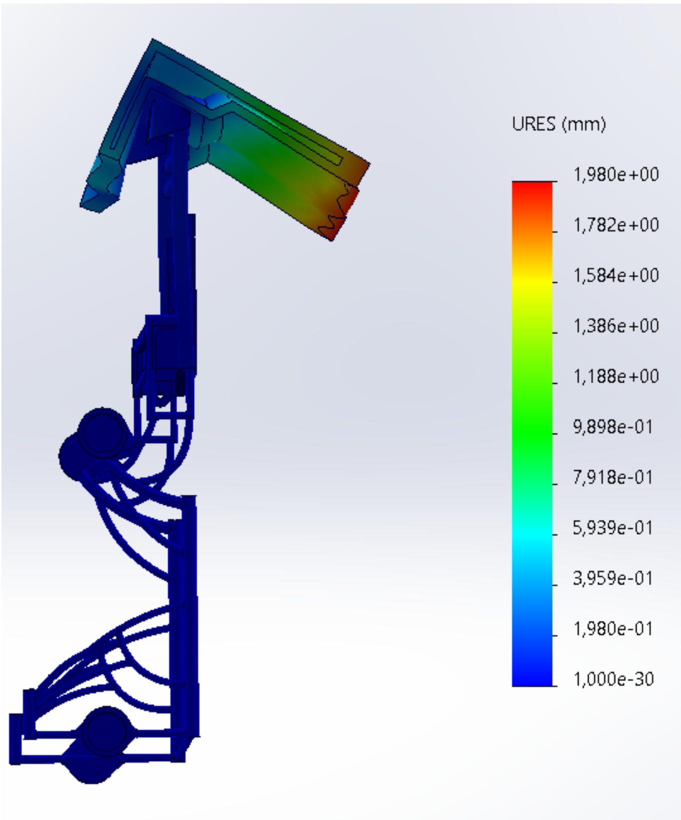


Figure 82 - URES ABS [mm]

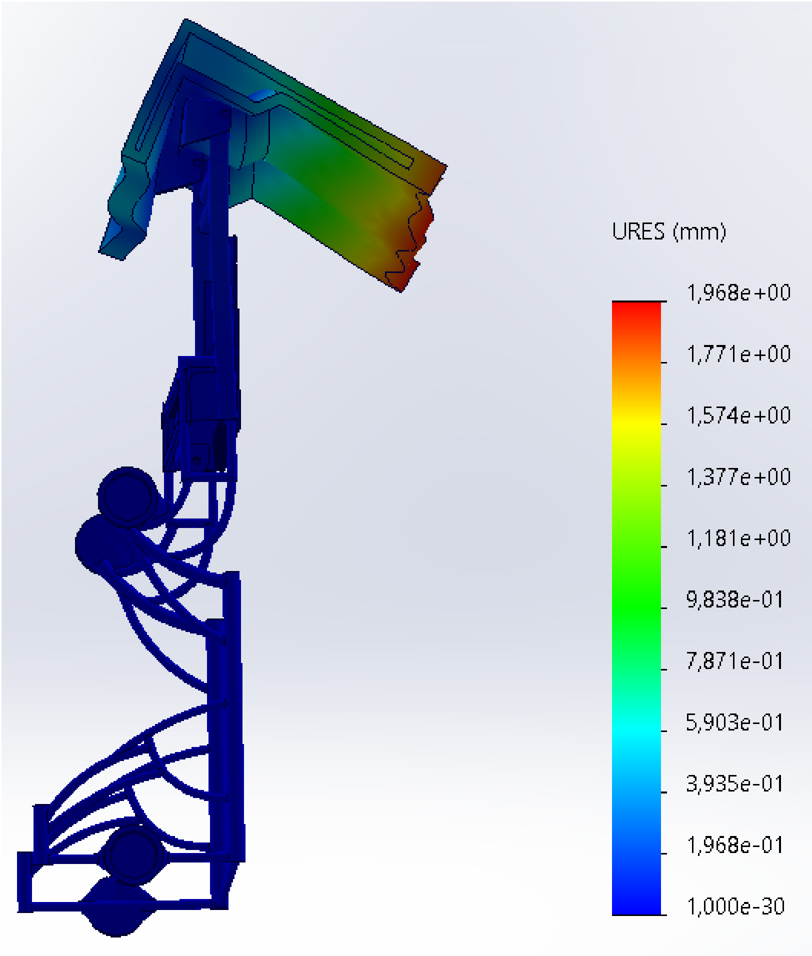


Figure 83 - URES PA12+20%CF [mm]

Strain

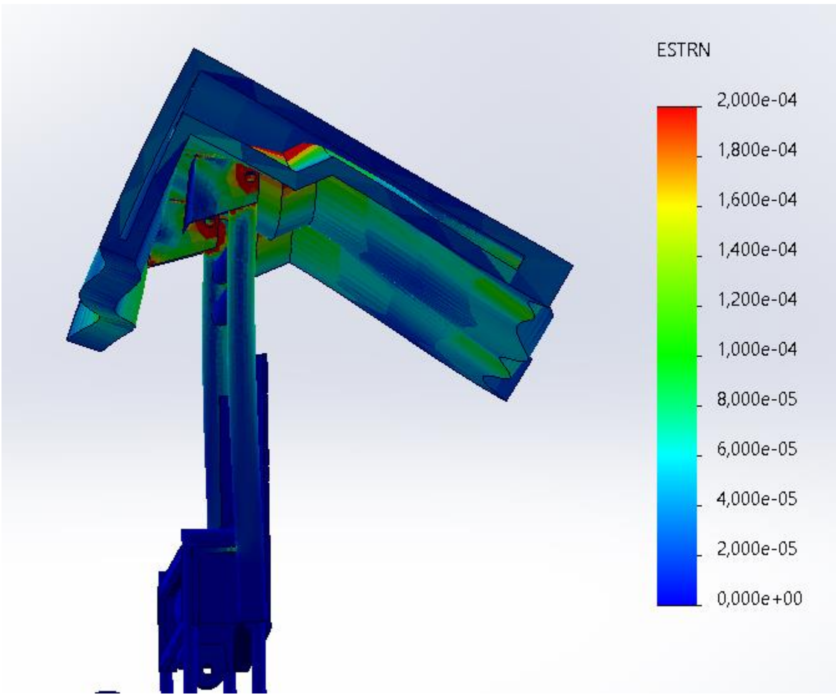


Figure 84 - strain ABS

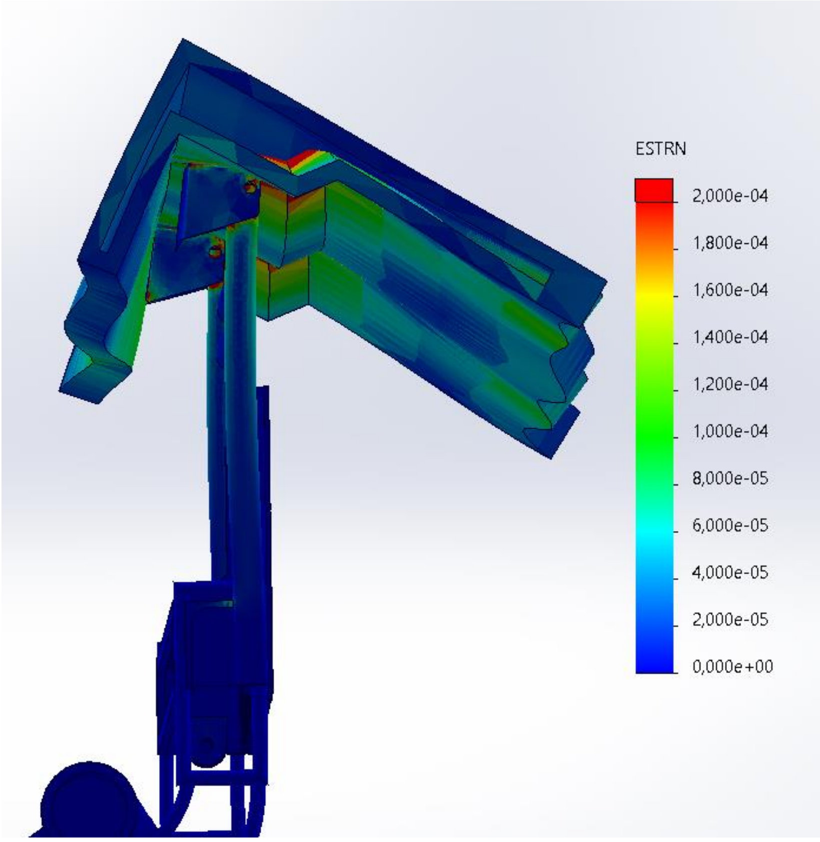


Figure 85 - strain PA12+20%CF

Case 4: combined action of work area and appliance

Von Mises stresses

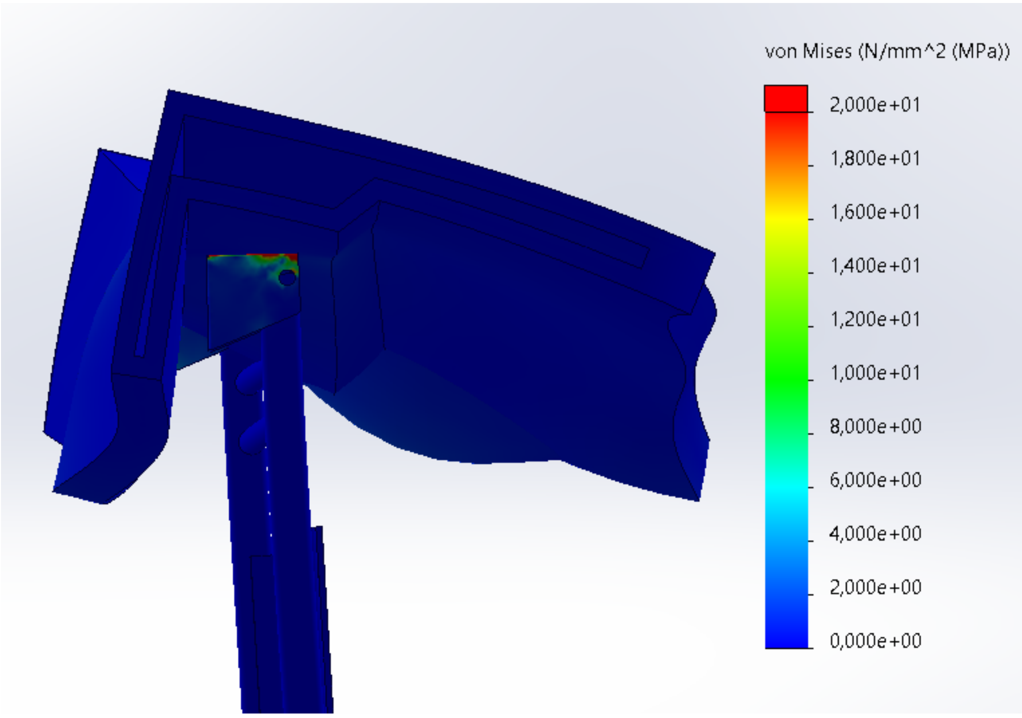


Figure 86 - Von Mises stresses ABS [MPa]

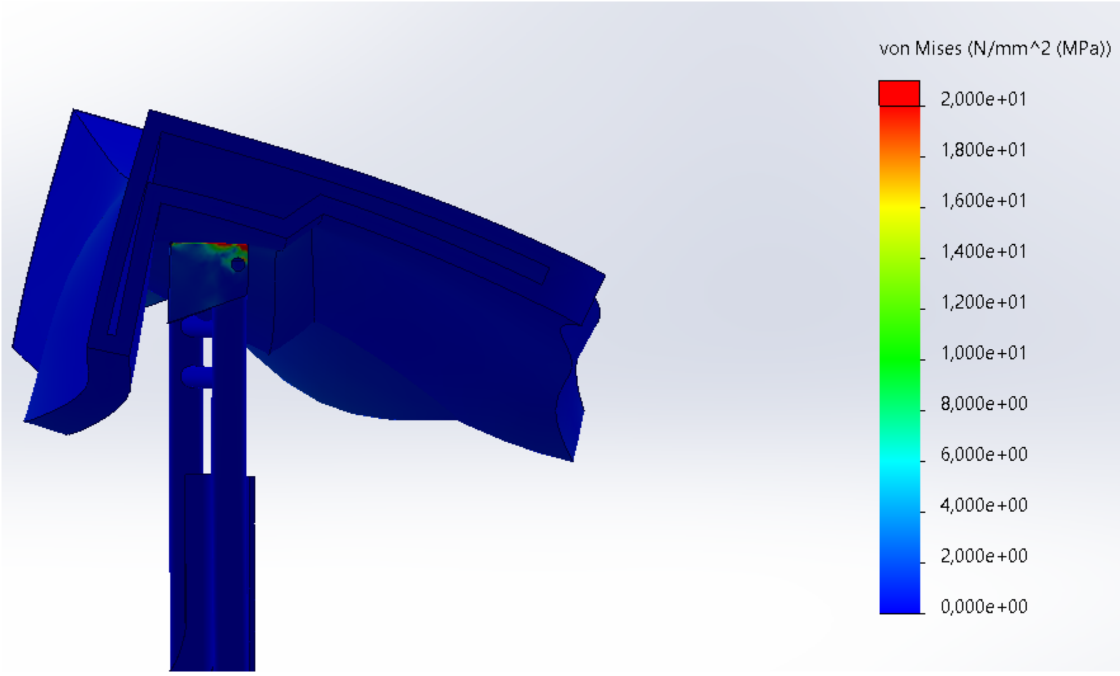


Figure 87 - Von Mises stresses PA12+20%CF [MPa]

Assessment of Maximum Stresses

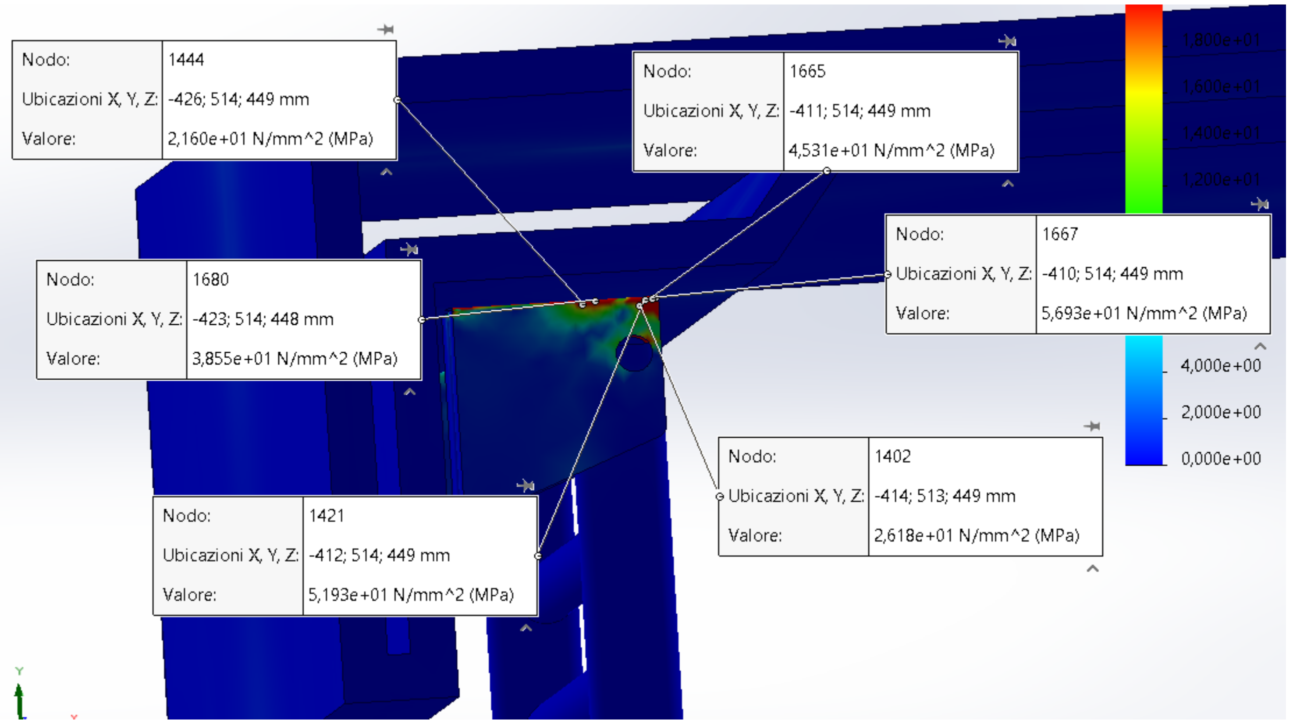


Figure 88 - maximum stresses ABS [MPa]

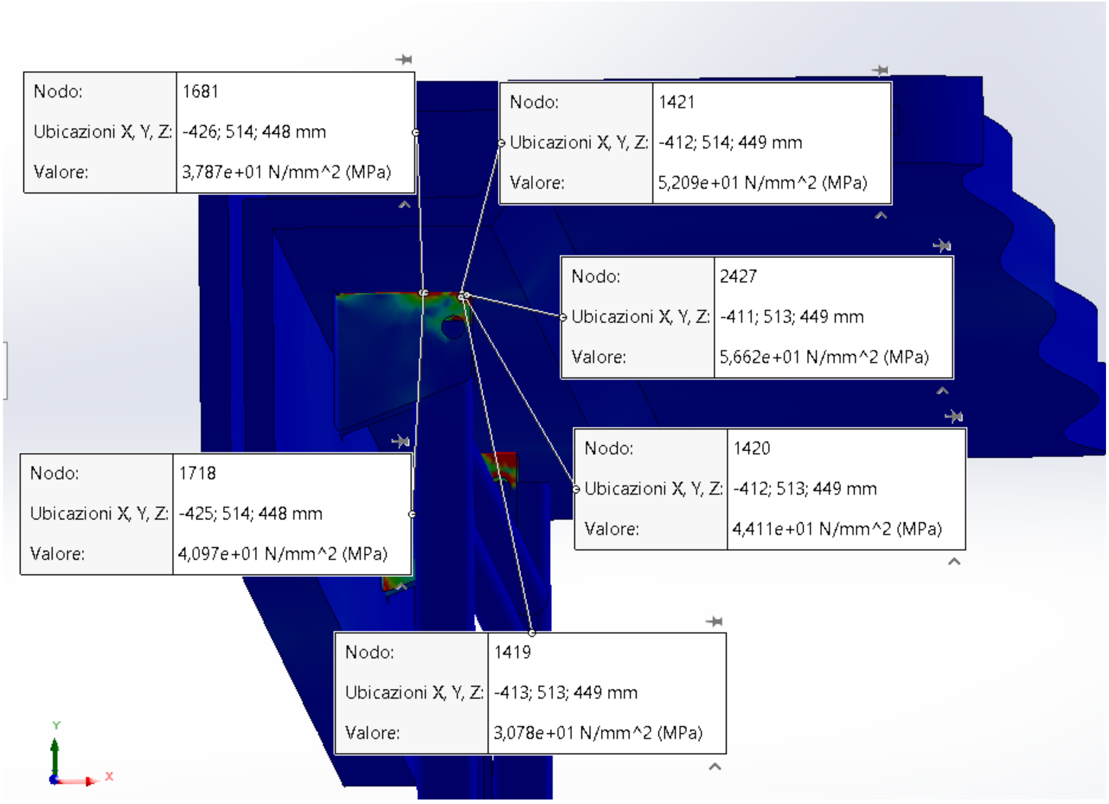


Figure 89 - stresses PA12+20%CF [MPa]

Displacement URES

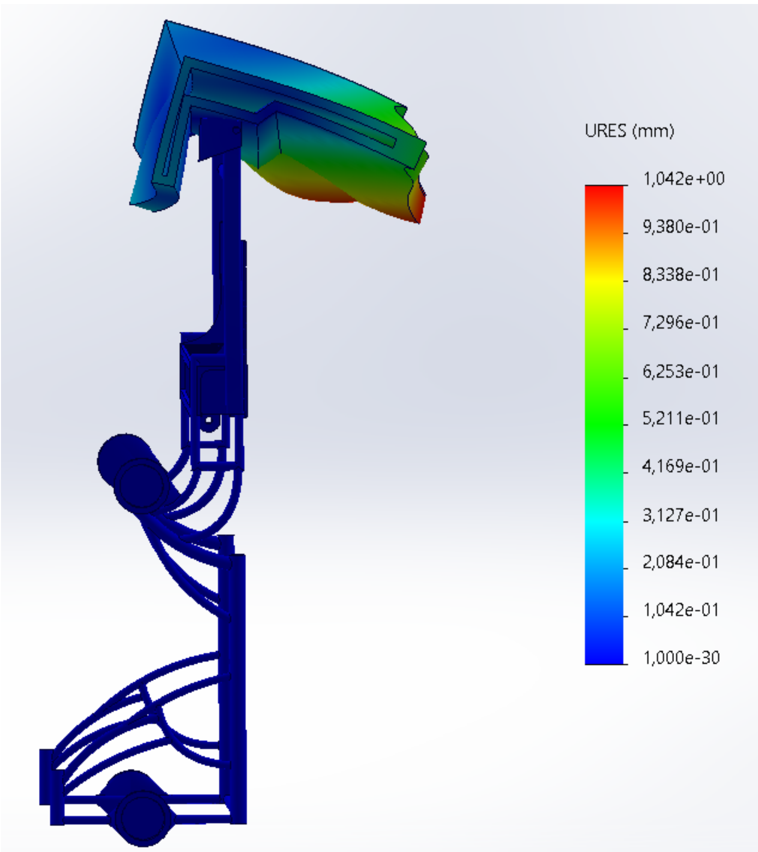


Figure 90 - URES ABS [mm]

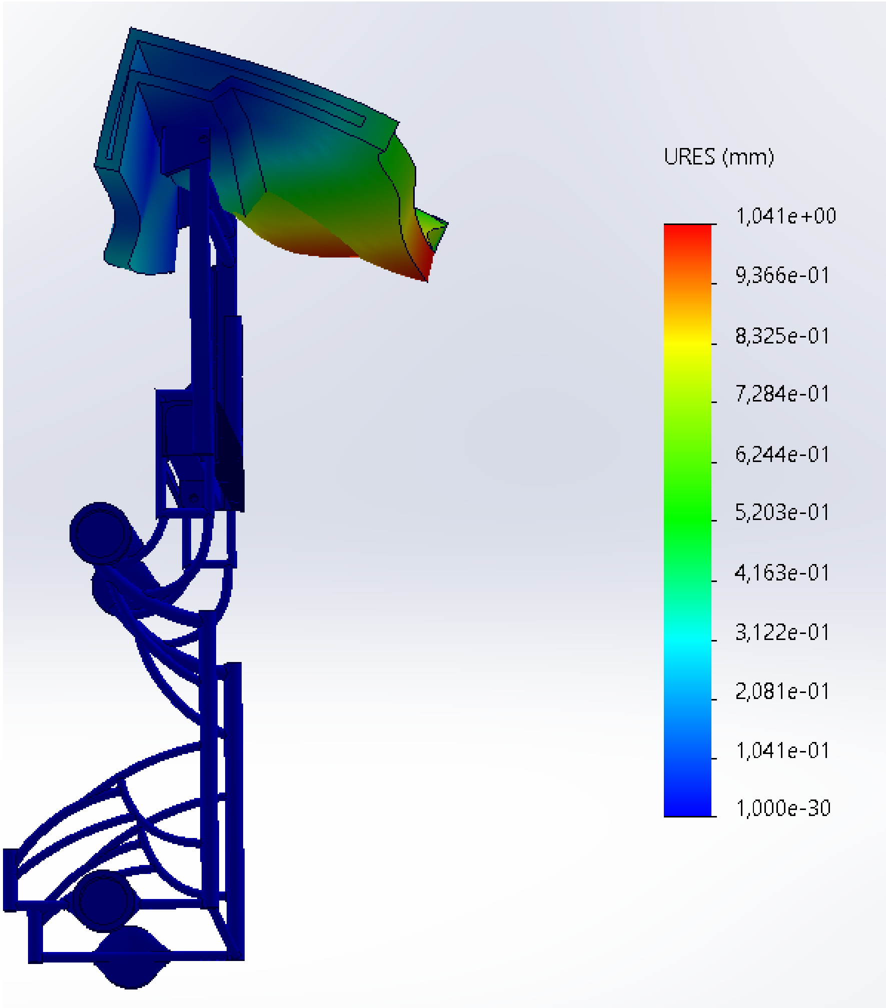


Figure 91 - URES PA12+20%CF [mm]

Strain

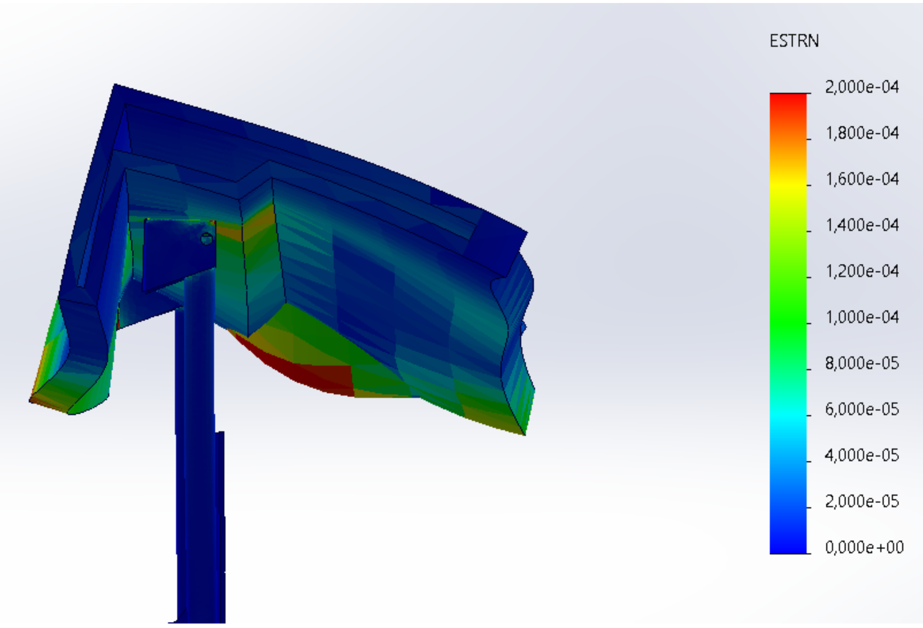


Figure 92 - strain ABS

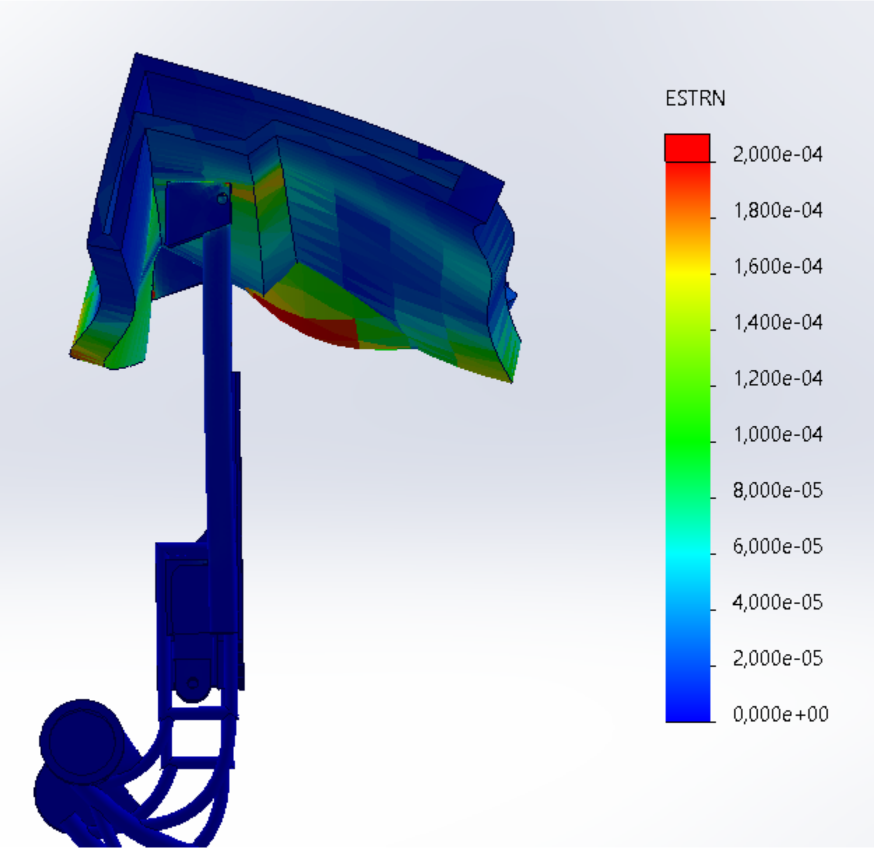


Figure 93 - strain PA12+20%CF

Case 5: asymmetric load

Von Mises stresses

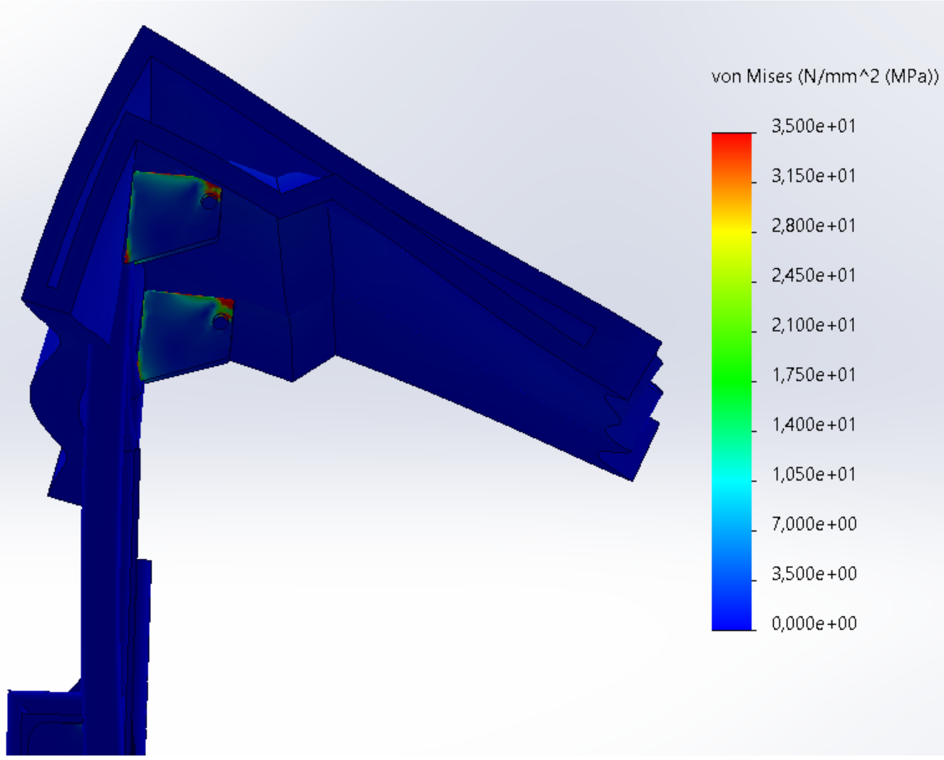


Figure 94 - Von Mises stresses ABS [MPa]

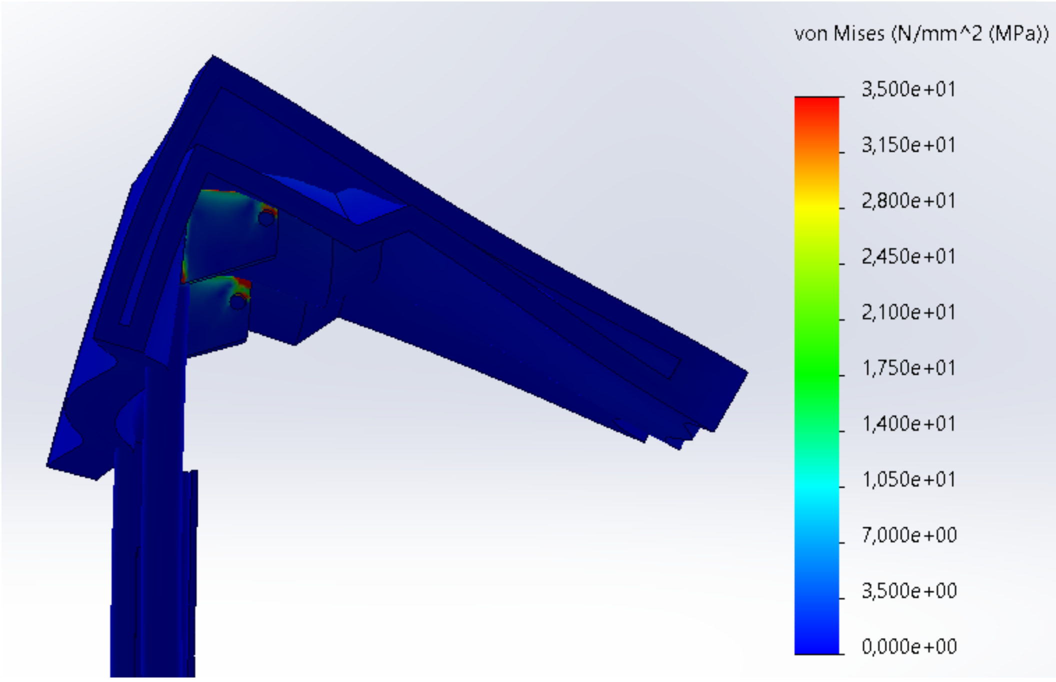


Figure 95 - stresses PA12+20%CF [MPa]

Assessment of Maximum Stresses

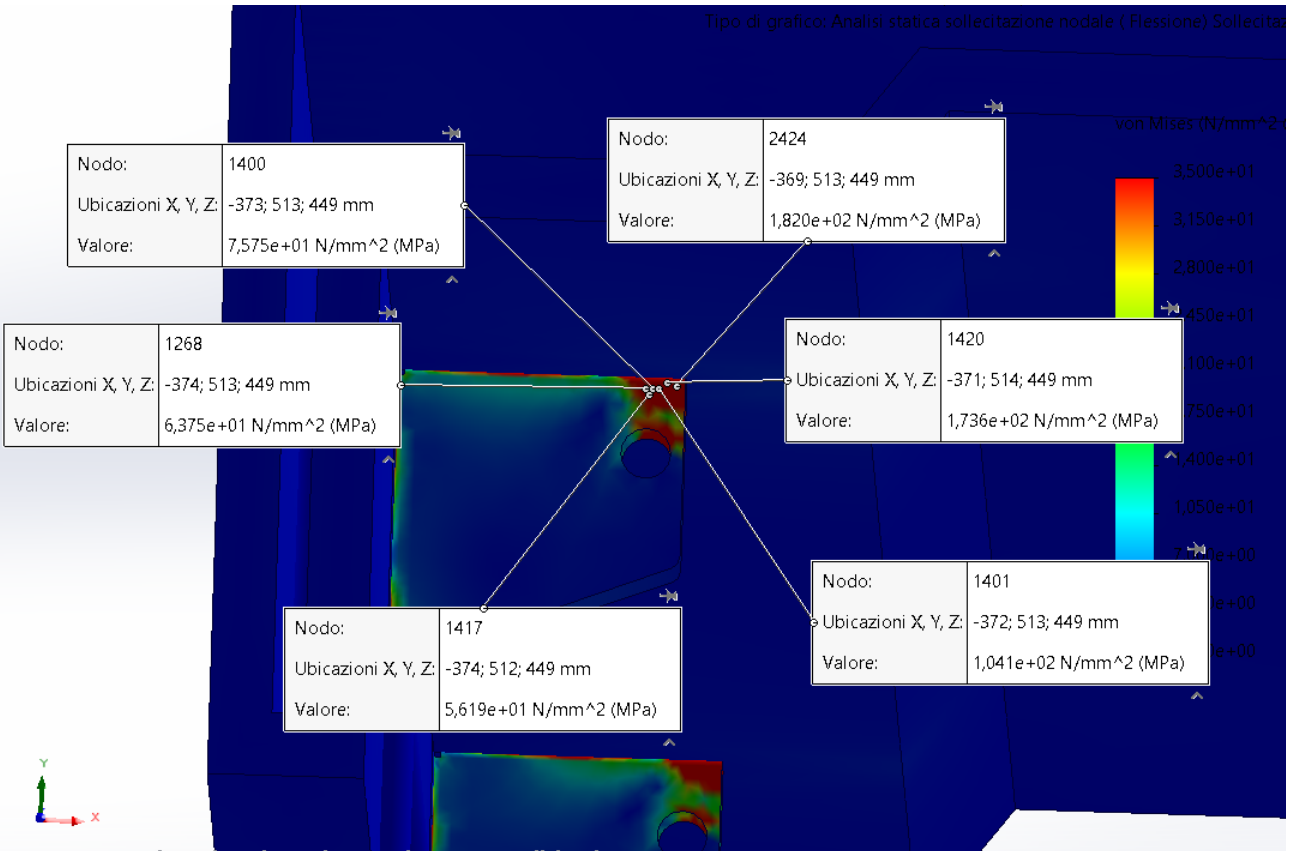


Figure 96 - maximum stresses ABS [MPa]

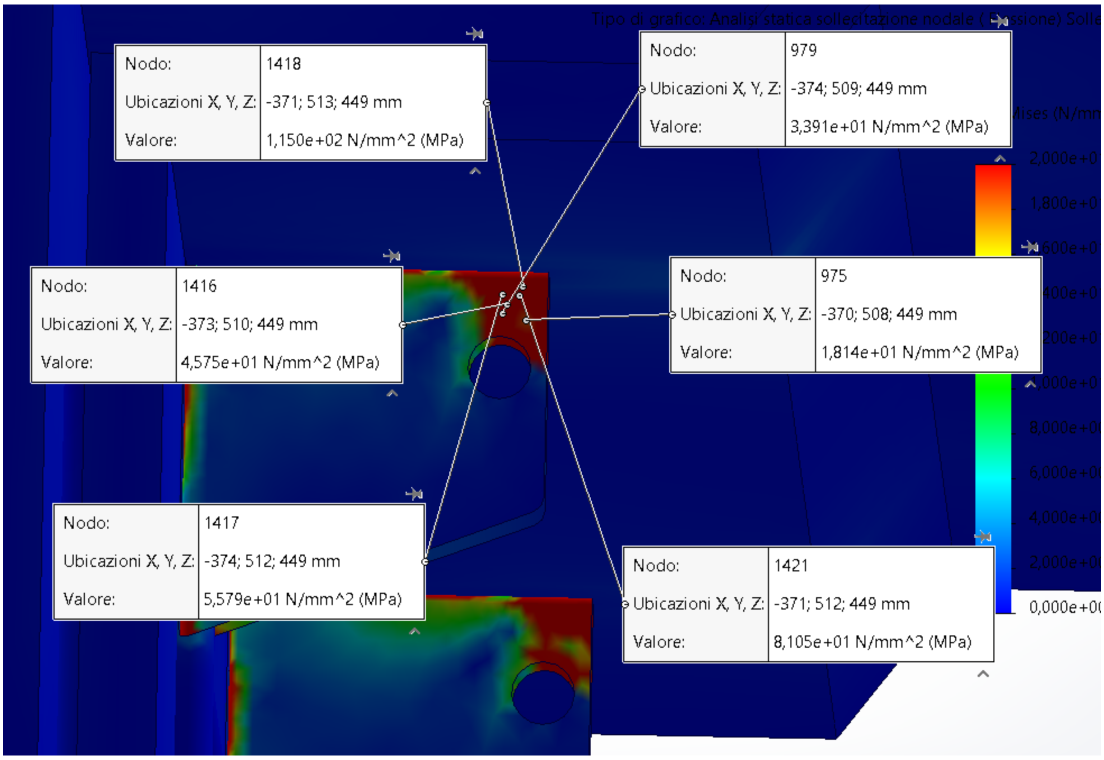


Figure 97 - maximum stresses PA12+20%CF [MPa]

Displacement URES

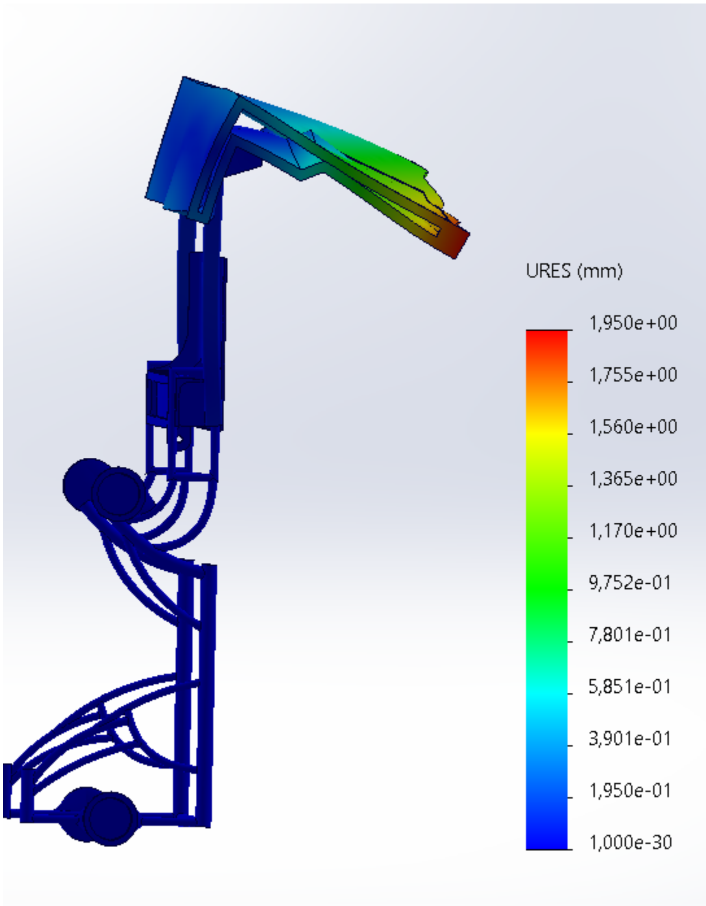


Figure 98 - URES ABS [mm]

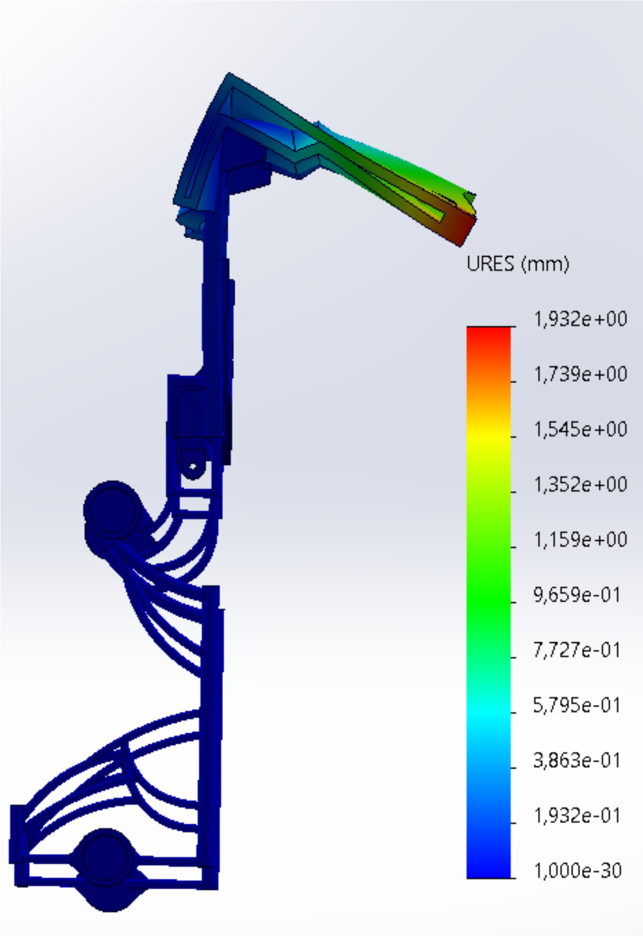


Figure 99 - URES PA12+20%CF [mm]

Strain

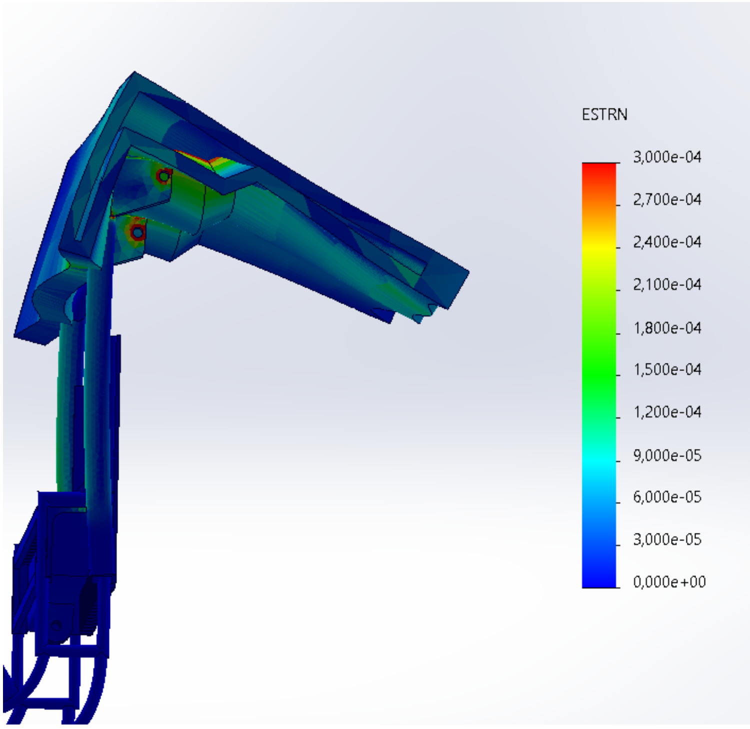


Figure 100 - strain ABS

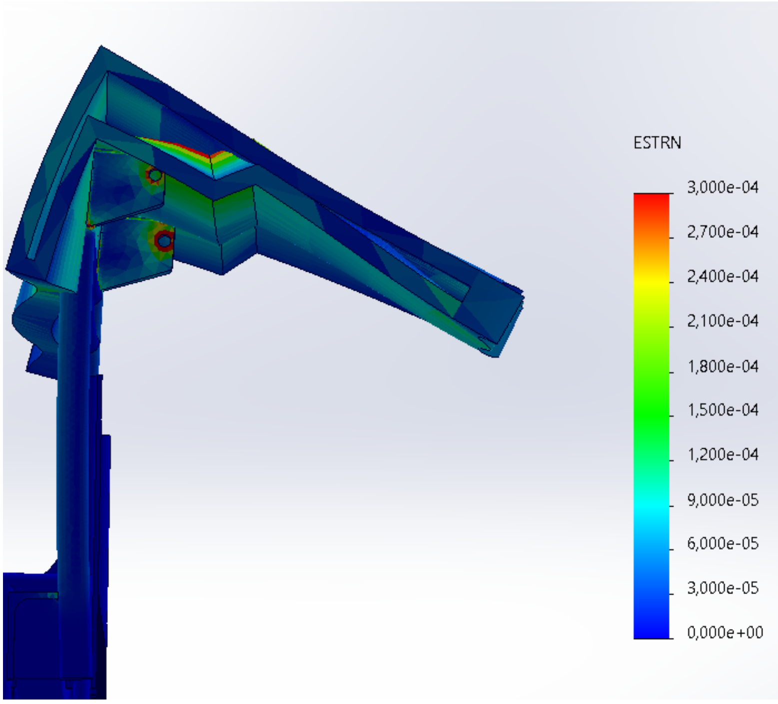


Figure 101 - strain PA 12+20%CF

Comparing ABS and PA12 +20%CF

After completing the analysis of the five cases, the main results for each condition are summarized below in Table 22. This enables a direct comparison of the configurations of the most demanding scenario for the component. Differences are assessed in terms of global displacements, stress distribution, and design/economic implications.

Cases	Materials	Stresses [Mpa]	Ures [mm]	Strain [mm]
1	ABS	191	3.56	0.00203
	PA12+20%CF	333	3.54	0.00184
2	ABS	192	3.87	0.0109
	PA12+20%CF	239	3.86	0.0098
3	ABS	183	1.98	0.00126
	PA12+20%CF	372	1.97	0.00115
4	ABS	57	1.04	0.00042
	PA12+20%CF	56	1.04	0.00039
5	ABS	173	1.95	0.000885
	PA12+20%CF	115	1.93	0.000806

Table 22 – ABS vs PA12+20%CF

Main Results

Global displacements (URES)

The maximum URES occurs in Case 2.

$$URES\ (ABS)\ =\ 3.87\ mm$$

$$URES\ (PA12 + 20\%CF)\ =\ 3.86\ mm$$

The difference is ~0.6%, so global displacements are essentially identical. The assembly's global stiffness is governed by kinematics/constraints and the steel hinges rather than the polymer alone.

Stress concentrations

With PA12+20%CF, higher local stresses appear near hinge nodes/holes than with ABS. This stems from its higher elastic modulus and strength: being stiffer, it transfers load more locally to steel–polymer interfaces, producing higher peaks at stress risers. This is typical in hybrid structures where a relatively stiff component works with steel. Peak stresses, however, occur in Case 3.

Under the same load, a stiffer material such as PA12+20%CF tends to show lower local strains than ABS, while stresses may be higher at concentrations.

Maximum stresses near the pin fall largely in the steel and remain below its yield strength $\sigma_y = 500MPa$

In the polymer, nodal peaks can be affected by contact definitions and mesh density.

Overall, the differences between ABS and PA12+20%CF do not change the assembly's global performance (identical URES). Higher concentrations with PA12+20%CF do not imply an inferior component; they reflect its greater stiffness and the resulting load localization at nodes and steel interfaces.

We conclude that varying the polymer does not materially alter the study outcome: the global response is dominated by the steel hinges and boundary conditions. If service requirements (temperature, environment, creep, fatigue life, dimensional stability) are met, choosing ABS is reasonable for cost and manufacturability. PA12+20%CF remains a valid alternative when higher polymer strength margins, better thermal/environmental behaviour, or improved long-term stability (creep) are required.

In summary the most highly loaded parts are steel, not polymer; therefore, polymer choice has limited impact on global performance in this case.

Conclusions

For material selection, the most demanding ABS scenario is adopted as reference. The worst case is defined by the maximum calculated stress, which occurs in Case 2 with a concentrated load of 1500 N. The results comply with NTC 2018, so the static analysis is verified. The thesis objective—redesigning an internal mechanism for additive manufacturing—is fully achieved. Combining additive and conventional processes delivers a sound production compromise in terms of ergonomics, productivity, and process simplification.

The iterative cycle enabled: streamlined assembly, lighter components, reduced waste, and overall simplification. The redesign created more complex geometries without complicating the manufacturing. Using 3D printing groups all polymer components in a single build, and the proposed design deliberately departs from conventional production schemes. The company therefore selected ABS—despite lower flexural strength than carbon-fibre-filled composites—prioritizing impact resilience, ease of production and machining, cost reduction, and greater reliability in day-to-day operations. This choice supports a leaner process and easier customization or rapid geometric changes, which are typical needs in flexible industrial environments. Thanks to the use of additive manufacturing technologies, the replacement of certain steel components with ABS parts, and design optimization, the weight decreased from 12.477 kg to 2.559 kg resulting in a reduction of 9.918 kg (about 79.5%)

Limitations

The analysis has limitations that frame a more realistic design context. Only static loads are considered; accidental loads such as impacts and intense vibrations, as well as dynamic effects, are neglected. Real loads are neither perfectly point-like nor perfectly uniform. Dropping heavy objects (e.g., the lighting system) is also excluded because it is outside standard prescriptions for indoor furniture and would require complex dynamic modelling not mandated by codes. Time-dependent degradation (humidity, corrosion, wear, and missed maintenance) is not considered. Prolonged overloads or abnormal use could reduce safety.

Potential Improvements

In conclusion, the current model provides a solid base for structural verification and a realistic description of the physical problem. The model could be improving modelling the glass shelf system and including a dynamic analysis. Another improvement would be to pay close attention to material durability and sustainability. In addition, new case studies could be explored. Consistent with engineering practice, this work underscores that deeper study and continuous learning are the path to continual improvement.

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