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STUDY OF THE COST EFFICIENCY AND LAMINATE QUALITY USING DIFFERENT MOULD-MAKING TECHNOLOGIES

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Abstract

The aim of this paper is to compare the different laminate qualities, studying the various mould-making technologies and materials, exploring their building process, efficiency and time-cost relationship for a small-medium number production. In particular, the focus will be on MDF CNC-milled moulds, PLA Additive Manufacturing moulds, using FDM (*Fused Deposition Modelling*) technology, and epoxy gelcoat and fiberglass laminated moulds. Parts that are going to be produced will be in carbon fibre, layering two ply of 200 gsm twill and performing a wet-on-wet process with a vacuum bagging technique. In the latter parts produced it has been tried to apply heat to enhance the final mechanical properties and speed up the process. Thus allowed to conduct a more in-depth analysis on the ability of the mould to endure heat application.

Keywords: Composite Materials, Carbon Fibre, Additive Manufacturing, Mould-making, Seaplane

1. Introduction: Team S55

The research proposed in this paper is part of the larger project of Team S55 [1] & [2], a student team of the *Politecnico di Torino*, Department of Mechanical and Aerospace Engineering.

The Team S55 [3] was born in February 2017 from a small group of students of the Politecnico di Torino, driven by the passion for aeronautics and with the aim to help the "Replica 55" [4] & [5] group in the design of a flying replica of the *Savoia Marchetti S55X*. The S55X also has a strong link with the Politecnico di Torino. Professor Giuseppe Gabrielli, in fact, designed a metal version of the S55X seaplane becoming the first italian model of an air plane made of metal.

The Team S55 focuses its activities on the realisation of a flying prototype in 1:8 scale ($3\ m$ wingspan) of the S55X seaplane, carrying out a 360° aeronautical project. Starting from the CAD project fig.3, through structural analysis (carried out with NASTRAN Finite Element Code, using ANSA pre-processor, developed by BETA CAE System) and aerodynamic analysis (carried out through CFD simulations using STAR CCM+ by Siemens) [6] & [7], the team scaled and adapted to the smaller dimensions all the components of the aircraft, always paying attention to the Weight & Balance side, in particular to the centre of mass position and the MTOW (*Maximum Take Off Weight*) of the scale aircraft, to ensure good flight characteristics. Then, the prototype is experimentally tested for the structural part: WST (*Wing Static Test*), experimental determination of the centre of gravity and moments of inertia, and thrust experimental test of the propellers; for the on-board systems, in particular experimental tests of EMC (*Electromagnetic Compatibility*); and for the fluid-structure interaction during the ditching phase [8] & [9]. Finally, the aircraft is tested during the flight tests.

It is evident that the real driving force of the team is the possibility of living an integrated design experience between the various disciplines not only technical and managerial but also of interpersonal relationships, as if it were a matter of anticipating a company simulation, in the form of “training on the job”.

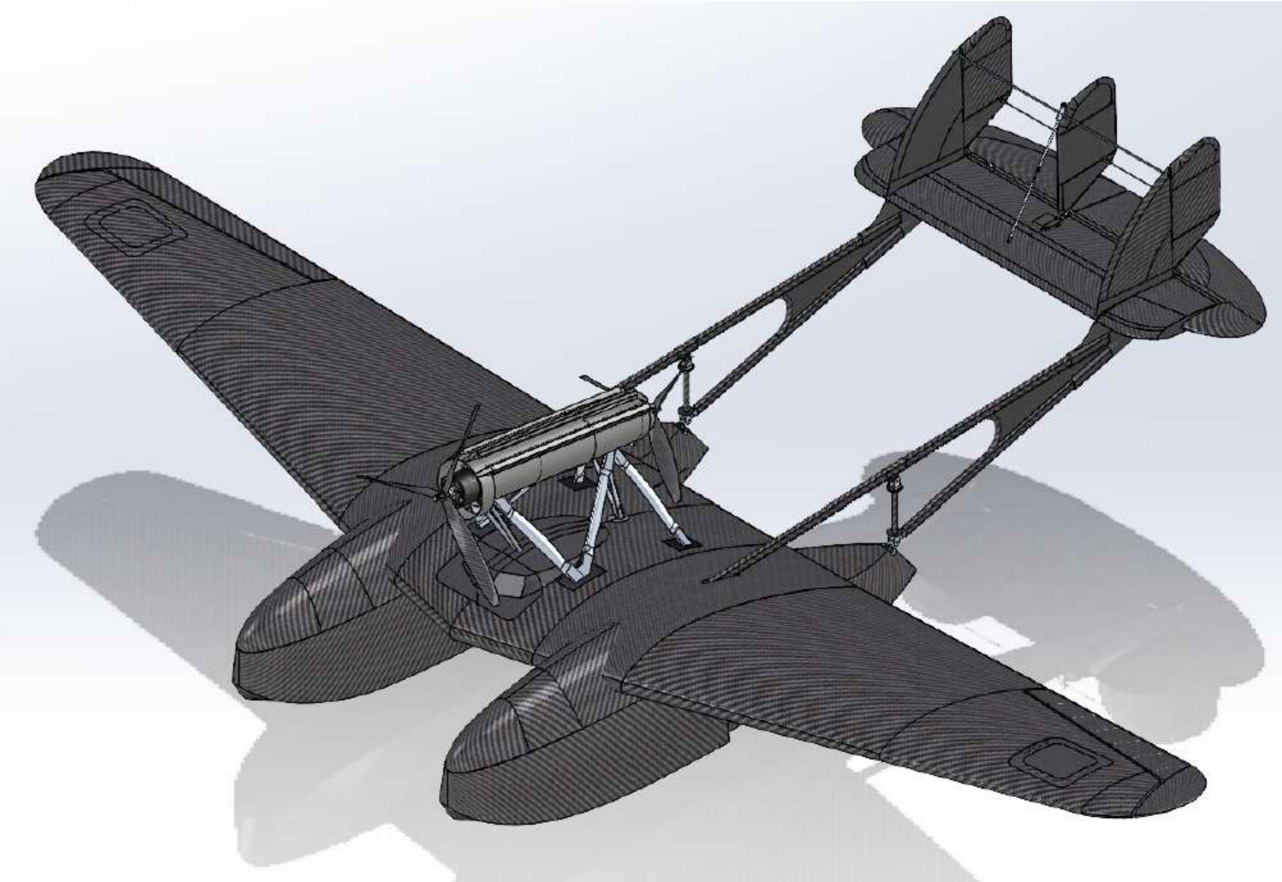


Figure 1 – Model aircraft CAD of Team S55

2. The purpose of the research

The S55X seaplane is a catamaran configuration, equipped with twin engines, one pulling, one pushing. Three rudders surmounted a tail-plane linked to the fuselage by four beams.
The manufacturing of the seaplane model has asked for a complete study on more suitable materials to comply with the requirements of the international competition F4 - Scale World Championship [10]. This competition has specific requirements as regards both the aesthetics of model aircraft, that must be the closest to the original aircraft, and its maximum weight (MTOW of $25\ kg$). For this, the material choice and so the production process are carried out with attention to the structural analysis output and are oriented to modern lightweight composite solutions (such as carbon, glass and Kevlar fibres) [11]; metallic and plastic AM *Additive Manufacturing* is also involved in the project [12].
The need to produce all the components by means of lamination on mould has addressed the investigation and the research to the best methodology for the realisation of the aircraft component's moulds.
The present paper focuses on the choice of construction technology and material of the mould. The quality of the mould directly affects the quality of the final component, so it is essential to carefully choose the type of mould suitable for own purposes and possibilities.

3. Geometry definition

The rib is a forming element of the structure of a wing. Its main function is to sustain shear stresses distributed along the wing. It follows the same aerodynamic profile of the skin, as well as providing a custom hole for the wing spar.
While performing this work research, a NACA-2416 profile is used, due to its asymmetric and convex curvature. The ribs produced do not feature any holes since they would just complicate their production process and they would not really have a relevant impact on the moulds deterioration which is the main point of this analysis.

Apart from the geometrical side, the component is also chosen due to its compact form factor. The chord-line, in fact, is $300\ mm$ long, fig.2. In this way, a greater number of different parts can be produced without using extensive amount of materials. Figure 3 shows the CAD of rib's mould in the female, fig.3a and male, fig.3b version.

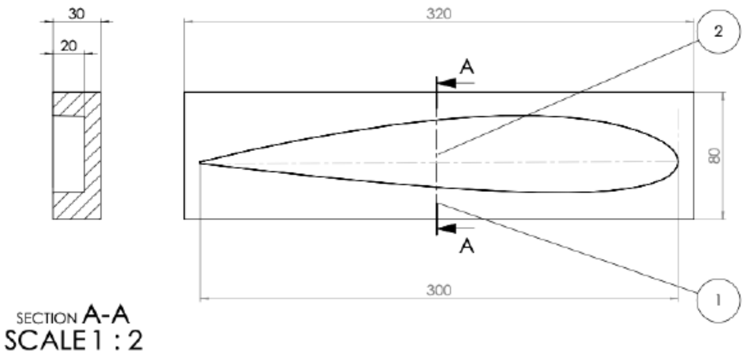


Figure 2 – Dimensioned drawing of the rib

(a) CAD of female mould

(b) CAD of male mould

Figure 3 – CAD of rib's mould

4. Mould production process

In this paragraph the authors are going through an explication of what kind of mould have been produced, what are the characteristics of every type of mould and why they have been chosen.

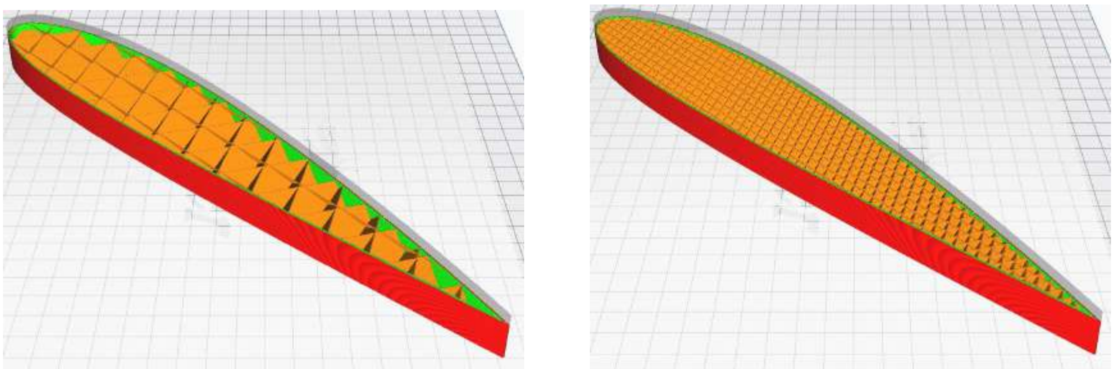
First of all, the moulding technology [13] is one of the most studied in the recent days: it is so important to have good mould surface finish and quality since it massively affects the final product results and cost. In fact, for the manufacturers it is important to have a mould that allows as many prints as possible and with constant tolerances and finishes and at the same time be as cheap as possible.

It has been decided to take three different moulding techniques and apply those to the team's field of experience: the decision falls back to an additive manufactured PLA *Polylactic Acid* mould (FDM technology), a CNC *Computer Numerical Control* milled MDF *Medium Density Fibreboard* mould and a Gelcoat and glass fibre mould. Each of those is employed for different reasons and applications.

4.1 Additive Manufacturing PLA moulds

This mould making technology can be described as the "easiest way to produce a mould" due to its characteristics of being easy-to-use, straightforward out of the CAD model, and very economical (both in the production material used and in the machine used) [14]. It can be very useful in case of very few pieces production, because it allows to have moulds ready in a matter of hours that can have every desired shape and in a very economical way. Although, the cons are that the finish quality of the mould is not as smooth and perfect as other methods, also tolerances are limited and not reliable on 3D printers that cost hundreds of Euros. Also, there is no possibility to bring up the temperature during the curing process due to the low glass transition temperature of PLA.

In the case of this research two different moulds, one with 7% cubic infilling, fig.4a and one with 27% cubic infilling, fig.4b are made. This is made to understand the role of the infilling on the integrity of the mould. If there is a correlation between mould durability and infill, it will be shown after the production of few components.



(a) 7% cubic infilling (b) 27% cubic infilling

Figure 4 – Slicer of PLA moulds with different cubic infilling

The design process of the part starts using a CAD software (*SolidWorks*) and then uses a slicing software (*Ultimaker Cura*) to produce the g-code for the printer. The process is quite easy, the only important things to take into account are the parameters that have to be given to the printer, in particular the temperature of the nozzle, the temperature of the plate, how many walls and top and bottom layers and the infill, tab.1, the other parameters are less important and come up when the need is to improve the quality of the print [15]. Those are quite difficult to set and require a lot of practise and trials before mastering the technique.

Type	Layer thickness (mm)	Filling (%)	Printing Temperature (℃)	Plate Temperature (℃)	Nozzle diameter (mm)
X_P7	0.12	7	205	55	0.4
X_P27	0.12	27	205	55	0.4

Table 1 – PLA Production Data

4.2 CNC milled MDF moulds

CNC milling technology [16] is, nowadays, well implemented and optimised in costs and quality management. However, it is still an expensive method due to the machinery needs and its operational costs. CNC milling can be one of the most cost effective methods, thus it depends on the material milled. In this paper work, it was used the MDF which is the perfect compromise between price and results. Moreover, CNC milling is so reliable and so precise that it finds many applications in the industry of the mould making.

In fact, it is fast, reliable, has optimum finish quality that requires very few touch ups and manual work. Also, the achievable tolerances are in the order of $0.01\ mm$, which, compared to 3D printing is much more precise.

However, a 5 axis CNC work centre could cost millions of euros, requires experts to operate, needs a lot of space to operate and it is energy demanding. It is true that small CNC millings are also very affordable and also very limited on the kind of jobs that they can perform.

The production process is quite similar (in the first steps, at least) to the additive manufacturing one. It starts using a CAD software (*SolidWorks*) and then uses a slicing software to produce the g-code for the CNC (*Autodesk Fusion 360*). The major difference is that in the CNC g-code, fig.5 it has to be set the zero point for the tool (set the point where the piece of material is placed) and decide which tool to use for the process, normally the production starts with a roughing tool, a tool that operates at high speed with less precision, then switching to an intermediate tool or a finishing tool, which are much slower in operating but allows to obtain high precision and fidelity to the CAD design [17] & [18].

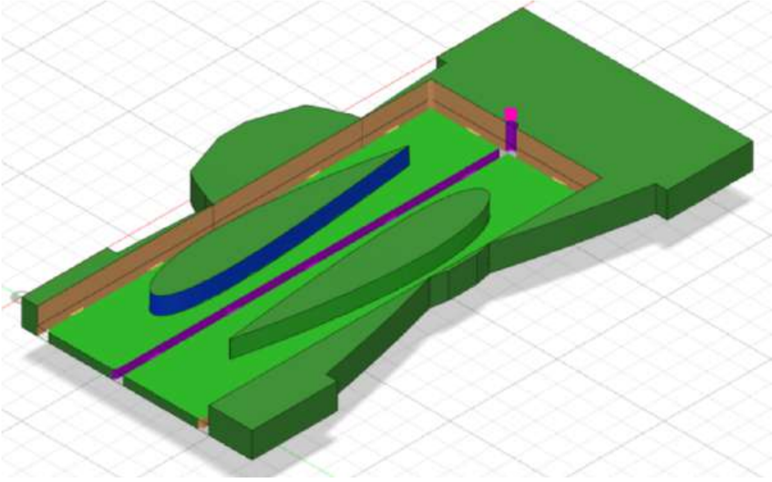


Figure 5 – CNC G-code of MDF moulds

During this research work, it has been used a common 3-axis CNC milling, OverHead M50, (similar to a desktop machine, capable of working on small pieces of material and majorly wood or aluminium), that uses a hand milling cutter (roughing tool) with a diameter of $10\ mm$ for the first part of the process and then switched to ball end mill (finishing tool) with a diameter of $4\ mm$ fig.6 for the final part, fig.7.

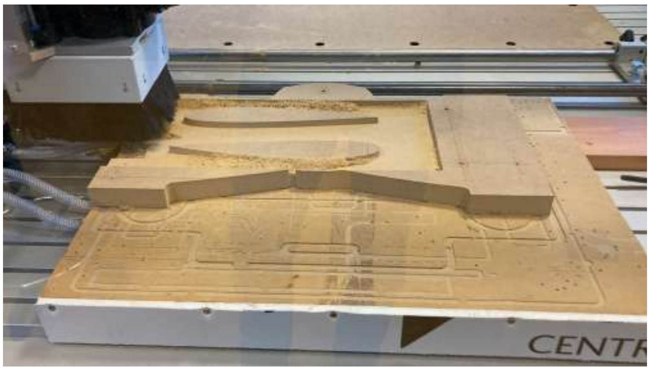


Figure 6 – CNC milling of the MDF moulds in progress

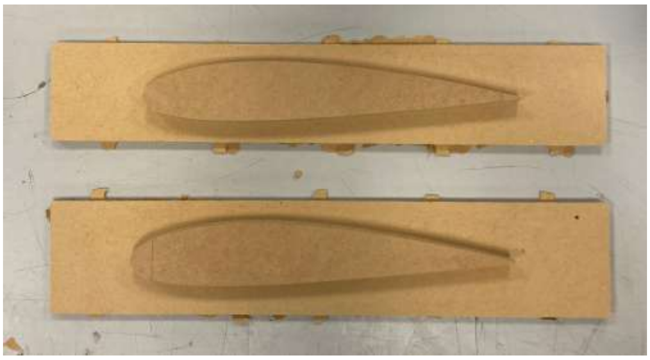


Figure 7 – MDF milled moulds

It has been produced one mould with no draft angle and another one with a 1.5° draft angle. The draft angle has the aim to ensure an easier release of the manufactured object from the mould itself.

It has been opted to use MDF material since it offers good compromises between costs of the raw material and mechanical properties. The milling ease is one of its best characteristics, it is easy to process and smooth out and with very few steps moulds can perform good. Aluminium or Epoxy Resin [19] would have been an optimum choice. However, the costs of both materials are too high to justify the use into this specific case. Also, both are most used in case of pre-preg and autoclave use and for high production numbers.

4.3 Gelcoat and fibreglass moulds

These moulds are part of the FRP (*Fibre Reinforced Polymers*) family, in particular GFRP (*Glass Fibre Reinforced Polymers*), [20].
Gelcoat and fibreglass is probably one of the most time demanding process. This is due to the fact that it is needed a model from which the mould can be built up. This implies one of the two recently described technologies to manufacture the model and after a good preparation to ensure the model is as polished as possible it is time to build the actual mould.

Although the process is quite demanding, it is easily rewarded by the durability and fidelity of these moulds, second only to the carbon fibres one (which is used in case high temperature and pressure are required during the curing process of a same fibres laminate).

The process, after having the model ready fig.8a, consists in laying down a quite thick layer of gelcoat, normally an epoxy product that tends to be much more viscous than the resin used during the lamination. The aim of the gelcoat is to create a strong, thick and perfect "copy" of the model surface. Once the gelcoat is going beyond its pot life (which means that is starting to harden) another layer has to be put on top of the other. This second layer is thinner than the previous one, fig.8b.

(a) Model for gelcoat and fibreglass mould

(b) Layers of gelcoat applied on model

Figure 8 – First and second step for gelcoat and fibreglass mould

After these two coats, fibreglass and resin have to be laminated on top. The target is to reach at least $4-5\ mm$ of thickness, fig.9.

Figure 9 – Lamination with fibreglass of mould

This, in order to reach an adequate level of stiffness of the mould to ensure that is not going to bend and change its shape during the usage [21]. Also, for bigger size moulds a wood, or even better steel chassis is needed to ensure no bending or torsion of the mould.

After the curing process for the mould is done, demoulding process takes place. It is a very delicate process where the aim is to detach the mould from its model. The use of the mould can be immediate or a post-hardening process could be needed (depending on the gelcoat, the resin and the use of the mould). It is very important to carefully process the sealing phase and the application of the release agent on the mould, because once new, the process could require at least 4 to 5 layers of each (depending on the type of product used).

5. Laminating process

The laminating process can be defined as the series of actions and activities that led to produce a laminate, in other words, it is the set of operations that someone has to follow in order to go from a dry fibre cloth to a manufacture that can be used for any kind of purpose. During the research project it was necessary to define as much as possible a productive process that could be employed repetitively without putting into account operator errors, wrong operations and any issue that could have led to bad laminate components. The stack of plies is made by 2 layers of $200gsm$ carbon fibre $+/-45°$.

The process that the work group has developed can be divided in three main parts and summarised as follow:

- First part, prepping and getting ready: preparing the moulds, cleaning if already used, appliing releasing agent. Preparing all the tools and equipment needed, cutting the right amount of fibre needed, weighting every tool used to have better control on fibre-resin ratio, preparing the vacuum bag and anciliaries.

- Second part, laminating process: in this phase the component is laminated. It has been found that in case of small components production it is much more efficient to manually pre-impregnate the fibres on a flat, easy to work surface, then placing down the laminate on the mould. In this case, the use of a releasing film is highly recommended. Also, the dry cloth is placed down on a slightly impregnated releasing film, then more resin is added on top, spread with the use of a silicon spatula and then the excess of resin and levelling process is done by using a paint roller. After that, another ply of dry cloth is placed down, spread down with the spatula without any extra resin to remove any air bubble that could have been trapped. After that the process starts again with the resin being added on top and spread with the spatula and the paint roller again and the process repeats for as many time as the layers are, fig.10.

  Figure 10 – Lamination of the component in progress

  The last ply, normally, is the peel ply. Peel ply is a particular glass fibre cloth that has mainly two roles: the first one is to give to the surface an elevate roughness so that it is easier and ready for a correct bonding. The second role is to create an even surface, without resin voids and discrepancies in the surface.

  After this, the laminate is separated from the release film and gently placed on the mould, with the use of the hands is shaped down till it takes the right form. Then, everything is put inside the vacuum bag and the vacuum is pulled to $-0.78bar$, fig.11.

- Third part, demoulding and cleaning, preparing for the next lamination: after having completed the curing cycle the vacuum bag is opened and the mould with the laminate are extracted. Using the demoulding wedges the laminate is separated from the mould without causing any damages (demoulding wedges are made of rigid plastic and rubber). After that, moulds are cleaned from any residues of resin and filleting wax, cleaned and then the process could start again.

Figure 11 – Laminate is put in vacuum bag

6. Qualitative results

The following section describes the various tests produced, pointing out some qualitative observations. For each mould type, the results are shown in a progressive order, from the first to the last made.

6.1 PLA 7% results

As shown in the fig.12, the result of the mould manufactured in additive, with a 7% filling, does not maintain its outer surface structure when put in the vacuum-sealed bag.

Figure 12 – Final result of the additive mould (7% filling)

Thus it is not useful for both a multiple and a single lamination process due to its fragility.

6.2 PLA 27% Results

The pictures displayed in fig.13 show how the PLA with a 27% filling, progressively, tends to deteriorate over multiple lamination process.
The following naming is used: "x_P27" where *x* is a consequential number representing the rib while *P* stands for *PLA* and *27* is the rate of filling.

It is easy to see that for the first five ribs the PLA mould is not visibly ruined. The only noticeable defect is that the angles in the mould frequently caused the ribs to delaminate as shown in fig.14.

In order to solve this problem for the subsequent ribs the filleting wax is used to chamfer the corners of the mould, fig.15.

The mould in PLA with a 27% filling does not show any signs of deterioration during the first six laminations. To be able to stress it, an oven at about $50°C$ was used in the subsequent laminations.

As it is displayed in fig.16 the PLA starts to soften when exposed to high temperature. It can be concluded that PLA moulds with 27% filling are a valid alternative if it is possible to wait for the hardening of the resin used to laminate at low temperature because it is impossible to speed the process using an oven without ruin the mould.

(a) 1_P27

(b) 2_P27

(c) 3_P27

(d) 4_P27

(e) 5_P27

(f) 6_P27

(g) 7_P27

(h) 8_P27

(i) 9_P27

(j) 10_P27

Figure 13 – PLA 27% results

Figure 14 – Angle deterioration

Figure 15 – Use of the Filleting Wax on the corners of the rib

Figure 16 – Comparison between the mould after the first (top) and the last (bottom) lamination process

Moreover it is important to point out that PLA moulds work quite good for limited dimensions item while for bigger ones different types of moulds are to be preferred. Previous works shown in the section 8.show indeed, the problems that this kind of mould can have.

6.3 MDF results

The next part describes the results of MDF produced parts. As for the PLA, those components have been named using two different naming structures:

- "x_MS" to describe the moulds with the draft angle;
- "x_M" to describe the moulds without the draft angle;

It is possible to see in fig.17 that the first type of MDF moulds (the ones with the draft angle) does not sustain the release of the ribs. This is due to an incorrect separation of the component from the mould: the different wood layers are parallel to the extracted part, hence they are pulled during this operation.
The presence of the draft angle does not affect this issue. To avoid the problem, an all-through screw can be inserted to tighten the different layers. This solution is further demonstrated in the other kind of MDF mould.

(a) 1_MS

(b) 2_MS

Figure 17 – MDF with draft angle results

Conversely, those ribs, fig.18 does not encountered any particular problem (both with or without any type of forced heating). To sum up, the advised improvements are the placement of a screw to reinforce the mould and the use of filleting wax to chamfer the edges.

6.4 Gelcoat results

For the gelcoat mould the naming structure is similar to the previous ones: "x_GV" where *G* stands for *Gelcoat* and *V* stands for *Vetro* that is the italian name of *Glass*.
As shown in fig.19 the mould suffers surface defects due to the application of the gelcoat. The final quality of the ribs is not affected by these irregularities if the filleting wax is applied into them. In fact, as shown in the previous pictures and despite the small lacks of material, all the parts have the same surface and shape quality compared with the other moulds. Due to the composition of this mould (gelcoat, resin and fibre glass) it is not affected by the forced heating process.

7. Data comparison

Different data have been collected to compare the results, tab.2 & 3 & 4 & 5. In particular, as for the different outcomes, the following factor have been taken into consideration:

1. Fibre Quantity 60% (g)
2. Resin Quantity 40% (g)
3. Curing Temperature ($^{\circ}C$)
4. Humidity
5. Production Time (h)
6. Production Cost (€)

Rib	Fibre weight (g)	Resin weight (g)	Curing temperature (℃)	Humidity (%)	Notes
1_P27	35.0	23.3	21.0	70	
2_P27	40.0	26.7	21.8	64	
3_P27	26.1	17.4	24.0	60	
4_P27	23.3	15.5	23.0	60	
5_P27	18.5	12.3	21.8	44	From here on: filleting wax on corners
6_P27	25.7	17.1	23.2	47	
7_P27	26.3	17.5	45.0	10	From here on: hardened in oven
8_P27	25.6	17.1	47.0	10	
9_P27	27.0	18.0	50.0	10	
10_P27	23.3	15.5	55.0	10	

Table 2 – PLA 27% Data

(a) 1_M

(b) 2_M

(c) 3_M

(d) 4_M

(e) 5_M

(f) 6_M

(g) 7_M

(h) 8_M

(i) 9_M

(j) 10_M

Figure 18 – MDF without draft angle results

(a) 1_GV

(b) 2_GV

(c) 3_GV

(d) 4_GV

(e) 5_GV

(f) 6_GV

(g) 7_GV

(h) 8_GV

(i) 9_GV

(j) 10_GV

Figure 19 – Gelcoat and fibre glass results

Rib	Fibre weight (g)	Resin weight (g)	Curing temperature (℃)	Humidity (%)	Notes
1_MS	26.1	17.4	24.0	60	
2_MS	23.2	15.5	23.0	60	Mould Broke

Table 3 – MDF with draft angle Data

Rib	Fibre weight (g)	Resin weight (g)	Curing temperature (℃)	Humidity (%)	Notes
1_M	26.1	17.4	24.0	60	
2_M	23.2	15.5	23.0	60	
3_M	18.5	12.3	21.8	44	
4_M	25.7	17.1	23.2	47	From here on: filleting wax on corners
5_M	26.3	17.5	45.0	10	From here on: hardened in oven
6_M	25.6	17.1	47.0	10	
7_M	27.0	18.0	50.0	10	
8_M	26.8	17.9	55.0	10	
9_M	23.3	15.5	63.7	10	
10_M	24.0	16.0	61.5	10	

Table 4 – MDF without draft angle Data

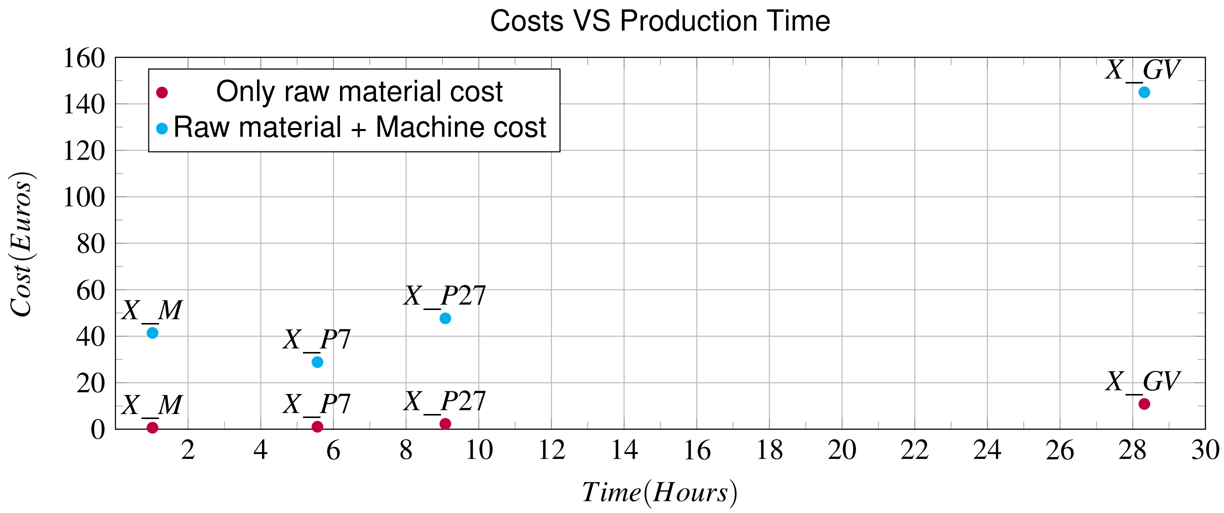
Rib	Fibre weight (g)	Resin weight (g)	Curing temperature (℃)	Humidity (%)	Notes
1_GV	40.0	26.7	21.8	64	
2_GV	26.1	17.4	24.0	60	
3_GV	23.2	15.5	23.0	60	
4_GV	18.5	12.3	21.8	44	From here on: filleting wax on corners
5_GV	25.7	17.1	23.2	47	
6_GV	26.3	17.5	45.0	10	From here on: hardened in oven
7_GV	25.6	17.1	47.0	10	
8_GV	27.0	18.0	50.0	10	
9_GV	23.3	15.5	55.0	10	
10_GV	23.9	15.9	63.7	10	

Table 5 – Gelcoat and fibreglass Data

Type	Production time (hours)	Raw material cost (€)	Machine cost (€/h)	Total machine cost (€)
x_P7	5.56	1.06	5.00	27.8
x_P27	9.08	2.30	5.00	45.4
x_M	1.02	0.63	40.00	40.8
x_GV	28.32	10.87	5.00	134.1

Table 6 – Costs and Production Time

As shown in the graph7.the cheapest mould is the MDF one followed by the PLA. In this case the high cost of the gelcoat mould is due to our choice to make the female mould using PLA with a high infill ratio (27%) that increased time production ($26.82\ h$) and cost production.



8. Applications in Team S55 project

In the first prototype made in 2021 by Team S55, moulds made by 3D printing, with FDM, were used for the lamination of the skins of half-wing and central plane [22] & [23] & [24]. Despite the different types of available additive manufacturing processes, the Fused Deposition Modelling is one of the most used and dates back to the 80s [25]. & [26].

For the design of half-wing's CAD, fig.20 the mould was divided into an upper part and a lower part, subsequently the two parts have been subdivided themselves into six smaller parts, because the mould was printed by a Creatbot 430, that has a print volume of $300\ mm$ x $400\ mm$ x $300\ mm$. Each part has been connected to the adjacent ones, in order to complete the entire mould of the upper and lower part, with some *butterfly* shaped joints.

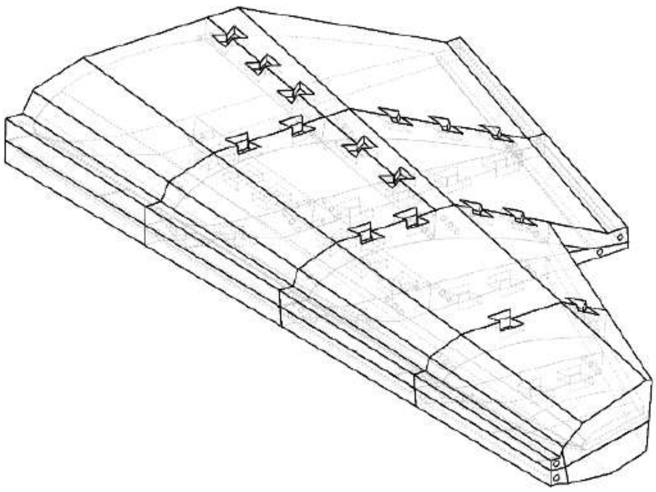


Figure 20 – 3D Half-wing mould concept

The material used for this application is the PLA, this is not a common choice for this application because it has a glass transition temperature of $60\ °C$, above this temperature it loses all the mechanical properties and obviously it is not suitable for an autoclave curing process at a typical temperature of $120/180\ °C$. In the fig.21 there is the assembled mould of the half-wing's upper part.

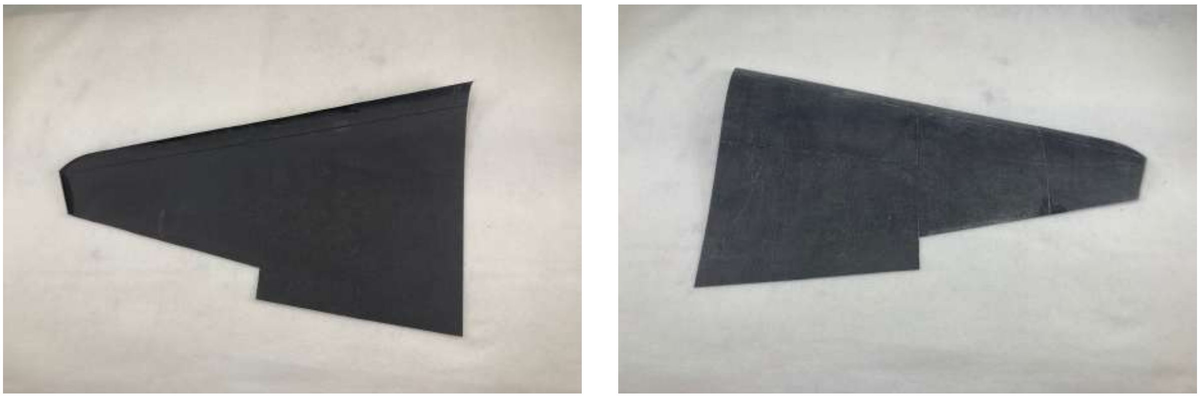
Figure 21 – 3D Half-wing mould

The lamination of half-wing was performed at room temperature by means of epoxy resin and using a vacuum with $-0.6\ bar$, fig.22.

The stack of plies is made by 3 layers of $200\ gsm$ carbon fibre $+/-45\ °$ and one of glass fibre $40\ gsm$ for the external part of the covering. In fig.23 is reported the result of the laminated skin.

In the fig.23b it is possible to notice how the surface quality of the laminated skins is very rough and has numerous surface defects. These are mainly due to the presence of *butterfly* joints between the six pieces that make up the mould.

Figure 22 – Laminated skin in the vacuum bag



(a) Inside of the laminated skin (b) Outside of the laminated skin

Figure 23 – Result of the laminated skin on PLA mould

For this reason, in the making of its second prototype, Team S55 chose to opt for the production of CNC milled MDF moulds.
This type of moulds production starts with the stacking and gluing (with vinyl glue or epoxy resin) of different MDF sheet one on top of the other to reach the height needed of virgin material, ready to be milled, fig.24. It is important to note that there is the need of at least $20\ mm$ to $40\ mm$ of residual material in order to avoid any breaking of the mould.

Figure 24 – MDF sheet ready to be milled

The mould is then placed in the milling base, positioned and clamped down with grips. The CAM model (which is basically a g-code that the machine has to follow in order to achieve the process, where it is also indicated which tool to use, which speed etc.) is uploaded to the machine and the machine is set to zero position (the position that corresponds to the starting position inside the g-code). After that delicate part, the machining process starts. The first part is a high speed, large tool, great feeding process, where the fundamental task is to quickly remove as much material as possible from the raw mould. This part takes the name of roughing process, fig.25.

Figure 25 – Roughing process

After this phase is completed, the low speed, small tool, little feeding process starts. Using a ball end mill, the aim is to achieve the best finish possible, fig.26. This means trying to reproduce, with as much fidelity as possible, the CAD model. This operation is very time consuming, however, it is also very important in order to reduce the manual work needed afterwards.

This last is not always mandatory. Thus, very helpful in case the end of the piece is not clearly marked. It takes the name of marking, normally performed with a very small end mill (in the order of $0.8-1\ mm$), and it is needed to clearly show where the piece finishes inside the mould. The idea is that whenever the extraction of the print is done, a fine line will remain visible, indicating the so called "end of figure".

After the CNC milling process is completed, the mould is not ready to be used yet. Several few steps are needed in order to ensure the perfect superficial finish of the piece. In order to do that, epoxy primer is sprayed on top of the MDF mould. Primer function is to create an easy to sand and polish surface which, after dried, is grid up to 400P sanding paper. In some specific cases two to three layers of primer are needed.

After the sanding process, the sealing and releasing process starts. Sealer protects the mould surface creating a sort of barrier from scratches, resin infiltration and any other possible agent that could affect the performance of the mould. This phase is normally performed with special sealing agents that are well known to be expensive. In the specific case of Team S55's applications it was used the Mikon 399MC [27]. It was applied using simple paper cloth in four to five hands. After the sealing process, which has to be performed very carefully to be sure to maintain the surface as smooth as possible, it is time to apply the release agent. The aim is to ensure the correct mould detaching between the piece and the mould itself. It is, for sure, clear how fundamental this phase is. Depending on how the mould will be used one type of release agent is preferred to the other. Again, in the specific case of Team S55's applications, it was used a common semi-permanent release agent, the Marbocote PK4 [28].
Marbocote product claims to be one of the best releasing agent in the market, it is liquid and easy to

Figure 26 – Finishing process

apply with simple brush. After the application with a brush, it is wiped with normal microfiber cloth or similar. This product has to be applied three to four times on new moulds.

Consequently all this work, moulds are now ready to be used many times, fig.27. After every piece made, mould just need a light clean up and a reapplication of one to two coats of Marbocote PK4 and it is ready to go for other prints.

Figure 27 – MDF moulds of half-wings

Looking at just the mould itself it is clear how smoother and better prepared the surface of the MDF mould is. Also, the print that came out from it looks much better on the outer surface, it is cleaner, with much less superficial roughness and it is easy to see the marking line where the actual piece ends and it is to be trimmed. The inner surface looks similar to the print obtained with the PLA mould, this is due to the peel ply application on both the moulds, fig.28.

9. Conclusions, observations and final results

To sum up, the processes exposed above are aimed to compare the different type of moulds, both from a qualitative and a quantitative point of view.

From a mould-production perspective, by analysing the data of the various costs (visible in the table 6), it is clear that the fastest are CNC milling technology, which takes roughly an hour to complete, and Additive Manufacturing technology, which has a relative time-span of 7 to 8 hours. However, whenever it comes up to shape geometries, the latter manufacturing method is also more versatile for complex shapes rather than the others. Although, due to the poor thermal resistance (glass transition

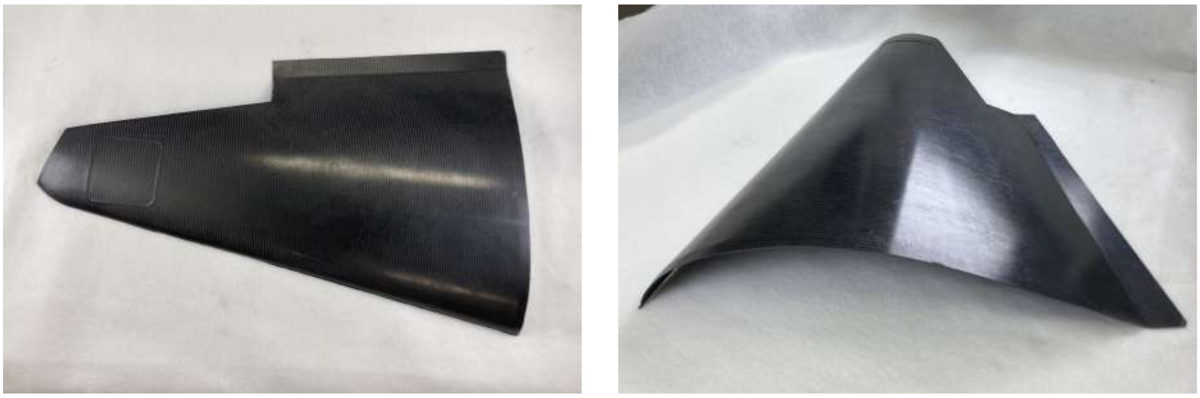


Figure 28 – Result of the laminated skin on MDF mould

temperature of $60-80°C$) of the material, it cannot be very useful in heating-related technologies (i.e. the use in the oven discussed previously). Other methods, such as Gelcoat and MDF are more keen to this type of process.

As to the effective lamination process, tab.7,. it is possible to see that all the products have been manufactured in approximately the same conditions, hence the only substantial distinction can be seen in the final state of the moulds.

The key difference can be better seen when the pieces have a larger form-factor. In this case, the PLA suffers an enormous quality loss, due to the limits of the printing plate dimensions. Thus, MDF and Gelcoat are more largely used in these circumstances. For instance our Team is currently producing wing moulds with MDF, chap.8. Hull moulds are made in Gelcoat and fibreglass, using an AM produced model which has been extensively worked to have a smooth surface.

According to costs, instead, the least expensive type presented is definitely PLA. But, Gelcoat takes a lot more time to be produced, thus explaining the difference. For example, this discrepancy is softened when larger and more complex pieces are produced.

In conclusion, for the production of items whose moulds are made in just one piece it is possible to use PLA casts. Meanwhile, if the mould dimensions are bigger and consequently it cannot be produced in one single piece by additive manufacturing, the results of a PLA mould tend to be really low quality, if not properly worked afterwards (with man-hours work needed). In order to make pieces of bigger dimensions it is recommended to use MDF or Gelcoat and fibreglass moulds. If an higher budget is available or an higher production number in required, it is possible to switch to aluminium or epoxy resin casts, which are by far better than MDF material. Overall, any kind of moulds made by a CNC process is extremely high-performance, much more than the Gelcoat ones, but they are more expensive especially for resin and aluminium ones. The latter mould technology that needs to be exposed is carbon fibre moulds: these types are by far the best, most expensive and high performance solution to implement. However, the costs are often mitigated by the request of low tolerances components, the use of an autoclave for the carbon fibre pre-preg curing (so that, both the mould and the component have the same thermal expansion with temperature) and whenever an high production number is needed.

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12. Copyright Statement

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