MANUFACTURING ASPECTS OF A HIGHLY INTEGRATED MULTISPAR WING

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Abstract
Integral composite, multispar, airfoil structures can be considered as an alternative to established differential skin/spar/rib designs and there are successful series applications like e.g. the monolithic CFRP Airbus A320 aileron. To evaluate the feasibility of a full wing scale application against the state of the art (two spar box designs with stringer stiffened upper and lower shells and demountable leading edges) the dimensions of a Dornier 328 wing have been chosen and analysed. The main focus during the assessment was on manufacturability since this seems to be a major challenge and risk. For the evaluation of the manufacturing effort, the cost drivers tooling, fibre & matrix material, equipment/infrastructure cost, supply cost and labour cost have been analysed and compared. The dedicated assembly procedures have been assessed by estimating the efforts for surface preparation, rigging, merging, fastening and quality assurance. Even though the approach is based on significant simplifications, the potential cost saving that has been identified for the multispar wing structure of about 70% seems realistic. On the other side, the estimated structural weight was affected in a negative way and showed a 15% increase when compared to the conventional reference.

1. INTRODUCTION

Carbon fibre reinforced plastic (CFRP) airframe structures have proven their weight reduction potential in applications like the Boeing 787 and the Airbus A350. On the other hand, cost effectiveness and high production rate capability are aspects that are still considered as weak points. Recently developed aircrafts like the Airbus A220 (former Bombardier CSeries) and the upcoming Boeing 777X may therefore have concentrated on CFRP wings and empennages.

Major differentiators between isotropic metallic structures and anisotropic fibre reinforced plastics are their sensitivity towards local penetrations required for bolting and riveting and their dedicated electrochemical potentials and electrical conductivities. When mixing especially light weight metal alloys and carbon fibre reinforced materials their different electrochemical potentials can lead to corrosion problems in case of insufficient insulation. For this reason, an approach that maximises structural integration and avoids metallic substructures is a viable recommendation. Lightning strike protection and electrical bonding aspects have to be investigated as well because of the comparably low electrical conductivity of CFRP structures.

With respect to climate neutral aviation, it seems that there is a new class of aircraft evolving at the lower range end of SMR (Short Medium Range) single aisle aircrafts.

A prominent contender is the hydrogen powered Airbus ZEROe study that focusses on 100 Pax, 1000NM range and an EIS (Entry into service) in 2035. Since this new market segment is expected to be significantly smaller than the booming, typical SMR segment with a production rate of currently 53 A/C (Aircraft) in June 2024 [2], there should be less pressure on productivity driven industrialisation. On the other side ecological aspects may also lead to a more automation driven, energy efficient manufacturing approach.

FIG. 1: Airbus short range ZEROe 100 PAX, 1000 NM

Basic features of the Airbus 100 PAX ZEROe concept that can be derived from current announcements [3], are:

- Propeller or open rotor (Combustion or electric motors, possibly distributed propulsion)
- Dry wing (no kerosene) and cryogenic Hydrogen tanks in the aft fuselage
- High wing configuration (Provides clearance for propeller/rotor, dry wing less weight/crash critical)
- Low drag, high aspect ratio, probably NLF (Natural Laminar Flow) wing

The presented wing assessment is mainly based on the LUFO project "CTNT" which was funded by the BMWK [1]

2. WING REFERENCE AND DESIGN OPTIONS

As a starting point, open access information [4], of the Dornier Do 328 have been collected to define a simplified baseline design. Especially the non-tapered, middle section of the three wing segments has been identified as a viable starting point.

FIG. 2: DLR Do 328-100 “UPLIFT”

The Do 328-100 has a typical MTOW (Maximum Take-Of Weight) of around 14 To and up to 33 Pax which means it can roughly be considered as a 1 to 3 scaled version of the mentioned Airbus 100 PAX ZEROe approach.

2.1. Simplified Reference Wing

The "**T**ragflügel **N**euer **T**echnologie" (TNT) was developed in the 1970s. In addition to the innovative aerodynamics, the special features of the TNT wing included a highly optimised production of the aluminium wing in terms of automation. The sophisticated, CNC-milled and then plastically deformed wing shells with integrated stringers and rib posts was very innovative. It is likely that this approach will be used in a slightly modified way for the upcoming Deutsche Aircraft D 328 ECO as well.

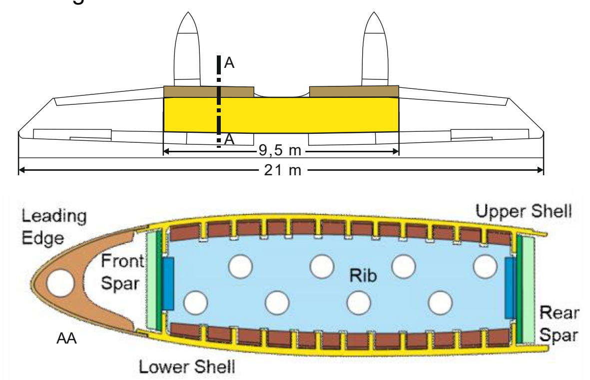


FIG. 3: Simplified Do 328 middle wing section design

A simplification that has been made from a design point of view is, that the ribs are joined to the upper and lower shell by using separate tie elements (dark brown) instead of shell integrated rib posts. In addition, instead of aluminium the wing will be considered to be manufactured from CFRP (Carbon Fibre Reinforced Plastics) for the comparison.

2.2. Wing design variations

In order to increase the degree of structural integration the following design options with either integrated or separated leading edges have been compared:

- **Option S1**

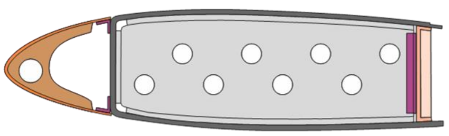


FIG. 4: Option S1

The S1 option has an interchangeable wing leading edge like the reference. The box structure approach, integrates stringerless upper and lower covers (monocoque) with the front spar. A prepared assembly of the ribs and the rear spar is inserted into the c-shaped box structure and then joined. Connection brackets are provided for attaching the wing leading edge and the rib to the rear spar. The rib features integral flanges on three sides.

- **Option S2**

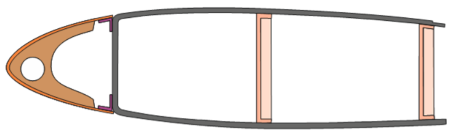


FIG. 5: Option S2

The S2 option also has a removable wing leading edge. The integrated cover and front spar approach is comparable to the S1 option. Instead of ribs, however, a multi-spar approach is proposed here, in which the C-profile beams are inserted and joined subsequently. The spars are reinforced with stiffeners on the web to improve structural stability against buckling.

- **Option I1**

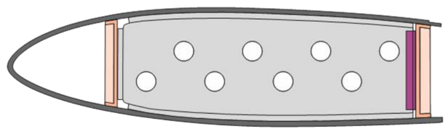


FIG. 6: Option I1

Option I1 is based on option S1 with its stringer free upper and lower covers. Instead of the front spar the leading edge is combined with the wing cover structures. The preassembled inner structure consisting of front spar, rear spar and ribs is inserted in a similar way like in option S1.

- **Option I2**

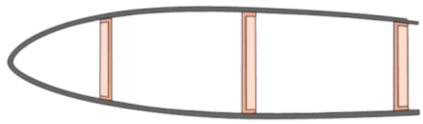


FIG. 7: Option I2

In option I2, the integrated wing leading edge is also combined with the upper and lower wing covers. The variation to the multi-spar option S2 is that three C-spars are used. The spar webs are also reinforced by integrated stiffeners like in option S2.

Option I3

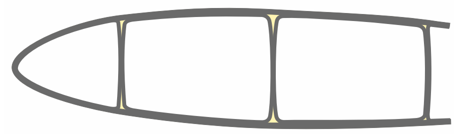


FIG. 8: Option I3

Option I3 follows a fully integral multi-spar approach. A filament winding technique is used to produce the front, centre and rear cells. The trailing edge closing structure is provided by cutting open the wound box. The three wrapped cells are reinforced by additional UD-layers in spanwise direction to increase the bending stiffness of the wing. The curved surfaces of the spar webs are supported by foam core inserts to increase the stability of the spar webs.

- **Option I4**

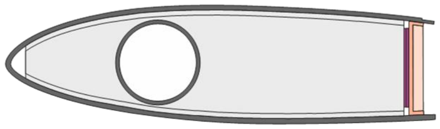


FIG. 9: Option I4

Option I4 is based on option I1. Essentially, the front C-spar has been replaced by a tubular spar, which is only connected to the wing shells via the C-ribs that have been extended up to the leading edge. If required, the tubular spar can be functionalised as a carrier for battery cells or as a hydrogen storage unit. This optional aspect is not included in the evaluation because the main focus of this analyses is structural integration.

3. MANUFACTURING

When manufacturing fibre reinforced composite components, the compression of the laminate plays a special role during production, as this is where the subsequent fibre content is set. A fibre volume content of 60% is a preferred target, as it offers a good compromise between matrix- and fibre-dominated properties. Manufacturing processes for fibre composite components differ in the application of compaction forces and can be divided into the three classes open mould / hydrostatic pressure, closed mould / mechanical compression and pre-stressed, geodetic layup in winding processes.

3.1. Open Mould Processing

In open mould manufacturing approaches the ambient pressure is used for compaction. This is done by combining a rigid, shape giving mould element with a flexible membrane cover that transfers the ambient pressure to the laminate stack. To enhance the compaction force, an autoclave can be used that is usually operated at a pressure between 5 and 10 bars. The increased pressure and related gas density in the autoclave are also contributing to an increased heat exchange which in turn has an impact on possibly shorter cycle times. The elevated, even, hydrostatic pressure can also reduce the void content of the laminate.

FIG. 10: Open Mould Processing

The use of hydrostatic pressure has the advantage that even complex geometries can be compacted uniformly. Open mould processing also means that the final laminate thickness is mainly determined by the bulk factor of the reinforcement fibre architecture. Functional surfaces are typically located at the rigid mould side but it is possible to use local shaping modules or caul plates on the membrane side if necessary. The basic characteristic of open mould approaches can be described as variable cavity / constant fibre volume content processing.

3.1.1. Example: HLFC Suction Rib

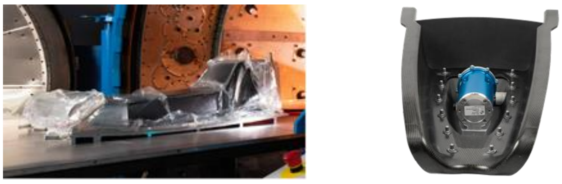


FIG. 11: Suction rib [EU CS2-HLFC-WIN [5]]

Open mould, autoclave processes are typically used to debulk and cure prepreg laminates. The example above shows that autoclaves can also be used for liquid resin infusion processes. The structure shown above is a leading-edge rib that includes a vacuum chamber with an integrated compressor. The setup is used to sustain a drag reducing laminar flow by stabilizing the air flow on the upper side of the HLFC (Hybrid Laminar Flow Control) wing. An inner mould line approach has been chosen to get an accurate flange geometry in the gas tight joining zone.

3.2. Closed Mould Processing

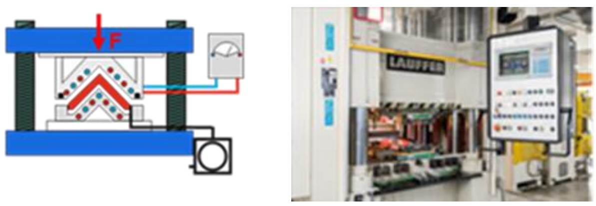


FIG. 12: Close Mould Processing

Closed moulds form a cavity that is geometrically defined on all faces. The closing kinematics defines the main direction of compaction of the laminate which means that considerable variations in fibre content can occur if the structure has different angles related to the compaction direction. Variations in fibre content will also occur when the inserted fibre preform does not exactly match the surrounding mould cavity. On the other hand, the fully defined cavity provides functional and smooth surfaces on both sides of the laminate and if required also finished ready to use component edges. Close mould processing of thermoset resin systems means that a low viscosity resin is injected into the cavity where the fibre preform has been placed before closing (Resin Transfer Moulding (RTM) Process). Since no compressed and heated gas is required for closed mould processes they can completely be carried out at elevated or even curing temperature (isothermal process). This in turn can be used to reduce the required processing energy significantly since no thermal cycling (heating and cooling) is required like in autoclave processing.

3.2.1. Example: Multi Spar Flap

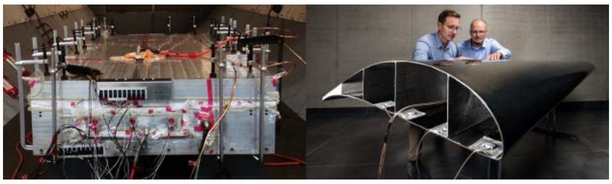


FIG. 13: Multi spar flap [BAB-VPH 2.0] [6],

RTM processes are typically carried out in a press like fixture. In case of the multi spar flap prototype, shown above, an autoclave has been used to keep the mould closed because no press with the required size was available. The flap has been produced with floating, rigid inner mould modules that shaped the four integral spar elements. A machined foam core element has been used to form the small trailing edge section of the flap airfoil.

3.3. Winding Process

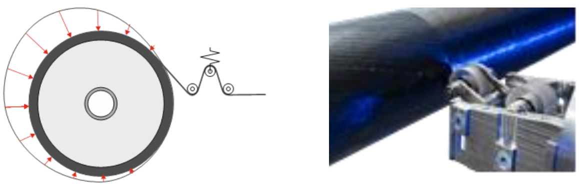


FIG. 14: Filament Winding

Positioning of a pre-stressed fibre on a geodetic path on a circular mould is a very special laminating procedure because the laminate compaction process takes place directly during layup. In addition, the compaction force depends on the layup angle. Maximum compaction is achieved with 90° hoop windings (see FIG 14) and minimum compaction will be present near 0° because the effective arc radius is significantly larger in that case. The classic filament winding process is continuous which means that there is no cutting and restarting. In case of a pressure vessel that is produced on a gastight liner, it would even be possible to avoid the matrix completely since all forces can be transferred by the filament wound fibre architecture. Even in conventional composite structures with a cured matrix this means that the matrix may be less important for the structural performance of the composite component. A variety of processing approaches has been developed for different fibre reinforcement semi-finished products. The positioning of pre-stressed, continuous, unidirectional fibre products on a geodesic path is the defining principle of the filament winding technology. Hoop winding will create near 90° reinforcements, polar winding will create near 0° reinforcements and helical winding everything in between. However, true 0° and true 90° angles cannot be produced directly due to the feed during lay-up and the axis of the lay-up mandrel. If true 0° or 90° ply are mandatory, areal 2D fibre products may be added.

3.3.1. Dry Fibre Winding

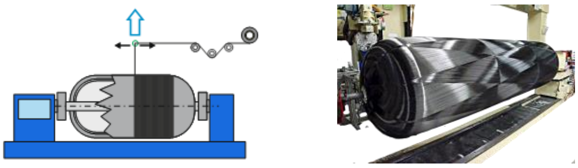


FIG. 15: Dry fibre winding [NBank -KOHONG [7]]

Application of highly cost effective, dry rovings without matrix is possible and reduces the contamination of the workspace with sticky resin. The matrix can be added in a later stage by applying a resin infusion process to the finished fibre architecture. Since the porosity of the dry fibre layup may be quite low, a pressure supported process may be advantageous to impregnate the dense preform. The added complexity of having a two-stage process (winding & infusion) is another relevant aspect that needs to be considered.

3.3.2. Wet Fibre Winding

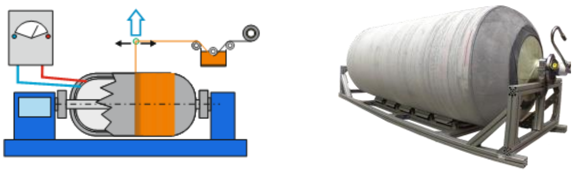


FIG. 16: Wet fibre winding [EU FP7-CHATT [8]]

The classic winding technique usually refers to the application of one (or more) dry rovings that are impregnated with resin just before placement. For impregnation, the dry rovings are drawn through an impregnation bath with low-viscosity resin directly before being deposited. The process is very well proven and produces components with very high performance (e.g. interstage of the Russian Proton 5 rocket). However, the open processing of the low-viscosity resin has a negative effect on the conditions at the workplace (dripping, splashing resin).

3.3.3. Tow-Preg / Slit-Tape Winding

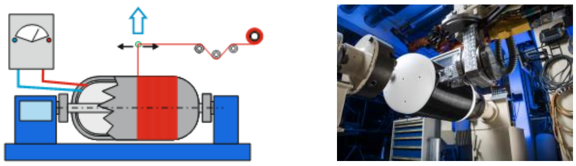


FIG. 17: Slit tape winding [DLR-NGT BIT]

The processing of prepreg semi-finished products, in which a typically high-viscosity resin is combined with the reinforcement fibre product at the product supplier, is more comparable to dry winding in terms of the processing conditions. The workplace is very clean and the fibre positioning is highly reproducible, especially for semi-finished products with a precise width.

3.3.4. AFP (Automated Fibre Placement)

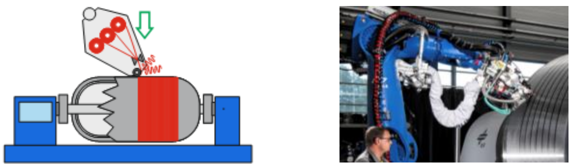


FIG. 18: AFP + rotating mandrel [NBank-HYTAZER [9]],

The placement of semi-finished fibre products with an AFP head does not actually follow the principles of winding technologies, as the thermally activated semi-finished product is fixed to the structure using pressure rollers. However, the AFP process can be interrupted and restarted at any point and limited pre-stressing of the fibre product may also be possible. The reduced dependency on the geodetic path increases the field of application.

4. ASSEMBLY

A key aspect in the design phase is the subdivision of a structural component into suitable substructures and assembly approaches tailored to them. In comparison to metal constructions, where riveting has traditionally led to reliable, light weight and cost-effective aircraft structures, alternative joining methods should be considered for fibre composite constructions. Preferably the joining procedure should have less influence on the fibre architecture like e.g. avoidance of drilled holes can open up the design space for thinner laminates. When bonding and welding is used to assemble a structure, the laminate itself is not weakened, but it must be ensured that the loads are safely transferred in the polymer joining zone. Another important aspect is that especially bonded joints can usually not be separated without damaging the components. Avoiding a joint entirely through structural integration is often advantageous from a lightweight construction point of view. The limiting factor here is the technical realisation and the effort required. In addition, there is the aspect of reparability, as damages to a performance-optimised, highly integral component can be irreparable.

4.1. Fastener Based Joining

Figure 19: Bolted and riveted joints

Bolted joints are very common, especially for detachable connections, and are available in a wide range of specialised designs. Typical bolt connections work according to the principle of frictional locking, i.e. the joining partners are braced against each other when the torque is applied. The design of the bolt connection as a form-fit connection is also possible and requires a more precise machining and alignment of the holes, as the shear strength of the bolt is utilised here. When combining metals with electrically conductive fibre composite materials (CFRP), the electrochemical potentials of the joining partners must be considered. If the joining partners are not sufficiently electrically insulated, contact corrosion of the less noble joining partner can occur. This applies in particular to the combination of aluminium and CFRP.

Most aspects of the bolted joint also apply to the riveted joint. In aircraft construction, however, form-fit connections dominate, i.e. the rivets are subjected to shear loads. While very inexpensive, plastically deformed aluminium rivets and efficient automatic riveting machines are used for the typical riveting of aluminium sheets, expensive titanium rivets with special closing heads are predominantly used for riveting CFRP laminates. Precise adjustment of the correct torque is achieved by the defined shearing of the closing head during tightening. As riveting the outer aerodynamic skin also has a major influence on aerodynamics, flush rivets with countersunk heads specially optimised for joining thin sheets are often used.

4.2. Bonded / Welded Joint

Figure 20: Bonded and welded joint

Important parameters of an adhesive bond are the cohesion in the bondline and the adhesion between the adhesive and the joining partner. The performance of the bonded joint depends in particular on the thickness of the bondline. The surfaces of the joining partners must be prepared in such a way that the adhesion is better than the cohesion of the adhesive. Accordingly, the failure of the bond occurs in a calculable cohesion failure and not in an adhesion failure that is difficult to predict. When a bonded joint is considered, a distinction must be made between film adhesives and paste-like adhesives, as each must be linked to specific technological boundary conditions.

When performing a joint with film adhesives, the compaction pressure is a key parameter. It must be ensured that the applied forces can be transferred to the bonding zone. A minimum adhesive gap thickness can be ensured by textile spacers inserted into the adhesive film if necessary.

With paste-like adhesives, the bonding gap is usually adjusted by the surrounding fixture. The paste-like adhesive is often applied with a reserve amount on one joining partner and, after adjusting the other joining partner, is partially pressed out of the bonding area and, if possible, removed.

In aviation, a distinction is made between three bonding scenarios (FAA, STO-MP-AVT-266) from an approval point of view.

“Secondary bonding" is the bonding of two cured laminates with a mostly thermally activated adhesive. As compliance with the surface preparation specifications and the bondline gap thickness are very critical here the risk of an underperforming connection is quite high. There is also no real possibility of non-destructive testing. Because of these prerequisites, the hurdle for approval is comparatively high for a secondary bonding approach.

In the "co-bonding" approach, one joining partner is cured and the other joining partner is not yet cured and therefore geometrically flexible to a certain extent. As this type of joining is considered less risky based on long term experience, an approval of a co-bonded joint is easier to achieve.

The term "co-curing" is used when both joining partners are not cured. Here, the matrix material of the bond is often the effective "adhesive". As it is difficult to differentiate between structural integration and a "co-curing" approach, the "co-curing" process is more comparable to normal production scenarios in terms of approval risk.

Laminates with a thermoplastic matrix can be welded by applying thermal energy to liquify the matrix. The matrix components of the laminate merge into one another, while the fibre reinforcement does not contribute to the reinforcement of the joining zone. Ultrasound is often used to generate the process heat in the joining zone or the required heat is generated by converting electricity into heat (utilisation of electrical resistance). Heating before joining or the introduction of heat via inductively generated eddy currents are also possible. In terms of process technology, welding is characterised by high performance and short cycle times. On the other hand, the very high temperatures of 300°C-400°C required for processing thermally stable, high-quality thermoplastics may be a limiting factor.

4.3. Structural integration

Figure 21: Integral structure

As an alternative to joining, the required functionality/complexity of a component can also be achieved via the three-dimensional design of the laminate. The transition to "co-curing" is not clearly defined here. The formation of two laminate architectures separated by the joining zone could be used as a distinguishing feature. The challenge with structural integration is in many cases the design and complexity of the mould. Mould weight and costs can limit the scope especially when easy demoulding and mould cleaning are essential demands. The difficult repairability must also be considered for highly integral structures but increasing weight reduction demands may overcompensate this disadvantage.

5. DESIGN EVALUATION

The design options presented in chapter 2 are compared with respect to weight efficiency, aerodynamic quality, producibility, system integration potential and amount of waste during production. The qualitative and experience-based evaluation is carried out with a spread of 4 levels or with an award of 0 to 3 points per variant and question. A selection of four individual aspects (1. Technology readiness, 2. Part complexity, 3 Manufacturing effort, 4. Assembly effort) has been evaluated to generate the production efficiency rating shown below.

Even though the chosen evaluation approach can only be a first qualitative step, the result is considered to be suited to do a more in-depth consideration of the manufacturing and assembly approach for the reference wing and the best rated alternative design option.

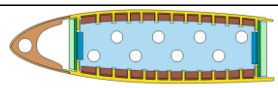
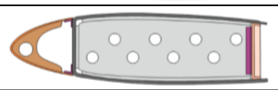
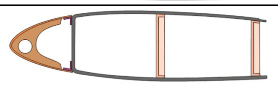
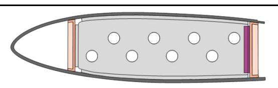
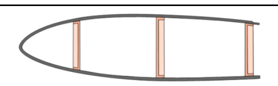
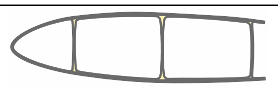
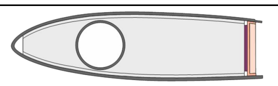
		Structural weight	Aerodynamic quality	Production efficiency	System integration	Waste	
	Relevance	High	High	High	Moderate	Low	**Rating**
Ref.		6	4	2	3	0	**15**
S1		4	4	2,5	2	0,5	**13**
S2		2	4	2,5	2	0,5	**11**
I1		4	4	3	1	0,5	**12,5**
I2		2	4	4,5	1	1	**12,5**
I3		2	6	5	0	1,5	**14,5**
I4		2	5	4	1	0,5	**12,5**

Figure 22: Qualitative expert design potential evaluation

With a rating of 14,5 points, the fully integral, multi-spar approach was identified as the best design alternative when increased structural integration is the main driver. The even slightly better rating of the reference wing (15 points) also shows, that the traditional way of producing aircraft structures is still a strong competitor.

5.1. Structural Weight (High Relevance)

The semi-moncoque design with stringer stiffened skins and ribs is considered to be highly adaptable to the wing loads. It is therefore superior when compared to the structural compromise that needs to be accepted in order to simplify the more integral multi-spar or monocoque structure. The tendency towards low drag, low Airfoil thickness, high aspect ratio wings may close the gap in the future. In case of hydrogen fuelled aircraft the volume of the inner wing is also less restrictive because it is not needed to store liquid fuel.

Figure 23: High aspect ratio, strut-braced wing

5.2. Aerodynamic Quality (High Relevance)

Apart from engine efficiency, drag reduction can be considered as the dominating lever to increase operating efficiency. High aspect ratio, no-swept wings with low chord length have a good potential to be laminarised when the required, extremely challenging surface demands can be met. Surface anomalies caused by gaps and rivet hats may not be acceptable and cause a laminar-turbulent transition which in turn increases the friction drag significantly. A fully integrated leading edge and rivet free wing covers have the best potential to provide a laminar flow wing. This has been demonstrated with an NLF (Natural Laminar Flow) outer wing that has been produced by SAAB within the Clean Sky “BLADE” project.

Figure 24: SAAB “Blade” upper wing cover with integrated leading edge (Clean Sky)

Laminar compatible leading-edge high lift devices have to be considered as well because traditional slats show inacceptable surface anomalies when retracted. If a leading-edge high lift device is mandatory, Krüger flaps and droop noses might be viable solutions to keep the laminar flow option.

5.3. Production Efficiency (High Relevance)

To evaluate the dedicated differences that have an impact on the production efficiency four aspects have been assessed

5.3.1. Technology readiness

A low Technology Readiness Level (TRL) increases the risk of complete failure or critical delay. A more robust and proven concept is therefore preferred especially in aeronautic applications.

5.3.2. Part complexity

High part complexity reduces the trustworthiness of the assumptions that have been made in the early phase of a project and often leads to unforeseen risks, certification delays, additional costs and efforts during realisation.

5.3.3. Manufacturing

A low production rate is limiting the margin for investment in sophisticated automation technology. A rather simple approach for the manufacturing of the required sub structures and well-known technologies are therefore preferable

5.3.4. Assembly effort

A low production rate is also limiting the margin for investment in sophisticated assembly technology. A flexible assembly environment that can be used for a variety of products may be the preferred approach. Versatile robotic systems may have an adequate cost-performance ratio. Minimising assembly effort by allowing dedicated, integrated design principles is also an option.

5.4. System Integration (Moderate Relevance)

Aircraft systems that are required to ensure safety and operability (e.g. high lift devices and wing ice protection systems) will remain mandatory but in case of a hydrogen fuelled aircraft the lack of fuel systems (pipes, pumps, valves, access holes) may enable a more integral wing design compromise.

5.5. Waste (Low Relevance)

Production waste may not be a significant design driver from today’s point of view but this might change with growing political impact in future regulations. The justification might be that the real social impact of wasted resources may not be correctly represented in today’s economy.

6. PRODUCTION CONCEPT

The following sub-structures and manufacturing technologies have been chosen for the assessment

6.1. Production Approach "Reference Wing"

6.1.1. Sub-Structures "Reference Wing"

The differential reference wing is made from the sub-structures shown in Figure 25 and listed in Table 1.

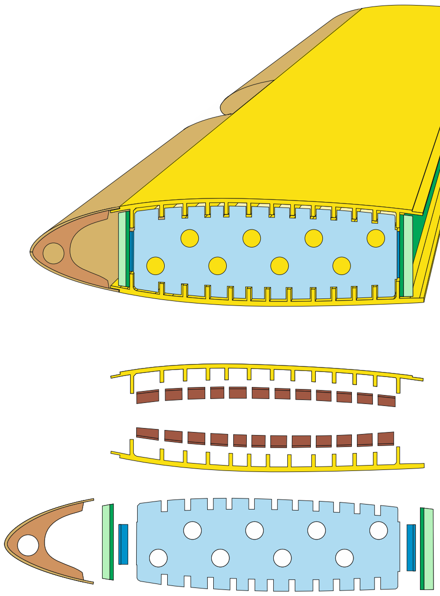


Figure 25: Sub-structures of reference wing [1]

Sub-Structures	Production	Qty.
Upper Cover	Autoclave infusion	1
Lower Cover	Autoclave infusion	1
Rib Ties	RTM (12x24)	288
Front / Rear Spar	Autoclave infusion	2
Ribs	RTM	12
Spar Ties	RTM	24
Leading-Edge	Autoclave infusion	1
Rivets	Purchase part	ca. 2000
Anchor Nuts	Purchase part	ca. 300

Table 1: Sub-structures of reference wing [1]

Open mould, autoclave Infusion is used for all larger structures, closed mould RTM (Resin Transfer Moulding) is used to produce all smaller components like e.g. the rib ties. Both processes will use dry fibre products (fabrics) and liquid resin. Autoclave infusion is a certified manufacturing technology that has been used to produce Do 328 Jet engine pylon fairings (MTS 57.30.21-046)

6.1.2. Assembly tree "Reference Wing"

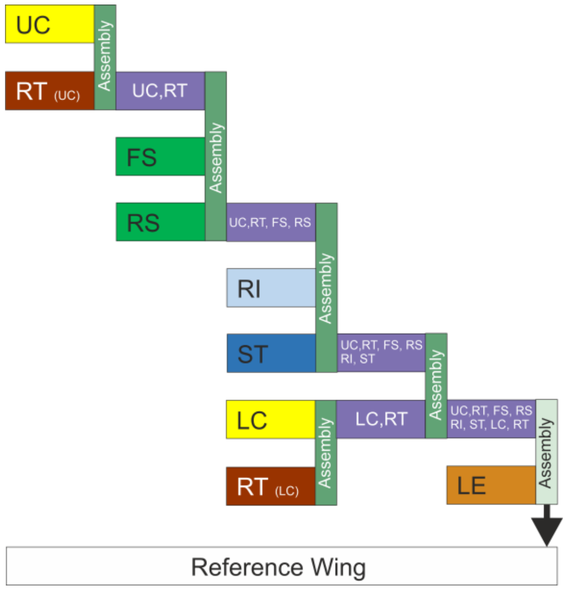


Figure 26: Assembly tree of reference wing [1]

The CFRP sub-structures are mainly joined by riveting. Floating anchor nuts are installed at the joggled upper and lower cover to attach the demountable leading edge

6.1.3. Characterisation "Reference Wing"

Weight of the sub-structures has been roughly assessed in most cases by defining laminate thicknesses and generating a volume by extending the cross-section in spanwise direction. A laminate density of 1,5 g/cm³ has been used to calculate the mass (60% Fibre volume content refers to the Do 328 Jet engine pylon fairings production)

Sub-Structure	Laminate Thickness	Mass
Stiff. Wing Cov.	10 mm	329 kg
Rib Ties	4mm	6 kg
Stiffened Spars	4mm	29 kg
Ribs	4mm	17 kg
Spar ties	4mm	2 kg
Stiffened LE	3 mm	22 kg
Fasteners	ca. 2300	ca. 9 kg
Total Mass		**414 kg**

Table 2: Mass estimation reference wing [1]

6.2. Production Approach “Multispar Wing”

6.2.1. Sub-Structures “Multi Spar Wing”

The integral multispar wing is made from the sub-structures shown in Figure 27 and listed in Table 3.

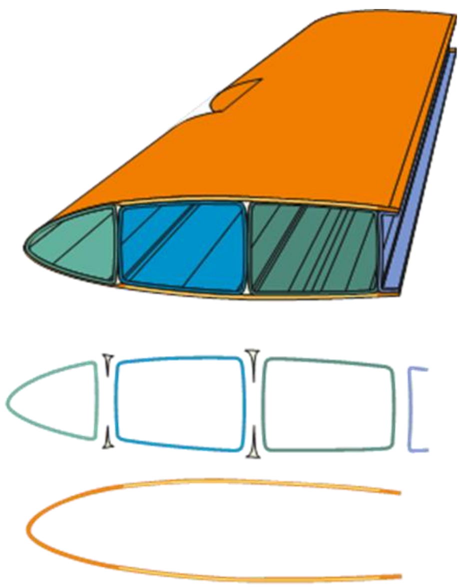


Figure 27: Sub-structures of integral multispar wing [1]

Sub-Structure	Production	Qty.
Front Cell Preform	Dry fibre winding	1
Centre Cell Preform	Dry fibre winding	1
Rear Cell Preform	Dry fibre winding	1
Closing Spar Preform	Dry fibre winding	0,5
Foam Core	Machined foam block	4
Skin with UD Preform	Autoclave infusion	1

Table 3: Sub-structures of integral multispar wing [1]

The production approach of the integral multispar wing is also based on dry fibre products (rovings, fabrics). The cell preforms are produced by dry fibre filament winding. Cells and skin are finally infused and cured under pressure in an autoclave. The closing spar is produced as a cell that is cut in halves afterwards. The design of the manufacturing mould is a major challenge because of the size and the complexity. The mandrels that are used to produce the three cell preforms remain in the preform and are used as rigid cores in the final manufacturing mould. Demoulding will be ensured by using a mandrel material with high thermal expansion (e.g. aluminium). The outer mould will ensure the required surface quality but will be designed with enough remaining elasticity to enable laminate compaction [10].

6.2.2. Assembly Tree “Multi Spar Wing”

The major difference to the reference wing is that instead of cured sub-structures, dry preforms are shaped and partly fixated by binder activation. The prepared preform components are than combined and arranged in the manufacturing mould where resin is added and the integral multispar wing structure is consolidated. The resulting laminate thickness of the final structure is defined by the combined thicknesses of the local preforms (e.g. LE laminate thickness is 4 mm (1 mm front cell + 3 mm skin))

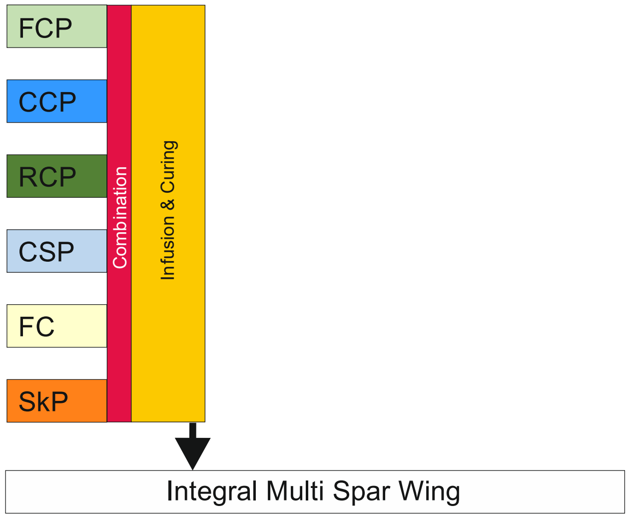


Figure 28: Assembly tree of integral multispar wing [1]

6.2.3. Characterisation “Multi Spar Wing”

To estimate the total mass of the integral multispar wing all preforms are considered as if they are produced separately with a fibre volume content of 60%. No fasters are foreseen for the integral, co-cured structure.

Sub-Structure	Laminate Thickness.	Mass
Front Cell	1 mm	14 kg
Centre Cell	7 mm	147 kg
Rear Cell	7 mm	147 kg
Closing Spar	7 mm	4 kg
Foam Cores		2 kg
Skin with UD P.	5 mm	164 kg
Fasteners	-	-
Total Mass		**478 kg**

Table 4: Mass estimation of integral multispar wing [1]

7. COST DRIVER ANALYSES

In order to estimate the production costs, assumptions must be made regarding the production scenario because it has a dominating impact on the equipment utilisation.

A production rate of 50 aircraft per year was assumed as the production scenario for this commuter like type of aircraft.

Depreciation of aircraft-specific investments (e.g. moulds) should take place within 5 years or 250 delivered aircraft.

A depreciation period of 10 years is assumed for general production equipment like e.g. the autoclave.

Production and assembly are assumed to be a one-shift operation with 8 hours per day and 5 days per week.

The very significant simplification of the wing structures will cause a visible shift towards overrepresented material cost. This is the case for both, the differential reference and the integral multispar wing and is therefore accepted for this comparison. A real wing has much more structural details and these details may be easier to integrate in a differential design. In case of the integral multispar wing it is important to find a suitable mould design that is able to realise the required details or another -usually less weight efficient- compromise needs to be found.

7.1. Costs Driver “Reference Wing”

7.1.1. Prod. Cost Drivers “Reference Wing”

A breakdown of the cost drivers (tooling, fibre products, matrix products, equipment/infrastructure, supplies, labour costs) has been chosen to illustrate the cost distribution for the individual components.

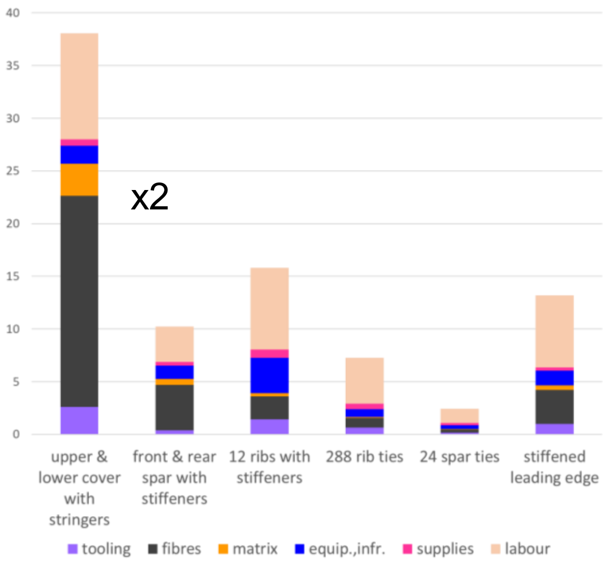


Figure 29: Production cost drivers, reference wing [1]

The wing covers, which dominate in terms of size and complexity, are the dominant components in the reference design (for a better overview, costs of only one of the two wing covers was broken down). For the estimation, the 2 wing covers, the 2 spars and the 12 ribs are simplified and assumed to be identical parts. This also applies to the 24 spar angles. The airfoil curvature of the covers is taken into account for the 288 rib ties (connection angle between wing cover and rib). The wing leading edge is produced with integrated ribs and is interrupted in the area of the fuselage. An interruption of the wing leading edge at the position of the engines was not considered in the assessment.

As anticipated the proportion of fibre costs dominates with a total of 41%. This value also includes a significant scrap rate which is typical for plotter trimmed fabric products. The second largest cost factor is labour costs at 35%. Equipment/Infrastructure, tooling and matrix costs are less decisive cost factors at 8%, 7% and 6% respectively. Consumables are the smallest cost factor at 3%. However, well-coordinated logistics are required here to ensure that production is not delayed by a lack of consumables.

7.1.2. Assembly Cost Drivers “Reference Wing”

A breakdown along the process chain was chosen to visualise the assembly costs drivers. Here, the process sections "surface preparation", "rigging", "merging", "fastening" and "checking" were estimated for the assembly steps.

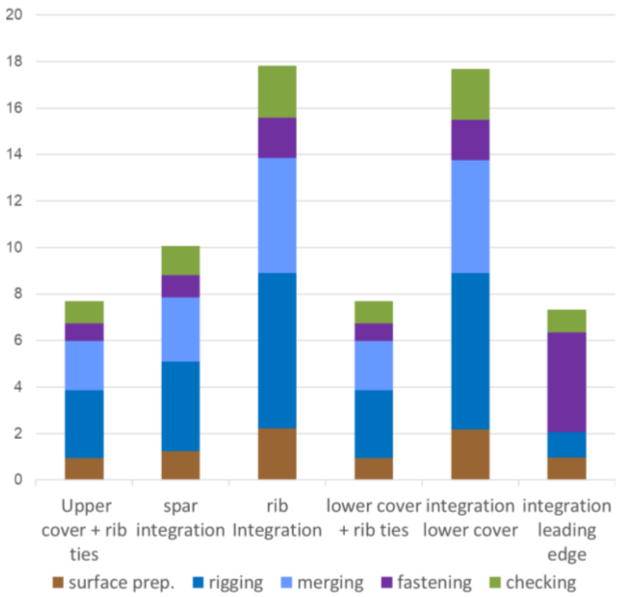


Figure 30: Assembly cost drivers, reference wing [1]

The dominant cost driver for manual assembly is labour costs, which account for 90%. The relatively expensive titanium fasteners and the necessary sealing and moulding materials were considered with a share of less than 10%. At just under 1%, the share of assembly jigs is not a critical cost factor.

Simple cleaning and grinding of the joining zone were the activities that have been considered in the "surface preparation" process step.

In the "rigging" process step, the components to be joined are clamped and aligned using positioning devices.

In the subsequent "merging" process step, the components to be joined are brought into contact and are provisionally fixed. After checking the gap dimensions and removing any burrs, the joining surface is then coated with sealant or moulding compound. The rivet holes are then drilled to the final dimension. Cure related spring-in deformations are a major contributor to geometrical deviations that need to be compensated in this step.

In the "fastening" step, the rivets are set so that the loads can be fully transferred.

The final "checking" step assures whether the rivets set and the riveted joint itself complies with the relevant specification.

7.2. Costs Driver “Multispar Wing”

7.2.1. Prod. Cost Drivers “Multispar Wing”

The breakdown of the estimated effort to produce the integral multispar wing is also visualised by showing the relevant cost drivers. As the multispar wing is an integral component, the dry fibre preform generation is analysed instead of cured sub-components. Impregnation with resin and curing in the autoclave are considered in the “skin & consolidation” production step.

The very low proportion of labour costs in the production of the box preforms indicates the very high degree of automation of the winding technology. The cost of the mould for infiltrating and curing the integral structure defined on all sides is comparatively high. However, as the mould is a to some extend elastic but still mainly closed mould, there is no need for a vacuum bag set-up with film and sealing tape that is typical manually applied for autoclave processes.

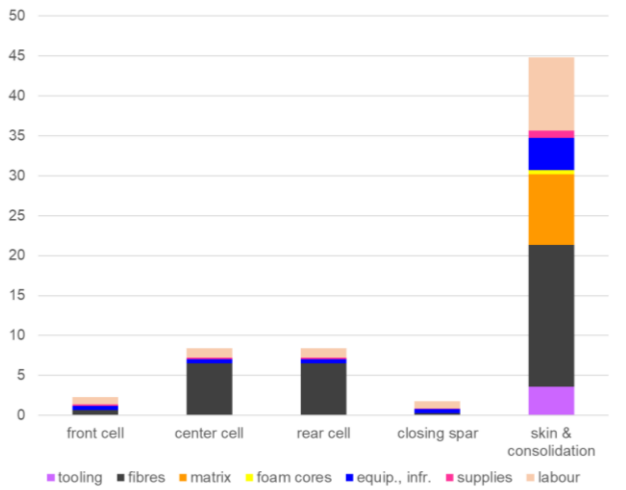


Figure 31: Production cost drivers, multispar wing [1]

The overstated (see introduction chapter 7) but dominant cost driver for the multispar wing is the share of reinforcing fibres, at 48%. At 20%, the share of labour costs is in second place and the share of the matrix system is in third place at 13%. Infrastructure and plant costs are also relevant at 9%. Tooling costs (6%) and consumables costs (2%) are less significant for the multispar wing. At around 1%, the costs for the foam cores are negligible.

7.2.2. Assembly Cost Drivers “Multispar Wing”

The structural result after curing and trimming of the integral multispar wing is comparable to the assembled reference wing. Therefore, no further assembly activities and related costs have been added to the comparison. Another advantage of the analysed closed cell integral structure is that cure related spring-in deformation will be minimal because of the very high planar moment of inertia.

8. RESULT

Even though the very high degree of simplification that has been made limits the applicability of the weight and cost results, the approach may still show a relevant tendency.

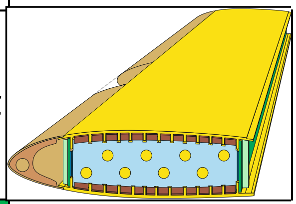
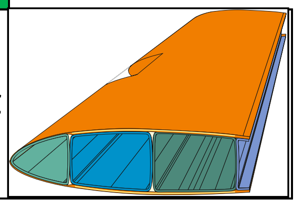
	weight	cost	
reference wing	414 kg	211 k€	
	115%	31%	
multispar wing	478 kg +15%	66 k€ -69%	

Table 5: Estimated weight and cost results [1]

With regard to the weighsaving potential, there is a clear tendency in favour of the differential semi-monocoque wing design. On the other hand, the massive reduction in the number of subcomponents and the considerable reduction in structural complexity show a very high potential for reducing the manufacturing costs for the integral multispar wing approach. The additional weight is also located directly where the lift is generated, which limits the relevance, because there are no secondary bending loads. Plate buckling is the dedicated failure mode of multispar structures which means a spanwise extension is possible without the necessity of ribs [11].

More detailed modelling is required for further statements and solutions for the integration of essential systems (e.g. wiring, de-icing and high lift systems). Wiring could possibly be integrated into the laminate [12] and an inductive WIPS could be realised by adding coils in the leading-edge cell and generate eddy currents in the aerodynamic surface (Joule loss principle) [13]. Adapted maintenance and repair solutions have to be developed as well. This also includes the access openings in the lower wing shell that are required for inspection and, if necessary, assembly. The design of the fuselage and engine load introduction also needs to be redesigned in case of the integral multispar wing.

When looking at the results in more detail, the very low labour costs and the very efficient use of the cost-intensive fibre reinforcement are the dominating advantages of the multispar wing design. Both aspects are closely related to the fibre winding technology which is very easy to automate and produces very little fibre waste. In addition, the processing of a dry roving is significantly cheaper than the processing of a pre-impregnated UD or areal (e.g. fabric or non-crimp) semi-finished fibre product. The considerably lower costs for equipment and infrastructure can also be partly explained by the extended use of winding technology.

9. CONCLUSION

With a double-digit weight penalty, the integral multispar wing is hardly a direct competitor for the Do 328-100 semi-monocoque middle wing section design. The challenges on the system integration side are also far from negligible.

However, a multispar wing with an undisturbed, smooth surface may well be the right choice for future “dry” wings with very high aspect ratios. Drag reducing Natural Laminar Flow wings may become a more important aspect with higher energy prices and it is likely that the weight penalty gets less critical with thinner airfoil thicknesses. These in turn are an option, when the inner wing volume is no longer needed to store fuel. Larger UAV (Unmanned Aerial Vehicles) wings are also potential applications with matching boundary conditions.

Energy efficient process automation and sustainable utilisation of natural resources are possibly aspects that are less prominent in today’s aircraft design decisions. Especially rotating mandrel layup technologies (see chapter 3.3) may have a currently underestimated potential for innovative technological solutions. A rather moderate investment risk combined with a potential, massive reduction in production cost should support a closer investigation of this production approach.

Last not least, the strong commitment toward climate neutral aviation until 2050 could open up the design space for sophisticated, future aircrafts in contrast to the rather conservative, often incremental optimisation strategies that dominate today’s aircraft design.

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Figure 1 https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe

Figure 2 https://www.dlr.de/de/medien/publikationen/magazine/alle-magazine-webversion/dlrmagazin-175/auf-kurs-in-richtung-klimavertraeglichkeit

Figure 23 https://www.dlr.de/de/bilder/2018/1/strut-braced-wing-konfiguration_29809

Figure 24 https://www.saab.com/newsroom/stories/2020/july/towards-safer-smarter-more-sustainable-skies

APPENDIX

	26,7%	26,7%	26,7%				13,3%	6,7%
			6,7%	6,7%	6,7%	6,7%		
			Production efficiency					
	Weight Efficiency	Aerodynamic quality	Technology readines	Part Complexity	Manufacturing effor	Assembly Effort	System integration	Waste
Fact.	2	2	0,5	0,5	0,5	0,5	1	0,5
Ref.	3	2	3	0	0	1	3	0
S1	2	2	2	1	1	1	2	1
S2	1	2	2	1	1	1	2	1
I1	2	2	2	1	2	1	1	1
I2	1	2	2	2	3	2	1	2
I3	1	3	1	3	3	3	0	3
I4	1	2,5	2	2	2	2	1	1

Rating:

0 → not good

1 → acceptable

2 → good

3 → very good

Relevance:

Factor 2 →	High Relevance,	26,7%
Factor 1 →	Moderate Relevance	13, 3%
Factor 0,5 →	Low Relevance	6,7%

Table: Expert design evaluation [1]

reference wing	Manufacturing	Assembly		
tooling	9	1	k€	share NRC
fibres	51	0	k€	RC
matrix	8	0	k€	RC
fasteners		6		RC
equip., infr.	10	17	k€	share NRC
supplies	3	0	k€	RC
labour	44	62	k€	RC
total cost	**125**	**86**	**k€**	
	211		**k€**	

multispar wing				
tooling	4		k€	share NRC
fibres	31		k€	RC
matrix	9		k€	RC
foam cores	0		k€	RC
equip., infr.	6		k€	share NRC
supplies	2		k€	RC
labour	13		k€	RC
total cost	**65**		**k€**	

RC: Recurring Cost

NRC: Non-Recurring Cost

Table: Cost distribution reference and multispar wing [1]

More accurate, FEM based preliminary sizing

An FEM based preliminary sizing of the reference and the mulispar wing has been done by Christian Ückert and David Zerbst within the LUFO project CTNT. The final Report [1] of the BMWK-LUFO project is available.