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DEVELOPMENT OF A MULTIFUNCTIONAL FUSELAGE DEMONSTRATOR

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ABSTRACT:

This paper discusses the development and underlying requirements of a multifunctional lower fuselage demonstrator for a new single aisle aircraft undertaken as part of the Clean Sky 2, Large Passenger Aircraft – Platform 2. The demonstrator will validate high potential combinations of airframe structures, systems, cargo and cabin technology concepts using advanced materials and innovative design principles. The top-level objectives of the demonstrator are:

- Enable a high production rate up to 100 aircraft per month
- Reduce a total fuselage weight by 10%
- Reduce the recurring cost by 20%

Differing from a multifunctional material, a multifunctional component is enabled by a highly effective integration of interdisciplinary technology concepts and concurrent development. This in turn leads to drastic technical and economic improvements. The specific demonstration assembly is shown in Fig 1.

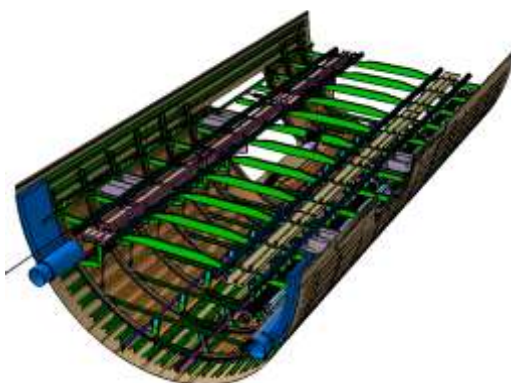


Figure 1: Overview of lower half of multifunctional fuselage demonstrator

Combining a variety of interdisciplinary concepts covering Structure, Systems, System Integration, Cabin and Cargo, it is the opportunities offered by thermoplastic joining which enable their seamless integration in a potential future aircraft production supply chain.

1. INTRODUCTION

The approach of this Innovative Physical Integration Cabin-System-Structure project is to provide the frame for large-scale complex demonstration at full size for validation and testing on the ground.

The target is to validate high potential combinations of airframe structures, cabin/ cargo and system elements using advanced materials and applying innovative design principles in combination with the most advanced system architecture in combination with the next generation cabin.

The driver of this approach is to attain a significant fuel burn reduction by substantially reducing the overall aircraft (A/C) energy consumption, applying low weight systems and system architecture/integration and to be able to cash in weight potentials in the structural design of the fuselage and the connected airframe structure. This must be achieved by the development and application of Industry 4.0 opportunities such as design for manufacturing & automation, automation, sensorization, data analysis and secure data exchange to demonstrate the desired manufacturing costs effects.

2. COST DRIVERS FOR COMPOSITE MANUFACTURING

In order to optimize a composite production process for low cost and high rate it is important to understand the main cost drivers and how a change of approach can affect them. The manufacturing cost for a part can be divided into direct cost and indirect cost as well as material, labour and other expenses [1]. In equation form this yields:

$$C_{part} = C_{MD} + C_{LD} + C_{ED} + \frac{1}{n}(C_{MI} + C_{LI} + C_{EI}) \quad (1)$$

Where:

C_{ED}	Cost other Expense direct
C_{EI}	Cost other Expense indirect
C_{LD}	Cost labour direct
C_{LI}	Cost labour indirect
C_{MD}	Cost material direct
C_{MI}	Cost material indirect
C_{part}	Cost per part
n	Part production rate per year

Fig. 2 provides an indicative view on the cost of a part, related to the rate per year and the influence of direct cost and indirect cost. Assuming that for a rate of 100 per year the direct and indirect cost per part are 50% each, at rate 1200 per year the direct cost would account for 92% of the part cost.

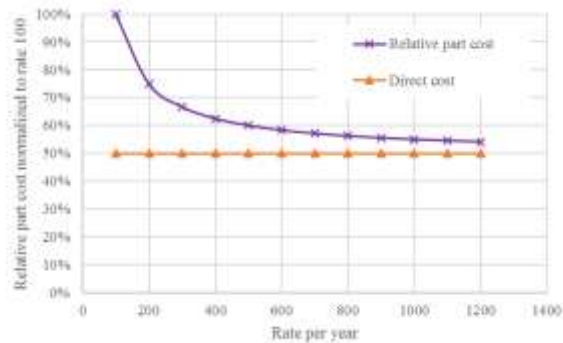


Figure 2: Indicative trend on direct and indirect cost related to product cost

When using high performance materials, the contribution of the material cost to the overall cost becomes relatively large. Due to trimming and other reasons, more material is needed to produce a part than the total volume of the final part itself. This is expressed as a Buy-to-Fly (BtF) ratio and relates to the material cost (C_{MD}) in the following manner:

$$C_{MD} = BtF \cdot W_{part} \cdot C_{W/kg} \quad (2)$$

Where:

BtF	Buy-to-Fly ratio
W_{part}	Weight of the part in kg
$C_{W/kg}$	Material cost per kg

For thermoplastic composites it is realistic to assume that material cost are about 50% of the part cost for relatively low production rates. Hence a reduction of the Buy-to-Fly ratio of 10%, may yield a reduction of the part cost of 5%, as shown by Eq. (2).

The direct labor cost are another important parameter to be optimized. With an increasing production rate, implementing a high degree of automation becomes more economically viable. The cost item for capital equipment would become part of the indirect cost. Lowering the defect rate to near zero-defect manufacturing is an aim, which not only improves the total production rate but also lowers the product cost.

3. ASSEMBLY APPROACH AND TECHNIQUES

The manufacturing approach and specific techniques are a dominant factor to reduce cost and to achieve a high production rate.

3.1. Modular assembly concept

One major innovation for this demonstrator is the modular assembly of pre-equipped sub-assemblies. This approach is the result of an extensive conceptualization phase early within this projects activities. Analysing the manufacturing of thousands of in-production aircraft a large number of lessons learned for future aircraft have been extracted. Of particular importance was the determination of design choice effects on current aircraft. With the typical Single Aisle aircraft for example having originally been foreseen for a two aircraft per month rate, it is fairly obvious that future aircraft production rates of 75 and more aircraft per month require completely different build concepts and hence a drastically increased focus on industrial build concepts. Adding in the clear return-on-experience that each major step in the manufacturing chain from parts manufacturing, assembly manufacturing, main component assembly to final assembly line increases in particular the labour cost, it quickly became apparent that future aircraft build concepts require a shifting of work to earlier phases. Main drivers for this are the lengthy non-value adding activities needed during main component assembly due to a lack of accessibility, unfavourable ergonomics, long travel times through closed assemblies, intermittent cleaning and required measurements. In fact, these non-value adding activities may contribute in excess of 40% of the total workload during main component assembly. This return-on-experience has the added consequence of promoting modularization, which in turn leads to the ability for modular assembly parallelization and in consequence a significant potential for manufacturing lead time reduction. As a result, the concept phase of this project investigated a very large number of possible modular configurations, which identified the current

quartet of modules as the most promising approach from manufacturing lead time and recurrent cost points of view while still enabling the consideration of needing to address non-conformities within the industrial system. The four main module areas identified are the upper and lower shells complemented by the main system carrying modules in the form of the floor and crown modules.

This in turn leads a number of new requirements and needs, such as high rate processes for high performance part manufacturing, rapid and clean joining processes and a very high level of early inter-disciplinary cooperation.

The latter in particular is considered a key driver in the reduction of Engineering Lead Time as previous, sequential mono-disciplinary iteration loops prior to hand-over to the next discipline are replaced by a single, interdisciplinary concurrent engineering approach. This is greatly facilitated by the experiences and developments from previous projects conducted with the kind support of the European Commission such as MAAXIMUS.

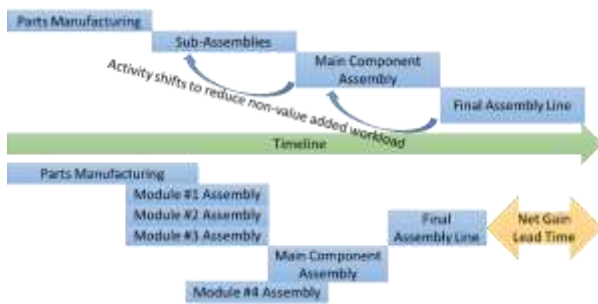


Figure 3: Principle sketch: Lessons learned focussing on recurrent cost reductions by the reduction of non-value-adding activities drastically cut lead time

3.2. Dustless assembly through thermoplastic welding

Thermoplastic composites have the benefit that they can be welded through locally melting of the polymer matrix at the contact surfaces between two parts or assemblies. Welding is a fast and affordable joining solution relative to more traditional joining techniques such as mechanically fastening or bonding. Welding is also a low energy consuming and dustless process. The latter aspect is of importance as it allows for pre-equipping of large sub-assemblies with electrical systems.

There are several different welding techniques usually classified by the main physical phenomenon relied upon to heat and melt the thermoplastic polymer at the welding interface [2]. Most welding techniques have, in principle, the potential to provide joints with excellent quality based on molecular inter-diffusion at the welding interface [3]. However each welding technique has specific features that define their current limitations and potential areas of application in the multifunctional lower fuselage demonstrator [3][4]. Tab. 1 provides an overview of the heating principle, applicability and limitations of the most mature and promising thermoplastic composite welding techniques currently available.

Among the techniques in Tab. 1, conduction welding stands out as a flexible welding technique applicable to both short and long welds, assemblies with gaps and ramps and materials with any type of continuous fibre reinforcement. Conduction welding is based on the application of a heated tool on one or both external surfaces to be welded. Heat is then transferred to the welding interface through conduction. Since this welding technique relies in through-the-thickness heating, it is especially well-suited to welding parts with ramps which might require local forming of one of the welding partners during the welding process.

Table 1: Overview of several thermoplastic welding techniques

Technique	Principle	Applications	Limitations
Conduction	Heat applied at external surface	<ul style="list-style-type: none"> • Short cycle times • UD & fabrics • Short & long welds • Gaps & ramps 	<ul style="list-style-type: none"> • Thin laminates • Heat source not at interface
Ultrasonic [3]	Friction at interface	<ul style="list-style-type: none"> • Very short cycle times • UD, Fabric, IM • Short welds 	<ul style="list-style-type: none"> • Gaps & ramps challenging • Long continuous welds (under development)
Induction [4]	Electro-magnetic heating at interface & cooling at exterior	<ul style="list-style-type: none"> • Medium cycle times • UD, Fabric, IM • Thick laminates 	<ul style="list-style-type: none"> • Lightning strike protection interfering EM field
Resistance	Metal mesh at interface heated by electricity	<ul style="list-style-type: none"> • Short cycle times • UD, Fabric, IM • Long welds 	<ul style="list-style-type: none"> • Short circuits • Foreign material • Limited automation opportunities

Given the intricate topology of the skin of the demonstrator (see Fig.3) conduction welding is an excellent technique for stiffener-to-skin welding. Ultrasonic welding also stands out due to ultra-short welding times of only a few seconds. It is based on the application of high-frequency and low amplitude mechanical vibrations to the parts to be joined. Heat generation, which is restricted to the welding interface, relies on surface and viscoelastic friction with heating rates between 1000 and 2000°C/s [5]. Ultra-short processing times make ultrasonic welding an outstanding candidate for the welding of the numerous clips and brackets in the demonstrator.

4. PART MANUFACTURING TECHNOLOGIES

This section will discuss various innovative manufacturing technologies applied to the demonstrator such as manufacturing of a large thermoplastic skin, press form technologies for UD laminates, out-of-autoclave technologies for larger parts.

4.1. Thermoplastic fuselage shell manufacturing

The skin has thickness variations with reinforcements around the cut-outs for doors. The lower skin has potentially complex interfaces on all edges: longitudinal interfaces with upper skin and circumferential interfaces with other segments.

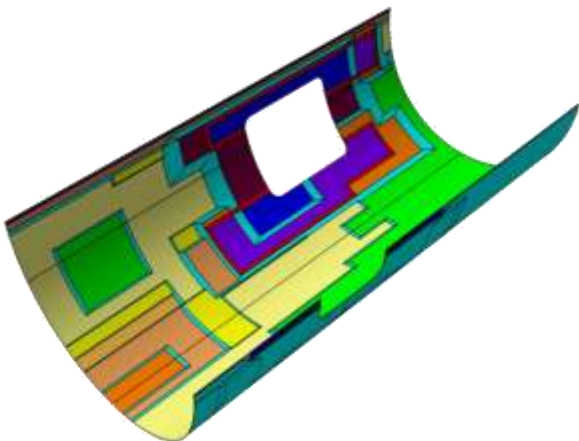


Figure 4: Impression of the thickness variations of the 8m long 4m wide fuselage section

The shell of the lower half of the multifunctional fuselage demonstrator consists of a thermoplastic skin, which is stiffened with welded stringers, clips and frames. The target industrial skin manufacturing process to be demonstrated

consists of three key steps. In the first step pre-preg tape material is laid on a flat table in an automated way. Large preforms of the skin are laid by an ultrasonic or laser automated tape laying (ATL) machine, whereas the remaining detailed parts may be laid in addition by an ultrasonic or laser automated fibre placement (AFP) machine.

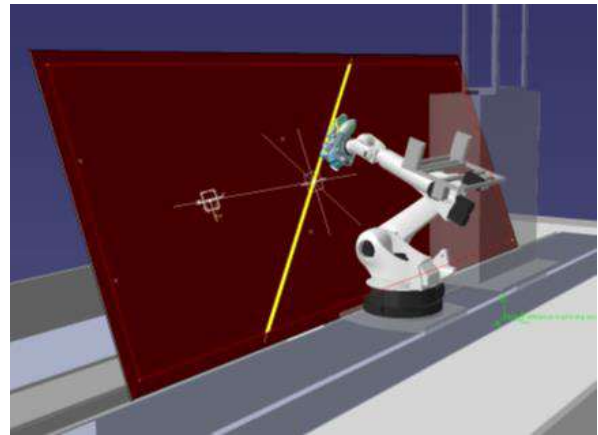


Figure 5: Flat lay-up concept for skin preforms with NLR's AFP machine (top); NLR's AFP machine placing a large thermoplastic pylon upper spar (bottom)

In the second step, the preforms are transported robotically with suction cups to a female consolidation mould and cold (at room temperature) draped in it. In the third step, after bagging, the skin is consolidated in an autoclave. Through application of ATL with considerably wider tapes than used with AFP, significantly shorter production cycle times can be obtained. The use of a female consolidation mould may also contribute to decrease the manufacturing cost. The mould surface is much simpler (flat) than for a male tool of which the surface is the counterpart of the complex inner mould line of the skin. This may reduce the mould manufacturing cost. In addition,

aerodynamic constraints on the skin's outer surface quality are controlled directly with a female tool, of which the surface is defining the skin's outer surface.

To have an affordable demonstrator the lay-up of the large skin of the demonstrator will be carried out on a flat, tilted table by NLR's existing laser AFP machine, taking into account its reach, see Fig. 5. The transport of the skin preforms will be with a suction cup system, which is operated manually rather than robotically. Consolidation will be carried out in a large autoclave.

Starting in parallel to the large multifunctional fuselage demonstrator, out-of-autoclave processes will be investigated in a subsequent smaller size demonstrator on their readiness for industrial high volume application and comparison with the autoclave-based target industrial process. In particular, in situ thermoplastic composite manufacturing in which consolidation is achieved during the lay-up, will be considered, since it may completely eliminate the autoclave step, and hence reduce the manufacturing to a single step procedure. Laser AFP is reported to offer high energy efficiency and superior dynamic control for in-situ manufacturing [6], [7] Referring to 5 other publications, [8] mentions that in-situ consolidation remains challenging even for flat panels while maintaining a high productivity.

Manufacturing developments at NLR are supported with corresponding developments in design for manufacturing and in virtual manufacturing. Virtual manufacturing focuses on the optimization of the lay-up process, the simulation of transport and cold draping, and on detailed analysis of the effect of heating and cooling processes during lay-up, consolidation, and welding on product characteristics and mechanical behavior.

4.2. Press forming of small parts

Press forming of thermoplastic parts is a manufacturing technology that offers advantages such as fast processing times, low tooling cost, and good product quality [9][10][11]. Fig. 6, shows two examples of press formed thermoplastic parts made of fabric material that are flying on aircraft today.

The demonstrator will have several press formed parts: struts, seat rail brackets, and X-paddles. All will be made from LM/PAEK UD material and will involve single curved features, see Fig 7. Fig. 7.a

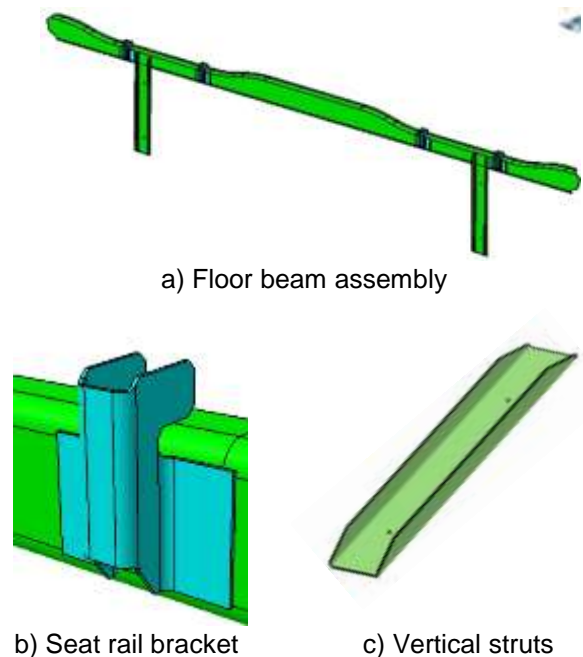
shows the final sub-assembly with welded seat rail brackets (Fig. 7.b) and vertical struts (Fig. 7.c).



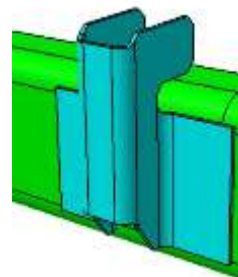
A380 leading edge rib Ribs on the AW169

Figure 6: Examples of press formed parts in aircraft produced by Fokker

The parts on the demonstrator will be of a constant thickness using pre-consolidated blanks that only due to the rectangular shape of the blanks, will result in a favorable buy-to-fly ratio. As described in ref [8], using automated fibre placement (AFP) of tailored blanks of near net shape offers benefits of thickness variations and improved buy-to-fly ratio. With a typical takt processing time in the order of 1 or 2 minutes and the ability to use multiple parts in one process step, press forming is a well suited process to meet the high production rate.



a) Floor beam assembly



b) Seat rail bracket



c) Vertical struts

Figure 7: Press formed parts on the fuselage demonstrator

4.3. Passenger floor beams

As depicted in Fig. 7a the passenger floor beams are a C-section with a varying web height over the

length of the beam. The mid-section the passenger floor beam supports the floor panels thereby integrating the function of a longitudinal member and thus reducing parts and assembly lead-time.

Fig. 8 shows an impression of the production process where a positive mold is used to robotic assisted winding of two beams. Upon completion of the layup, the laminate is cut at the top and bottom to provide 2 C-sections. This is a highly automated process and when used in combination with a laser allows for in-situ consolidation of the laminate. This approach would reduce a secondary consolidation step in an autoclave. Through layup directly onto the final shape, minimal material use is achieved and offers the opportunity for thickness tailoring. A challenge is that the takt time is limited by the maximum layup speed.

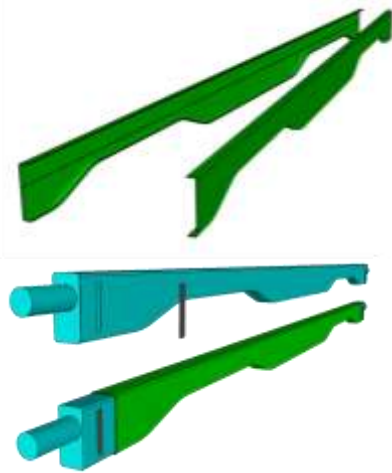


Figure 8: Passenger floor beams, robotic assisted winding

5. CONCLUSION

This project will demonstrate a high level of pre-installation of systems before the final assembly line. It will be a showcase of the latest developments on thermoplastic manufacturing and joining techniques, which are key to this particular assembly concept and cost reduction challenge. As discussed in the paper, the optimum between production speed and minimal material to reduce cost is a challenge can requires insight in the interdependencies.

6. ACKNOWLEDGEMENTS

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