1 Executive summary

In comparison to metallic parts, the process selection route for Carbon Fibre Reinforced Plastic (CFRP) parts is still on a lower development level. Whilst new technologies in CFRP manufacturing slowly emerge into markets, their cost saving potential is often neglected.

A cost estimation tool based on cost ratios for part attributes is discussed, with a show case for development programs. It serves experienced engineers as a discussion baseline and reduces the effect of subjective opinions on design and manufacturing routes.

2 Introduction

2.1 State of the art

The main advantage of composite parts in aircraft parts is their significant weight advantage. However, with industry margins being in the lower one-digit range and constantly falling (see fig. 1), cost considerations have already become a key factor for purchase agreements [9].

In comparison to metallic parts, the main cost driver for composite components are the high raw material costs, the intensive manual labour, the intensive investments on processing equipment and the higher requirements for quality control [10].

As of today, the vast majority of CFRP parts in the aerospace industry is manufactured from autoclave-cured prepreg systems.

Rivaling manufacturing techniques, such as Resin Transfer moulding (RTM), infusion or out-of-autoclave prepregs, have to demonstrate significant savings in order to outweigh their inherent risks caused by limited availability of material allowables, experienced process designers, aerospace certifications and factory capabilities [1].

The process downselection is one of the most important decisions during a part development program and therefore usually a milestone. The influence on production costs are very high, not only by Non-recurring costs such as tooling and machines, but also by raw material influence and process time [10].

It is therefore an obvious approach to link the process downselection to its estimated part costs, in order to reduce the overall costs or to demonstrate certain potentials for new process, when investment decisions have to be made.

The major challenge hereby is the availability of data respectively the level of confidence in it. At the stage of process downselection, the design is usually not finalized, which makes existing cost models mostly unsuitable for decision aiding, as their input requirements are based on a set of data derived from a finished part design.

Figure 1: Profit margins of aerospace manufacturing companies within the European Union [9]

An estimate for a cost range needs to be negotiated before an actual part is fully designed or even built.
2.2 Overview on existing cost models

As of today, cost prediction models have been developed and tested against real production environments. Three different families of cost modeling approaches are distinguishable:

- **Parameter models**
  - Parameter models extrapolate costs from already manufactured parts, either within a public database or from company specific sources [7]. Their range lasts from high-level parameter comparisons (such as double weight => double costs) to more sophisticated versions, which allow highly precise cost predictions, if boundary conditions such as processing routes or personal costs don’t change. However, most parametric models do not consider extra working steps (e.g., taking material off via milling improves model costs due to less weight).

- **Process-based models**
  - Many of the currently available cost prediction models are process based, so they transfer information created by the designers into processing steps first, which can be translated into cost figures via cost ratios. Extra costs, such as special machining or detailing work, need to be incorporated by margin factors. Whilst being very effective when done right, the “automatism of a manufacturing engineer” is still heavily based on the input quality [3]. For early design stages, the effort for bringing up the required input depth can usually not be justified [6].

- **Activity-based costing models (ABC)**
  - ABC-models improve the process-based models by reducing the influence of the margin factors by detailing all activities in conjunction with the part production. While being even more precise than process-based models, the input requirements are unfortunately about the same.

Although it is widely agreed upon that the cost influence possibility is highest in the earliest design phase, the availability of cost information in said stage is low [7] [8].

Fig. 2 illustrates the relation between information input requirement and design maturity for the three cost modeling approaches.

![Comparison of cost estimation models over development time](image)

Figure 2: accuracy capability of cost modeling approaches over project development (indicative)

An ideal cost model tends to be a combination of parameter-based comparison in the first engineering period, while for more mature designs, ABC-models or knowledge-based models offer a higher level of confidence on projected cost.

2.3 Value-driven design as a scoring mechanism

The value-driven design approach is usually used to compare items that differ in at least 2 different fields (e.g., Design A is cheaper to manufacture, but heavier than Design B), which can be used as a decision-making tool in early design stages. It allows the ranking of several process techniques by a direct comparison on currency level, whilst including non-cost effects (e.g., weight, emissions, thrust..) [2],[4]. This reduces the necessary information to a design engineer to an acceptable level for fast iterations of several design concepts [6].
A value driven approach for design choices has been used in the aerospace industry, but is mainly used on research programs [5].

3 Research aim

For this research project, a combined approach with elements of a parameter- and a knowledge-based cost model has been selected. For the purpose of evaluating early designs, this combination should allow a significant improve in accuracy from the start of the designing activities on to a level of design maturity, where a process downselection can be safely made, which is often made before the final design is released.

In an industry with life cycles up to 40 years of service, an revolutionary design change (especially the invention/design of a completely new part without a predecessor) is unlikely to happen, due to the high requirements on safety regulations. Therefore, an evolutionary design approach based on industry-wide knowledge is a fair baseline assumption for a design startpoint.

The approach to be discussed is inspired by a design-for-cost-approach by [11]. The main idea behind a design-for-cost-approach is to optimize a part design for manufacturability during the very early design stages, where design changes can be incorporated into the CAD-model and do not lead to expensive changes in (already manufactured) tooling and process chains. In contrast to [11], where a familiar approach has been applied for metallic parts and focused on machining features out of a solid part, the concept on composite parts needs to figure in many additional requirements, as most of the final part form is ideally given during the moulding process and not via machining means.

During an pre-mature design stages, usually several concepts are designed, which are then optimized for mechanical behavior. Manufacturability is often considered late or even not before the final design release. This might lead to a technically superior solution, however, the optimum point between sufficient part properties and lowest possible costs is seldom met. A currently often chosen strategy is to realize a technically sufficient part and, immediately after entry into service, start on a cost optimizing redesign.

A typical part development process and the suggested changes can be found in fig. 3. The earlier manufacturability is considered in a design process, the lower the costs for changes are. On the downside, the margin created is hard to make visible.

Figure 3: Standard design process and the improved variant

To support a design engineer during the “brainstorming phase”, a software algorithm for comparing the manufacturability of a part design for different manufacturing routes is under development (working title: FACE_RoaD).

The software, designed as a hybrid between parameter-based comparison for measure- and scalable design constraints (e.g. annual manufacturing rate, weight) and knowledge-based input for hard-to-predict constraints (e.g. scrap and rework rates) and undefined limitations (e.g. percentage of UD-Fibres) at this design stage, compares a defined set of input parameters by a transformation into cost values by the use of cost ratios. By summing up the cost influences, it can:

- Highlight a preferred manufacturing route by simply comparing the outputting numbers
- Advice the designers by highlighting the highest cost drivers in each manufacturing route and therefore give them the opportunity to influence the design to best match a process route

To support a design engineer during the “brainstorming phase”, a software algorithm for comparing the manufacturability of a part design for different manufacturing routes is under development (working title: FACE_RoaD).

The software, designed as a hybrid between parameter-based comparison for measure- and scalable design constraints (e.g. annual manufacturing rate, weight) and knowledge-based input for hard-to-predict constraints (e.g. scrap and rework rates) and undefined limitations (e.g. percentage of UD-Fibres) at this design stage, compares a defined set of input parameters by a transformation into cost values by the use of cost ratios. By summing up the cost influences, it can:

- Highlight a preferred manufacturing route by simply comparing the outputting numbers
- Advice the designers by highlighting the highest cost drivers in each manufacturing route and therefore give them the opportunity to influence the design to best match a process route

To support a design engineer during the “brainstorming phase”, a software algorithm for comparing the manufacturability of a part design for different manufacturing routes is under development (working title: FACE_RoaD).

The software, designed as a hybrid between parameter-based comparison for measure- and scalable design constraints (e.g. annual manufacturing rate, weight) and knowledge-based input for hard-to-predict constraints (e.g. scrap and rework rates) and undefined limitations (e.g. percentage of UD-Fibres) at this design stage, compares a defined set of input parameters by a transformation into cost values by the use of cost ratios. By summing up the cost influences, it can:

- Highlight a preferred manufacturing route by simply comparing the outputting numbers
- Advice the designers by highlighting the highest cost drivers in each manufacturing route and therefore give them the opportunity to influence the design to best match a process route
More detailed information on workflow and input parameters was published in [12].

4 Methodology

As a part of the calibration and validation effort on FACE_RoaD, the software is tested on an aerostructures part already in serial production for over 7 years.

Part description

The part analyzed is a centre hinge fitting (CHF) on Airbus A330 and A340, an actuator bracket between a spoiler and a wing (see fig. 4). Mounted on the spoiler, it provides both fixation and actuation and is therefore highly structurally loaded. Main challenge on designing this part was the limited freedom in part design, as the target was to replace the existing aluminum part by a CFRP version with no changes to either the spoiler or the wing. This led to a complex geometry, which could not be realized in conventional prepreg technology due to narrow tolerances and complex preforming. The resulting preform of is schematical displayed in fig.5 and gives an idea of the part complexity, which results in relatively high costs.

Manufacturing route

The part is manufactured in a standard RTM manufacturing route:

- Cutting
- Preforming
- Injection
- Machining
- NDT
- (Shipment)

Under the given restrictions, the part design is close to optimum. Most cost arise during the preforming stage, with raw material costs as runner ups. A cost distribution of the current manufacturing can be seen in fig. 6.

Figure 4: CHF assembled into an aircraft spoiler

Figure 5: exploded view on A330 CHF preforming
4 Experimental Work

This work focuses on a hypothetical possibility to adapt the current design in minor ways, as a redesign with full design freedom is not realistically performable.

The current design was run through FACE-RoaD and the highest possible cost margins were selected for further investigation.

In order to keep the study closely related to serial production, attachment features and tolerances were set to the current requirements. Factory influence was configured in a way that no process was ruled out by basic availability of machinery. Whilst this is true for the current manufacturing site, a direct transfer to other facilities must not necessary result in the same order of outcome. If a corresponding study was run in order to improve investment decisions for a manufacturing chain, the parameters are valid.

Baseline assumptions and input parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Input</th>
<th>Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part count</td>
<td>1200</td>
<td>[Pcs/year]</td>
</tr>
<tr>
<td>Part weight</td>
<td>8000</td>
<td>[gm]</td>
</tr>
<tr>
<td>Minimum radius</td>
<td>3</td>
<td>[mm]</td>
</tr>
<tr>
<td>Part thickness at minimum radius</td>
<td>6</td>
<td>[mm]</td>
</tr>
</tbody>
</table>

### Process selection study

With the given input factors, the virtual process downselection backs up the current manufacturing strategy. RTM is by a fair margin the most cost efficient way to produce such a complex shape. A cost comparison can be found in Fig. 7.
The main cost factor against the selection of RTM as a manufacturing route, the expensive, rigid, double-sided tooling, is in this case almost compensated by the tolerance requirements on all sides of the part, which would require additional tooling parts for standard autoclave and out-of-autoclave processes. In addition, the easier preforming of non-UD-dry fibres to high angles and the resulting shorter preforming time enhances the cost margin on RTM further, as the high part count reduces the cost effect of the tooling on the individual part.

Most of the positive values of RTM are also valid for the infusion process, as the preforming costs can be considered equal. However, the longer cycle reduces the cost benefit gained by shorter preforming. Depending on injection unit availability and actual part count, it might be interesting to consider infusion though, as the low pressure injection system is less expensive than the RTM unit.

Prepreg was ranked last due to expensive preforming and autoclave availability. At the given part count and the implemented utilized autoclave capacity, it is not feasible to aim for a prepreg solution. Due to a low trust in ooA-prepregs at the current development stage, ooA-prepregs are given a penalty in the cost programming. This is mainly enforced by the expected lower laminate quality, which results in either a higher scrap rate or in a heavier part. As of current studies [13], [14], [15], it seems that quasi-voidfree processing of ooA-prepregs is possible on panel level, so this result might change in the near future, as the investment costs for ovens are way below the necessary invests for autoclaves.

Once RTM has been verified as preferred production route, the optimization of the current design to best fit the RTM process has been started.

**Optimization study**

Under the assumption, that no knowledge from serial production of that specific part existed, a design optimization was run, in order to determine the high influence cost drivers and to optimize the part system for a minimum of manufacturing costs. The estimated cost distribution before optimization is shown in fig.8.

With the knowledge background database incorporated in FACE_Road, the highest influence factor is the relation factor between minimum radius and part thickness. Bending a thick layer of fibres in a very small radius results in very inhomogeneous permeability in this area, likely causing resin-poor and –rich areas or porosity. FACE_Road subsequently raises the expected scrap and rework rate by a factor of 1.4. In addition, it can also be expected that the preforming takes longer in time, so an additional 22 minutes of preforming are added. To reduce the effect on costs, a larger radius could be incorporated to the part, although this would require changes on the spoiler side as well, which weren’t considered in this study.

The very high bending angle is considered as second most important, design-based cost factor. It is a direct measurement for part complexity, as it accurately describes the three-dimensionality of the part.

The highest bending angle for a single layer can be found in the two front lugs of the CHF (see fig.5). An actual reduction of the bending angle can hardly be achieved without an interface change, when an integral solution is aimed for. The potential for cost reduction is very high in this area though, as an enormous amount of complexity could be taken out of the part when manufacturing of the front lugs is done separately and later joined via fasteners.

A differential design of the CHF with larger radii (6mm) and bolted-on front lugs (separate part, 8...
Fasteners) was optimized via FACE-RoaD cost optimization. The potential for cost optimization is higher than expected.

Figure 9: Cost distribution after optimization

Fig.9 shows the effect of two design changes which could have been incorporated in early design stages without much costs and had a severe impact on the later part costs. In comparison between fig. 8 and 9, the material costs rose due to the additional titanium fasteners, while the preforming time was reduced by about 7%. A lot of benefit came from the reduced scrap rate, which should be a clear target for an OEM anyway, which is why this approach is currently used on the Airbus A350 CHF development. In total, a part cost reduction of over 9% could be achieved.

In comparison to the actual process values (fig. 6), the optimized variant might not look as effective, but direct comparison is not valid in this case, as the serial production has undergone a learning curve over the six years of serial production, which is not incorporated in the software results.

5 Discussion and outlook

A manufacturing cost optimization on early design stages is a potent tool to reduce actual manufacturing costs. With a software algorithm approach, the individual biases can be reduced. It is demonstrated, that a limited set of input parameters can already aid certain design choices. Major limitation of cost based prediction systems in early design stages is the limited total figures of costs. Whilst the relative numbers are accurate enough to support design choices, an actual conclusion to part costs is not realistic at this stage. The main focus of further work will lie in the exact calibration of cost ratio factors, which shall allow more precise predictions, whilst keeping the input requirements low enough.

References


