PROCESS SELECTION OPTIMIZATION OF CFRP PARTS IN THE AEROSPACE INDUSTRY

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Abstract

A cost-based process selection tool for the predesign-stages of CFRP parts is developed and compared against decisions of experienced R&D engineers. It is shown that a limited set of input parameters can predict a suitable process, allows a ranking of different process types for a CFRP part, and can highlight major limitation points for certain processes. The tool is adaptable to specific companies, but needs calibration to given production facilities.

1 Introduction

Within the aerospace industry, freedom in part and process design is highly limited by external influences, such as strict industrial standards, laws and customer requirements.
Whenever an aerospace CFRP part has to be (re-)designed, a significant question is to find a suitable manufacturing process. Most often, this is decision is driven by company abilities and/or engineer experience. However, this doesn't necessarily have to lead to an optimal process selection, as company abilities shift over time, but engineers may also turn professionally-blinkered, which might or might not lead to a working solution. Chances to find an optimum solution tend to be generally higher with a neutral starting point though, which can then be adapted to manufacturers possibilities.
Existing cost prediction models (see chapter 2) often deliver accurate results on parts of the composite processing chain, but have limits in their significance for an industrial applier.

1.1 State of the art

During the last years, an enormous amount of scientific and industrial work has been published on the positive cost effects of CFRP parts on aircrafts. As a general conclusion, aerospace parts made out of CFRP tend to have higher production costs than their metallic counterparts [12], but, due to their mechanical advantages (weight, stiffness, dynamic strength etc.), they tend to become more effective in TCOs (total costs of ownership) in very large aircrafts due to higher payload and/or more efficient fuel consumption. This is proven by an increasing CFRP weight percentage on modern passenger aircraft (see fig.1).

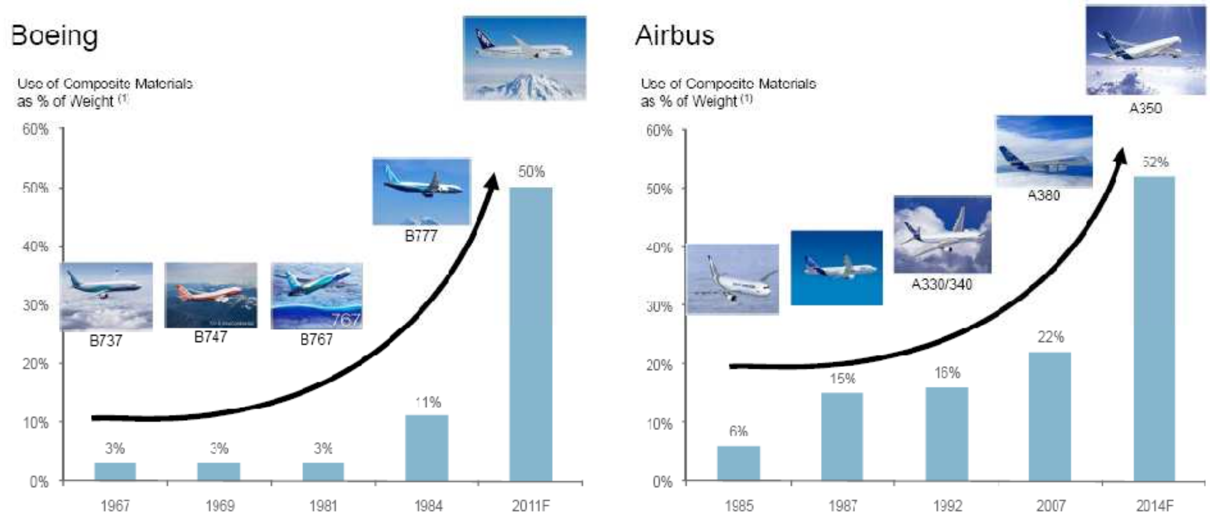

Figure 1: CFRP parts on passenger aircrafts as a weight percentage over time [4]

However, the higher costs of production have proven to be deal-breaking on smaller aircrafts (single aisle, business jets), as the market is highly competitive and the selling price is a major factor in the TCOs.

For an aerospace supplier specialized in the production of CFRP parts, it is therefore necessary to produce parts in an optimal process ("optimum" is usually defined cost-wise, as part quality, scrap rate and weight can be transferred to costs via given or estimated factors). In the aircraft industry, other influencing parameters as material selection are very limited, as all materials have to be aerospace and/or customer qualified, which limits not only the available material, but also the possible material suppliers severely [6].

A very important impact on the costs of CFRP aerospace parts is the non-destructive testing. By today's standards, almost 98% of all structurally loaded parts have to undergo non-destructive testing on a 100% scan rate[5]. In academic publications, this process step is often considered as equal in amount and therefore negligible in costs. For aerospace applications, this is not valid though, as different processes require a different level of detail in part testing, heavily depending on the existing experience with said process within aerospace industry, regulation authorities and the manufacturer. As NDT equipment is a fairly high investment, it often is a limiting factor for manufacturing output [5].

In addition, assembly costs can cause enormous cost raises due to complicated design (Fig. 2). As aerospace qualified workers hourly rates are fairly high, cost benefits can often be achieved by integrating part functions into a subpart, effectively reducing both assembly time and failure occasions.

In order to stay globally competitive with production sites in high-cost countries, it is inevitable to consider cost-optimized design and production at the very early stages of part design. Several cost models for CFRP parts have been developed since the 1970, but none of them seems suitable for very early design-cost estimations.

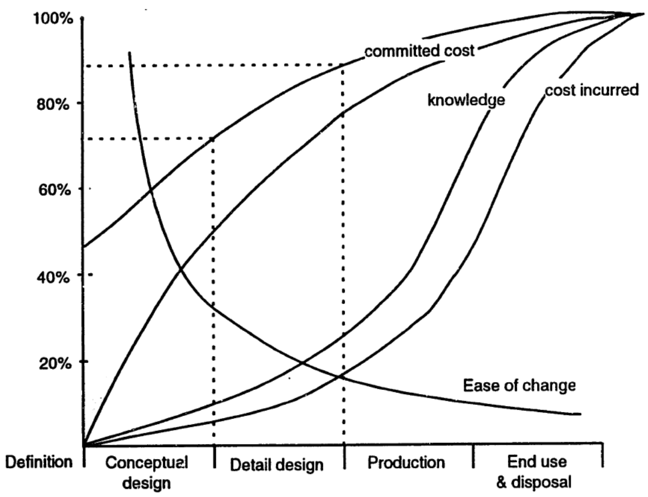

Figure 2: Cost incurrence and committal over a part development cycle [10]

1.2 Existing cost models

Existing cost models allow are often part specific, eg. for composite beams or wing-like structures [13], but there are some generic software tools available. Most of them allow to estimate costs along input parameters as part complexity and production steps, some allow process comparisons, hardly any include NDT.
Today's general models can be summed up in 3 major groups:

ACCEM (Advanced Composite Cost Estimation Model)
Developed in 1976 by Northrop Grumman, this model allows a fairly accurate cost estimation along a processing chain, by calculating time steps along industrial engineering standards and transferring them into cost units [8]. ACCEM can be seen as the benchmark for a widely accepted program, but it has limitations, such as missing support for different processes, ignorance of investment and inspection cost [3]. It does allow a certain degree of customization and fairly correct part geometries though.

First-order-model and its derivates
All cost models within this category are based on the theoretical work by T. Gutowski et al. in 1994. The model is based on the assumption, that part costs can be calculated as a linear equation of time steps for each process steps, which then are summed up to the total time of part processing [1]. In comparison to ACCEM, it is highly limited by its limitation to very general part geometries. Latest addition to this models are the support for other processing techniques and a user-friendly web interface [9].

Knowledge-based models
The third known major approach for cost estimation is based on existing knowledge. It basically determines critical part areas and compares it to an existing cost database, and estimates costs along comparable parts that are already in serial production. This type of model is often used within companies to transfer knowledge gains in predecessor projects to new developments [11]. Whilst being very accurate on known parts, its limits lie within its discrimination of unfamiliar processes.

An overview characterization of existing cost models can be found in table 1.

	RC	NRC	NDT	Assembly	user calibration	process variants
ACCEM	+	-	-	-	+/-	-
First order model	+	-	-	-	+/-	+
Knowledge based models	+	+	+/-	+	+/-	-

Table 1: Overview on benefits and limits of existing cost prediction models

Benchmarking of cost estimation models show that the margin of error between projected and real costs can be up to 30% [10]. From a manufacturer perspective, knowledge-based models seem to offer the highest potential, if a model can be created that allows accurate estimations for different processing techniques.

2 Theoretical approach

Most likely boundary conditions for an early design stage are a known envelope for the part, major force loadings and connection points. A preliminary design is usually not optimized regarding part costs, but the potential effect on cost optimization within this stage is significantly greater than anywhere else during part development and production.
For almost all parts within an aircraft, more than one manufacturing process is theoretically possible. Within the early design stage, a part can often be optimized to perfectly match a certain processing strategy. Therefore, an ideal pre-part cost estimator does not necessarily need to produce exact figures, but needs to highlight the best process for the current design, as well as to show major limitation on the follow up processes, which can potentially be reduced or eliminated by acceptable design changes. For R&D programs within FACC, an alpha version of a new model for early design stages has been developed (FACE_ROAD: **F**ACC **A**dvanced **C**ost **E**stimator for **R**esearch **O**r/**A**nd **D**evelopment projects).
This cost calculation sheet for R&D projects works with a limited set of input parameters, that allow a rough preselection along best-practice-standards within the aerospace industry (e.g. a 60m²-part is not suitable for RTM due to press limitations) and highlights the limiting factors for the follow-up process. A schematic flow chart can be seen in figure 3.

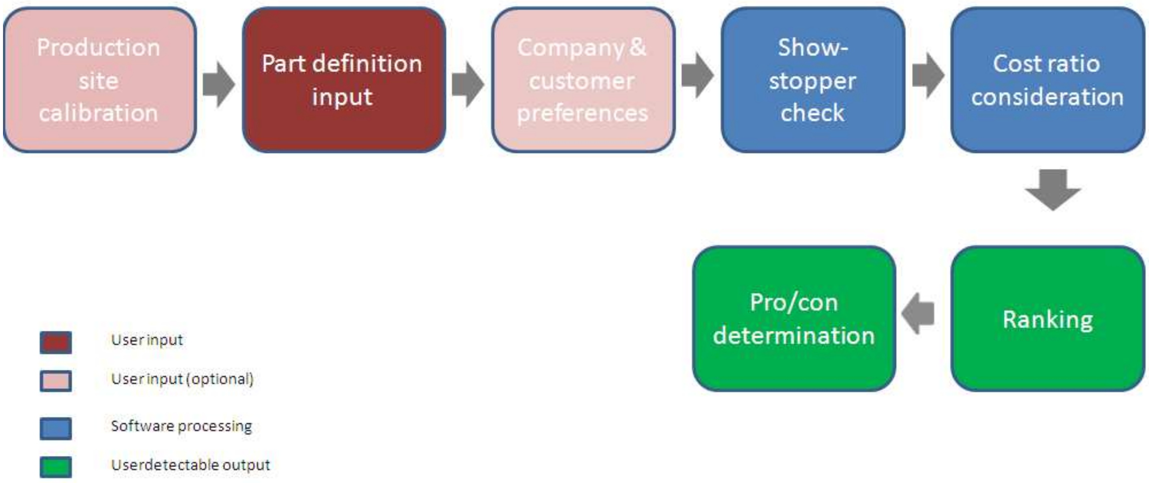

Figure 3: flow chart of FACC_ROAD

After literature study and expert interviews, a set of important influence factors for process selection for CFRP parts has been set up and integrated into an excel sheet. With input numbers from the user, the file automatically compares those inputs against technical, economic or company related limits. An excerpt of the input parameters can be found on table 2.

Process influence	Company influence	Customer influence list
part count per annum	experience	material qualification
projected area	autoclave availability	preferences
surface tolerances	press availability	cost expectations
minimum radii	tape laying avail.	qualification know-how
Curvature	preferences	
part tolerances	cost targets	
% of UD fibres		
tooling complexity		

Table 2: Influence parameters (excerpt)

Not all input parameters are hard-based facts. Limited know-how or non-existing hardware may eliminate a certain process, even if it might be an optimal solution for other manufacturers.
In order to achieve comparability between this range of various influences, the software model is based on cost ratios. Cost ratios are used fairly commonly within the aircraft industry to allow a comparison of typically not directly related characteristics of a part. Most widely known example would be cost-to-weight ratios. Cost-to-weight ratios are used mostly to determine whether if a lighter part is worth additional costs or not. Ctw-ratios can reach up to 1000€/kg and are a key factor for the success of CFRP reinforced parts in the aircraft industry, but are heavily depending on customer and certain part features.
Said cost ratios are available or can be calculated or negotiated for almost all part features and therefore are a viable comparison method. This allows FACE_ROAD to compare part designs and manufacturing methods very effectively, but, for accurate results, needs calibration on both manufacturer and customer.

3 Experimental work

During an ongoing research program, FACE_ROAD has been used to test a process selection that has been set by experienced process engineers.
The part is an annulus filler, that is used on large scale passenger jet engines to close the gap between two fan blades. Due to the part rotating with the fan blades, it is highly centrifugally loaded, whilst having to keep its shape to allow proper engine functioning (Fig. 4). A list of requirements and constraints (excerpt) can be found in table 3.

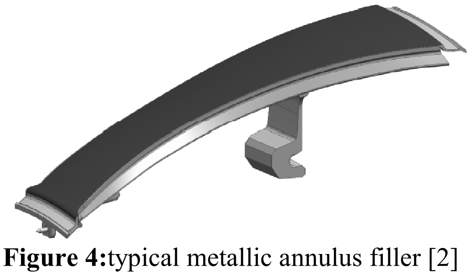

Figure 4:typical metallic annulus filler [2]

Annulus filler requirements		**Remarks**
part count	~1000 [P/a]	
projected area	~98000 [mm²]	
surface tolerances	very narrow	Balancing
minimum radii	3 [mm]	
Curvature	Double	
part tolerances	very narrow	Balancing
UD fibres	< 10%	Impact
tooling complexity	Medium	
material qualification	prepreg, RTM	Customer req.

Table 3: Constraints for an annulus filler [2],[5]

With said list of requirements, FACE_ROAD proposes manufacturing in RTM, with Out-of-Autoclave-Prepreg as runner up and conventional prepreg as close third.
This matches the decision of the project team, although conventional prepreg and OoA-prepeg change places due to personal experience (Fig. 5).

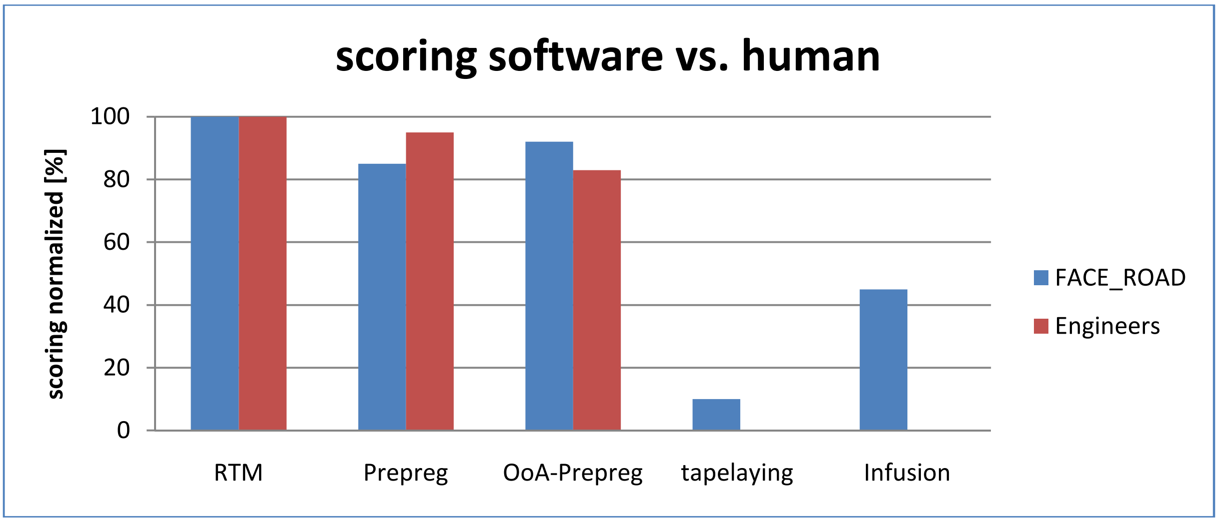

Figure 5: comparisons of processes software vs. human (normalized to 100%)

Main success point for RTM is the best tolerance behavior in part dimensions and surfaces. Its main issue is the high tooling costs, but this is reduced by the high part count.
Prepregs main advantage is the customer requirements, but the limited autoclave availability hinders its success. This is company specific though, and can be different on other manufacturers.
OoA-Prepregs prove to be almost equal to prepreg technically , but are limited in availability and aerospace qualification. It's main economic advantage, the avoidance of an autoclave, is reduced by the higher raw material costs.
Tape laying is hindered by geometry , as the part is too small to even consider automated tape laying.
Infusion has not been considered by the project team due to missing experience. Although not being perfectly matching this components needs, this case is an example for the necessity for a neutral advice.

5 Outlook

The program is currently in its early alpha stage. Whilst the input based concept seem to provide fairly realistic results, the quality of the input is still heavily depending on the user. An average subset of input data for comparison reasons will be created to reduce the human influence. The usability will be improved continuously.
Within a certain time frame, the project will allow quicker process preselection based on very early geometries, whilst allowing quick changes and highlighting possible improvements.
Within an ongoing R&D program, parts will be produced in different manufacturing techniques in order to benchmark the software results against real –life working conditions.

6 Acknowledgement

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