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A composite cost model for the aeronautical industry: Methodology and case study

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ABSTRACT

This paper presents a novel composite production cost estimation model. The strength of the model is its modular construction, allowing for easy implementation of different production methods and case studies. The cost model is exemplified by evaluating the costs of a generic aeronautical wing, consisting of skin, stiffeners and rib feet. Several common aeronautical manufacturing methods are studied. For studied structure, hand layup is the most cost-effective method for annual volumes of less than 150 structures per year. For higher production volumes automatic tape layup (ATL) followed by hot drape forming (HDF) is the most cost-effective choice.

1. Introduction

Lighter components and structures optimize resource use, both during production and product lifetime. Weight is especially important for vehicle and aeronautical adaptions as it governs the lifetime fuel consumption. There are several ways to decrease the weight of a component. One way would be to use a lightweight material, another would be to integrate several components into one and thereby eliminating weighty joints. Composite materials are lightweight and have high specific strengths compared to steel and aluminium. Furthermore, the manufacture of composite materials enables increased integration. The use of composite materials therefore addresses both of these strategies towards decreasing weight. However, the production of composite materials, as well as its raw material, is often expensive. The use of composite materials therefore ultimately presents a trade-off between potential weight save and higher production cost. Research has been devoted to this trade-off through multi-dimensional optimization [1], knowledge-based engineering [2] as well as the development of performance indices [3]. However, more focus on the estimation of production costs during the development phase of a composite structure is needed to further study the relationship between weight reduction and production cost.

The high manufacturing cost of a composite piece can be attributed to its processing complexity as it involves the combination of two essentially different materials into one coherent material. Moreover, the variability between manufacturing methods is high; ranging from resin-injection methods to traditional hand-layup, each implying different processing steps and parameters. The applicability of a certain manufacturing method is also a variable, dependent on component geometry and complexity as well as possible achievable mechanical properties. As a consequence of processing complexities mentioned above, the production cost is challenging to estimate and must be tailored to specific manufacturing and assembly method. Early research within composite production cost estimation [4,5], treats parts of the production chain of a general composite structure. A simple system to determine the manufacturability of a component is also introduced in Ref. [5]. These developed methodologies are generally applicable as both estimate cycle times related to certain levels of part complexity. More current research include [6–8]. First [6], proposes a model which can be used to compare differences in cost and weight of a compression moulded component made from either metal, composite or sandwich. Second [7], demonstrates a similar, if somewhat simplified, model where a component can be cost-estimated for different aeronautical manufacturing methods. Finally [8] presents a cost model to be used for comparing two different resin transfer moulding techniques, adapted to be used for the automobile industry. In addition [9], presents an interesting overview of aeronautical cost models and propose a model derived

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from these. None of these models determine manufacturability and only [6] and [9] introduce and scale production costs with increasing component complexity. With the presented limitations in mind the purpose of this paper is to present a new general production cost estimation model drawing from the strengths of each study previously mentioned. The model is set to be applicable in an early design stage of a general composite structure with involved composite parts being evaluated with respect to complexity and manufacturability. Also presented in this paper is a case study consisting of a cost evaluation of a typical wing box cover, representative for the aeronautical industry. The wing box cover contains components of different sizes and complexities, including a large skin, long curved stiffeners and several shorter curved rib feet. This mix of components makes the cost analysis interesting also for individuals outside of the aeronautical industry.

2. Strategic assumptions

The processing methods presented in this paper are those common to the aeronautical industry today. The model is focused on high-performing structures and considered material system is carbon fibre reinforced epoxy prepreg. Furthermore, production costs are modelled from scratch meaning all machinery and tooling are considered as new acquisitions. Another assumption is that the weight of the considered structure is the same regardless of chosen production method. In reality final weight will differ between production method according to achievable quality. Some costs involved in studied processes are not included in this paper. First, non-recurring costs of product development, test and certification are not considered in this paper as studied manufacturing methods are assumed to be equally mature and their costs of similar size. Second, recurring costs due to final part testing, NDT, as well as resulting repair, concessions and scrapping of parts are also not considered in this paper as these costs are future work. Finally, the assumption that studied processes are of equal maturity also supports the final assumption; that involved costs due to non-value added process steps are of similar size. In presented comparative study, specific non-value added process steps are therefore of lesser importance.

3. The cost model

The production cost of a structure is calculated by summarizing the costs of each process step involved in chosen manufacture and assembly method. For the methodology to be generic the costs of the process steps involved is a function of structure geometry, see Fig. 1. This is done through the use of a structure complexity measure that allows the estimation of the process production time as well as governs producibility limits. Necessary input data are structure geometry, through a standard CAD STEP file, and production data which includes facility properties such as number of days of active production and sought annual manufacturing volume. The number of active production days also reflect days of downtime for instance due to maintenance or other, from a lean-perspective, wasted operations. The model is implemented using the open-source programming language Python [10].

3.1. Geometry complexity

The process cycle time and producibility of a part is dictated by its geometry. It is therefore necessary to connect the part geometry with its production. This is done through defining a measure of part complexity, derived from the basic method of composite manufacture. Composite manufacturing methods are mostly additive, meaning that the process involves placing and draping of fibre tows or prepreg sheets. The behaviour necessary to record is therefore different types of forming. To describe the act of forming, the process difficulty is assumed to follow the added difficulty due to the drape of individual features. To accurately describe forming, all forming mechanisms such as fibre bending, shear and in some cases ply sliding, would need to be taken into account. However, a first approach is used in this paper, which only includes the forming due to in-plane fibre bending, normally including some degree of shear, and out-of plane fibre bending. The simplified approach, using fibre bending and the geometry curvature as the basis of the geometry features defined in this paper, means that further calibration towards experimental data is necessary to give the full picture of forming. It is further important to note that layup strategies differ greatly between operators and laydown time depends on unexpected material properties such as tack. These issues again show the importance of matching the theoretical model with experimental data.

A CAD-solid can be defined by bounded 2D-surfaces. Complex 2D-surfaces need to be split into several sub-surfaces that together describe the full surface. Each such sub-surface is here referred to as a *face*. The complexity features are determined for each face of a part. Defined complexity features are the *face fibre bending angle*, *face curvature radius* and *overall face curvature degree*. The *face fibre bending angle* is defined as $\theta_{face} = max(\theta_{IC}, \theta_{NF})$, where θ_{IC} is the curvature inside a face defined as the largest angle difference between the centre face normal, $\hat{n}$, and the two centre edge face normals, $\hat{n}_{E_i}$; see Fig. 4. The neighbour to face angle, θ_{NF}, is defined as the most severe angle difference between the centre normal of the face and its neighbour faces; see Fig. 4. Neighbour to face angles close to 90° are treated as outer edges of a part. This definition is chosen as angular transitions to be formed generally are designed with either a radius or a chamfer, lowering the neighbour to face angle to below that of a right angle. The *face curvature radius* of the face fibre bending angle is calculated using the curvature–radius relationship $r_\kappa = \frac{1}{\kappa}$ of the curvature κ, using either the internal face centre or the neighbouring face centre depending on chosen face fibre bending angle. The *overall face curvature degree* is either single curved or double curved where a c-spar illustrates the latter. A double curved face increase the manufacturing difficulty as it involves distorting a prepreg in two directions. A double curved face is in this paper considered to represent a doubled manufacturing difficulty, as shown by evaluated data within the Australian composite industry [11].

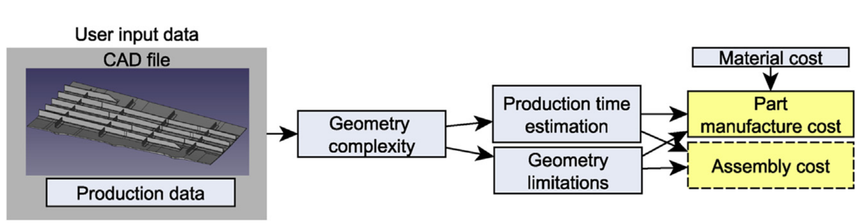

Fig. 1. Composite cost model flow and hierarchy.