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Estimation of production cost in an early design stage of CFRP lightweight structures

Berend Denkena[a], Peter Horst[b], Carsten Schmidt[a], Matthias Behr[a,]*, Joscha Krieglsteiner[b]

[a]*Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Ottenbecker Damm 12, 21684 Stade, Germany*
[b]*Institute of Aircraft Design and Lightweight Structures, Technische Universität Braunschweig, Ottenbecker Damm 12, 21684 Stade, Germany*

* Corresponding author. Tel.: +49-4141-77638-21; Fax: +49-4141-77638-10. *E-mail address:* behr@ifw.uni-hannover.de

Abstract

Development of composite structure which are both light and economically competitive is challenging. A new method for the development of CRFP lightweight structures implements a frequent interaction of design and production planning starting in an early design stage. As part of this, production alternatives need to be compared in terms of cost and impact on structural mass. This paper describes how a software module automatically determines suitable process chains based on a preliminary structural design. Cost of production is estimated using analytical process models dealing with imprecise design information. Applied to an aircraft fuselage panel, the method estimates cost and mass of different production alternatives.

Keywords: Production; Development; Methodology; Design method; Planning; Composite

1. Introduction

The use of carbon-fiber-reinforced plastics (CFRP) in lightweight structures has increased in the last years, especially in aviation [1]. Entering a market of high-rate serial production, manufacturing cost gained importance in CFRP-related research. Besides specific developments in the single disciplines of structural design, materials, and production, a demand for new solutions for interdisciplinary problems can be observed. In the research project “High Performance Production of CFRP Structures” (HP CFK), the universities of Brunswick, Clausthal, and Hanover formed a research cooperation focusing on these problems. One of the group’s fields of investigation is the methodology of product development and production planning.

While methods for the design of CFRP-structures as well as methods for the planning of their production have been subject to research in industry and academia, the interaction of both fields is hardly covered. As conventional development procedures do not account for the particularly high interdependence of both disciplines in the case of CFRP-structures, a method for the systematic interaction of product development and production planning is required.

In the context of HP CFK, a development method was designed to coordinate a frequent interaction of both disciplines throughout the development stages [2]. Aiming at an automated process, a software environment and a data model were created to serve the needs of the different perspectives on the product. This contribution focusses on the estimation of production cost in the context of this automated development process.

2. Development method

The method targets the development of lightweight structures that are efficiently producible by coordinating the interaction of both disciplines from an early design stage on. It is based on the classical product development approach described in VDI 2221 [3] and the production planning phases described in [4] (see fig. 1).

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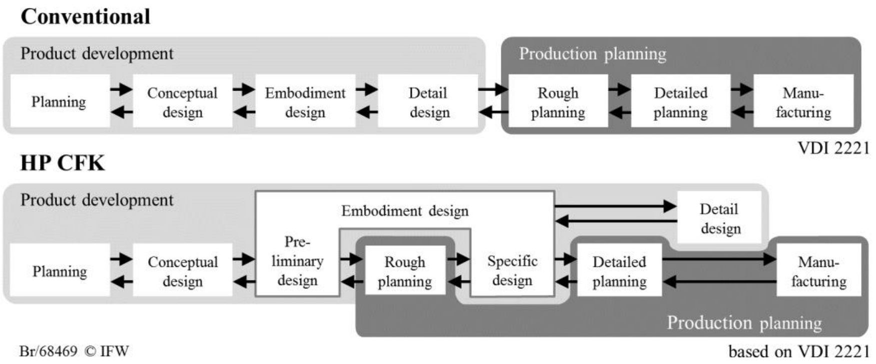

Fig. 1. Development: Conventional and HP CFK approach

In the conventional procedure, a first interaction of both disciplines is intended to take place not earlier than after the last phase of product development. Thus, production feedback to earlier design stages is very costly. The HP CFK approach, however, intends structural design, materials, and manufacturing technology to interact more efficiently throughout development and production of CFRP-structures. It ensures a frequent interaction starting at an early stage. The embodiment design phase is split into a preliminary and a specific design phase. These phases enclose the rough production planning phase. First, this allows an interdisciplinary concept definition, and second, it enables the phases of specific design and detailed planning to interact directly. These two changes are considered the key elements of improvement in this approach.

The following chapters take a closer look at single phases. An example structure is used to explain the different steps more vividly. According to the focus of this contribution, the rough production planning phase is shown in detail while the activities on the product development side are only described briefly. Phases following the specific design are not described here.

2.1. Planning

During the planning phase, the requirements for the product to be developed and the framework for its production are collected and analysed. As a sample development task, a panel is defined in the side section in the rear of an aircraft fuselage (see fig. 2). It is chosen to help understand the activities of the following steps. Its position and dimensions are not taken from any existing aircraft sub-structuring concept. Window and door cut-outs are not respected.

Fig. 2. Aircraft fuselage side view with panel

A set of design criteria is defined covering different failure phenomena (strength, residual strength, stability). The panel is required to withstand a set of load cases derived from typical flight conditions without violating any of these criteria.

The production scenario is the planning of a new production with no existing resources and with the presented side panel being the only product. The assumptions for this scenario are presented in table 1.

Table 1. Assumptions of the production scenario

Assumption	Value	Symbol	Unit
Units per year	720	n^{annual}	
Shifts per day	3	n^{shift}	
Shift duration	7	t^{shift}	h
Work days per year	250	$n^{workdays}$	days
Depreciation period	10	$t^{depreciation}$	years
Imputed interest rate	6	I	%
Hourly rate of worker	50	R	€
Facility cost with air-condition	15		€/m²
Facility cost without air-condition	8		€/m²

2.2. Conceptual design

In this phase, different solution concepts are created and compared. For the given example, this step is skipped and the panel is assumed to be stiffened by a typical stringer-frame-layout (see table 2) with the frames connected to the skin via clips. A common part strategy is applied so all stringers are of identical geometry and material. The same applies to the frames and clips. For the following embodiment design phase, laminates and profile dimensions are defined as variable.

Table 2. Structure concept definition

	Frames	Stringers	Skin
Pitch	540	220	-
Profile geometry	C	Omega	-
Profile dimensions	variable	variable	-
Laminate	variable	variable	variable

2.3. Preliminary design

Prior to all definitions of the production, the concept solution goes through a preliminary design phase. Due to the lacking production definition at this point, it is not possible to use adjusted material properties. Therefore, material is assumed to be on the higher end of the spectrum of available production quality. Furthermore, the mass of design elements for joining the different substructures of the panel are not taken into account at this point.

For the sizing of the structure, the methods implemented in the design environment are used. The result is stored in the earlier developed data model holding information about product structure, part geometry, and materials. The sample structure is depicted in fig. 3.

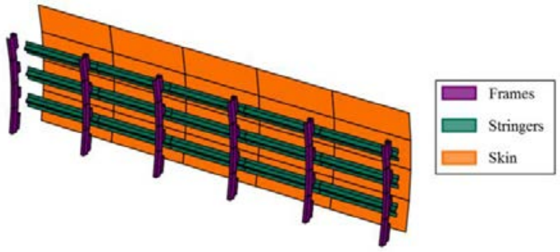

Fig. 3. Panel after preliminary design (exploded view)

2.4. Rough production planning

Input for the rough production planning phase is a preliminary design of the panel, based on which a production is planned on process level. Describing the production on process level, instead of the more specific machine level, allows a more general evaluation of the production. This is considered the appropriate approach for this early development stage. The achievable precision of the machine level is not needed in this development stage and can be added later in the course of a production concepts' evaluation. The goal of the rough planning phase is to provide a set of valid, alternative process chain definitions and their respective estimated costs. Further, the influence of the process history on material characteristics is described, and design restrictions for the following specific design phase are derived.

In the example, the planning considers only the main processes of the production, necessary preparation processes, e. g. vacuum bagging, are not included. The following processes are considered:

- Autoclave
- Automated fibre placement (AFP)
- Automated tape laying (ATL)
- Manual draping
- Profile forming
- Resin transfer moulding (RTM)
- Surface forming
- Vacuum assisted resin infusion (VARI)

For the implementation of the panels' assembly tasks, the following joining methods are considered: adhesive bonding, co-bonding, co-curing, and riveting.

The rough production planning consists of six sub-steps (fig. 4), of which the first three set up a production concept and the last three are used to estimate the production cost. These sub-steps are explained in the following sections.

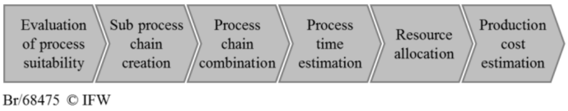

Fig. 4. Steps of the rough planning phase

2.4.1. Evaluation of process suitability

For each possible combination of structural component and process, the suitability is evaluated prior to the actual process chain creation. The evaluation is based on exclusion criteria. These criteria represent process-specific geometric restrictions, which the dimensions of the pre-designed part are checked to comply with. The same geometric restrictions are used to define allowable limits for part dimensions in later design phases. Processes that do not fulfill all exclusion criteria are not suitable for the production of this component.

Economic criteria do not apply here because the production costs are unknown at this point and are evaluated for the entire production later on.

In this example, only the maximum length and width of a component are used as exclusion criteria. All eight processes of this example are suitable to handle the components of the panel.

2.4.2. Sub process chain creation

A sub process chain represents the production of a single component. To create all possible sub process chains, the suitable processes are combined independently for each component. They consist of the five fundamental procedural steps of impregnation, layup, forming, consolidation, and curing. A sub process chain is complete if all five steps are included.

The procedural steps occur in two typical sequences. One is characteristic for prepreg technologies and the other one for infusion technologies (see fig. 5).

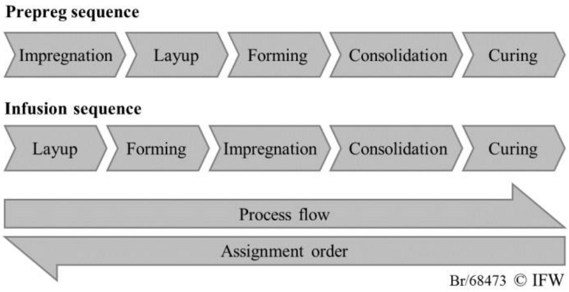

Fig. 5. Typical procedural step sequences for CFRP with thermoset matrix material

Each single process is able to cover at least one procedural step or more and fits in one or both of the sequences. The processes are assigned in reverse order starting with curing as the final procedural step and continue along the sequence until the assigned processes in the sub chain cover all five procedural steps. For the considered components and processes, this step leads to 15 different sub process chains.

2.4.3. Process chain combination

The components are combined by using different joining methods. Four joining methods are considered. Riveting and adhesive bonding require both joining partners fully cured. In contrast to this, for co-curing, both partners have to be in a pre-cured state. The two components share the curing process and form one rigid part. For co-bonding, one component has to be in cured state while the other one is still pre-cured. Depending on the used joining method, the topology of the resulting process chain changes. The product structure defined during preliminary design holds information about chronical order and involved components for each joining step. The sub process chains are combined in a full-factorial pattern.

In the sample structure, stingers and frames are assumed to be common parts. Common parts share their sub process chains and use the same joining method. Therefore, all stingers and all frames are treated like one single component but with increased quantity during the process combination. The maximum number of possible process chains n^{chains} depends on the number of sub process chains s, the number of individual components m, and the number of suitable joining methods j.

$$n^{\mathrm{chains}} = \prod_{i=1}^{m} s_i \cdot \prod_{k=1}^{m-1} j_k \qquad (1)$$

This results in 54,000 possible process chains for the production of the panel. One example is shown in fig. 6.

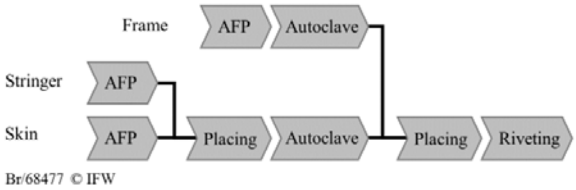

Fig. 6. Example process chain with co-curing and riveting as joining method

2.4.4. Process time estimation

Process time is an important factor for the resulting production cost and the number of required resources. It is estimated using analytical models and typical values for machine properties of the particular process. For most processes, the process time is equal to the lead time of the component. In some cases, however, multiple components are involved, e. g. in the placing process. In these cases, the lead time is the sum of the individual process times.

For VARI and RTM processes, a formula based on Darcy's law is used to estimate the infusion time. It is assumed that a point shaped inlet gate is used with a constant inlet pressure p_0. It is also assumed that the viscosity μ and the permeability K are constant and an isotropic material is used. With these assumptions, the time to infuse a circular area t^{infusion} can be calculated as presented in equation 2 [5].

$$t^{\mathrm{infusion}} = \frac{\phi\mu}{4K(p_{out} - p_0)}\left(r_{equ}^2\left(2\ln\left(\frac{r_{equ}}{r_0}\right) - 1\right) + r_0^2\right) \qquad (2)$$

Because the components are not circular shaped, the radius r_{equ} of a circle that has the same area as the component is calculated. The described values and the outlet pressure p_{out}, porosity ϕ, and inlet radius r_0 are set to typical values. For the RTM process, a curing time is added, which depends on the used resin.

The process time of the autoclave is only dependent on the defined curing cycle of the resin and on the machine parameters. It is calculated as the sum of the following times:

- Heat up time to holding temperature (if needed)
- Time at holding temperature (if needed)
- Heat up time to curing temperature
- Time at curing temperature
- Cool down time

The process time for the manual draping process depends on the component's surface and its thickness. An average number of layers is calculated, and it is assumed that the component is entirely covered with this number of layer. This number is multiplied by the time per layer to receive the process time. The time per layer is set to a constant value for components up to an area of 100 mm². For larger components the time is increasing linearly.

A fixed deposition rate is the basis for the model of the adhesive bonding process time, which therefore is proportionally dependent on the length of the component. The model for the riveting process is also related to the component's length. The assumed number of rivets, which is proportional to the component's length, is multiplied by the needed time per rivet. In the placing process model, a base time for each component is used and complemented with a time constant proportional to the component's length.

The process times of profile and surface forming processes are assumed to have no dependencies on the component's geometry and therefore have a fixed process time.

The models of the AFP and ATL processes use an approximation function for the process time estimation, which calculates the time per layer. The surface and perimeter of the component and process parameters are the inputs of this function. The following process parameters are used:

- Acceleration
- Layup speed
- Cutting speed
- Speed without layup
- Time to rotate the layup head 180°
- Setting and lift-off time
- Tow or tape width
- Number of tows (only for AFP)

To build the approximation function, a simulation model was developed, which for simplicity reasons takes the component's contour as a two dimensional polygonal line and features the mentioned process parameters. Within the simulation, the individual tows or tapes are generated. Based on their geometry, the course of the laying head is determined (see fig. 7). Within the next calculation, the machine-specific velocity profile and process time are calculated.

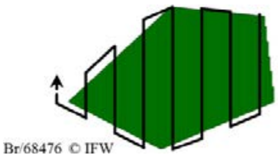

Fig. 7. Geometry example with generated tows and course of the laying head

A set of 1000 random geometries was used to fit the approximation function for the AFP process and a set 2000 geometries for the ATL process. Each geometry was simulated with a layup of four layers [0, 90, ±45] and for 50746 sets of process parameters. The time per layer is approximated and neglects the fiber orientation. For an independent set of 200 geometries with identical layup and typical process parameters, the approximation function has an average failure of 2.9 % and a maximum failure of 6.9 %.

The average number of layers is calculated, and it is assumed that the component is fully covered with this number of layer. The process time results from a multiplication of the average number of layers and the approximated time per layer. At the end of this step, all process times and lead times are available for the use in the following steps.

2.4.5. Resource allocation

Production resources are necessary for the calculation of the production cost. At this point, the considered resources are machines, toolings, and workers. Based on the process times, the lead times, and the amount of units per year, the required time per year on each resource can be determined. The available time per year $t^{available}$ of each resource is calculated as presented in equation 3.

$$t^{available} = n^{workdays} \cdot n^{shift} \cdot t^{shift} \cdot a^{tech} \qquad (3)$$

The technical availability a^{tech} is a resource specific value, and the remaining values are given in the production scenario. The necessary number of each resource can be derived from the required and the available resource time per year.

2.4.6. Production cost estimation

The estimated production cost $c^{production}$ consists of manufacturing and material costs of each component as presented in equation 4.

$$c^{production} = \sum_{i=1}^{N} \sum_{k=1}^{P} c_{i,k}^{process} + c_i^{material} \qquad (4)$$

N is the number of components in the considered panel and P the number of processes which the component is involved in. $c_{i,k}^{process}$ represents the costs for component i caused by process k. $c_i^{material}$ represents the material costs for component i. The process cost estimation is presented in equation 5. R represents the hourly rate of the individual resource, $n^{parallel}$ the number of simultaneously produced components, $t^{process}$ the process time, and t^{lead} the lead time of the component. M represents the number of machines working on the component, W the number of involved workers and T the number of toolings used for the component.

$$c^{process} = \sum_{i=1}^{M} \frac{R_i \cdot t^{process}}{n^{parallel}} + \sum_{j=1}^{W} \frac{R_j \cdot t^{process}}{n^{parallel}} + \sum_{k=1}^{T} R_k \cdot t^{lead} \qquad (5)$$

The hourly rate of a worker is given in the production scenario. For machines and toolings, it is estimated by the quotient of the annual cost of the resource c^{annual} and the time they are required per year $t^{required}$. As the panel is assumed to be the only product, no resources can be shared with the production of other parts. Therefore, the required time is taken instead of the available time.

$$r = \frac{c^{annual}}{t^{required}} \qquad (6)$$

The calculation of the annual cost for a machine is presented in equation 7.

$$c^{annual} = c^{depreciation} + c^{interest} + c^{maintanance} + c^{facility} \qquad (7)$$

A linearly imputed depreciation $c^{depreciation}$ of the purchase price $P^{purchase}$ over the depreciation period $t^{depreciation}$ is assumed.

$$c^{depreciation} = \frac{P^{purchase}}{t^{depreciation}} \qquad (8)$$

The purchase price is assumed to depend on the resource size and for toolings on process requirements additionally. The imputed interest cost $c^{interest}$ is equally distributed over the depreciation period with a given annual interest rate I from the production scenario.

$$c^{interest} = \frac{P^{purchase} \cdot I}{2} \qquad (9)$$

The annual maintenance cost $c^{maintenance}$ is assumed to be 5 % of the purchase price. The annual cost of the facility depends on the required floor space and the required climatic conditions for the process. Corresponding facility costs per square meter are given in the production scenario. For the annual cost of a tooling, maintenance and facility costs are neglected.

2.5. Specific design

During the specific design phase, the development method intends the sizing modules of the design environment to be applied to the structure again. The difference now is that the concept definition has been extended on the production side during the previous planning phase. Assumptions that were used during the preliminary design phase can now be substituted by production-specific parameters. Further, the effect on material properties is derived.

In the example, material properties are updated, by applicating analytical models [6], based on fiber volume content typically resulting from the respective manufacturing processes [7,8] (see table 3).

Table 3. Assumed fiber volume content resulting from manufacturing processes

Process	Fiber volume content
Prepreg/autoclave	60 %
RTM	55 %
VARI	50 %

Further, production-specific layer thicknesses are used during this phase. For the mass calculations, additional masses resulting from the respective joints are respected.

The method plans this phase to be followed by the phase of detailed production planning. The detailed definitions in both domains are found iteratively at the interface of both phases. In the example, however, only a single sizing iteration was performed with the updated material properties.

The following phases are not described here.

3. Results

A variety of production alternatives was created and analyzed with the presented method. For each solution, cost per panel area and relative mass compared to the mass after preliminary design are shown in figure 8. Maximum deviations of more than 50 % of the mean value 2179 €/m² show the strong influence that process selection has on production cost. All production-specific solutions have increased mass compared to the preliminary design (mean value + 9 %). This was expected due to the optimistic assumptions of material properties made in the preliminary design phase. Additional mass is contributed by the joining methods.

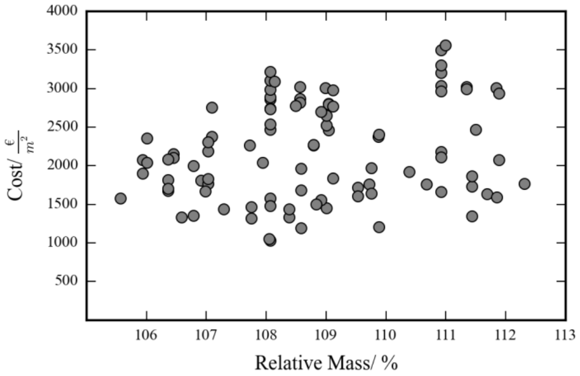

Figure 8. Production-specific panel designs rated by cost per panel area and mass compared to the preliminary design

4. Conclusion and Outlook

In the context of the development of an automated design process, a new method was presented to cover the crucial steps of creating and analyzing alternative production concepts. This is done on the basis of production processes while an evaluation on the basis of machines is to be developed in the future. Additional preparation process steps, e. g. the application of vacuum foil, will be accounted for in later versions of this module. The results for a sample structure show a strong variation of production cost for different process chains. Still, the significance of the results has to be proven. The dependence of material properties on their process history will be modeled in more detail and with respect to local geometries, e. g. misalignment of fibers on different scales, voids, and gaps. For the example, designs just went through a single sizing iteration with production-specific material properties. This adoption is to be extended to an iterative process alternating between the two domains of structural design and production planning. Further, more sophisticated modules for detailed modelling, analysis and design will be used in later iterations of this process.

The automated creation of production alternatives leads to a huge number of concepts for the small sample structure. Larger structures with more complex product structures and different structural design concepts will further increase the number of different concepts to be assessed. A new approach here questions that a concept has to go through all iterations of the detail design phases before it is compared to others. Instead, a multitude of concepts proceeds through each iteration simultaneously and is compared afterwards. To reduce the development effort, only the most promising concepts are selected to be further worked on in the following iterations. This approach is being worked on in the project “Integrated method for process planning and structural design of composite structures” (DE 447/145-1 and HO 2122/26-1) funded by German Research Foundation (DFG).

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