Systematic Process Chain Creation for CFRP Structures in Early Product Development Stages
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Abstract. A planning method is presented which allows to systematically building process chains based on a preliminary design of composite structures. The method utilises the specific sequences of procedural steps that occur in the production of carbon fibre reinforced plastic (CFRP) structures, to build sub process chains for each component of the structure. Process restrictions are considered to evaluate the suitability of different production processes. To obtain the whole process chain of the structure, different joining methods are applied in addition to combine the components and its sub process chains. The results of the presented method are used in an overarching development procedure to investigate resulting impacts on the solution. Possible impacts could be the production costs or the material characteristics.

Introduction

CFRP, as an enabler for weight reduction and efficient energy use, becoming more important in different industries. Studies show that the usage of CFRP material for lightweight structures will increase further in the future, especially in the aerospace industry [1]. To make the full potential of the material available in a broad range of application, efficient and integrated methods for the product development and the production planning are necessary [2].

There are very well structured and detailed production planning methods available for metal structures, which supports an interaction with the product development and a systematic process chain development. Fallböhmer for example uses technology classes and geometrical features to build process chains [3]. Instead of technology classes, Müller uses a product-technology-matrix, but he also relays on standardized geometrical features [4]. These features are not present in CFRP structures, which is why the methods could not be adapted easily for composite structures. This is hindered in addition due to some fundamental differing characteristics of the production methods of both material classes. For metal structures, manufacturing usually starts with semi-finished parts that have material properties mostly set as in the final product. The part is produced in sequences of features that can mostly be manufactured independently. For composite structures, the manufacturing processes mainly determine the material properties. Properties such as fibre volume content or fibre orientation have a huge impact on resulting mechanical properties. Usually each of the manufacturing processes affects the entire part and its mechanical characteristic. To consider these differences, specialised methods for composites were developed. Wille et al. focuses on the interdependencies between product design and manufacturing processes in an early design phase [5]. For a given process chain, the structure is optimized with regard to the processes and the desired mechanical properties. Numerical simulations are used to optimise the process parameters regarding the structural design. The work of Scholz-Reiter and Lütjen cover the modelling and the evaluation of composite manufacturing, but they also assume a given process chain [6].

Methods that are more general are known, like e. g. Simultaneous Engineering which purposes an increased interaction and parallelization of commonly consecutive organized task of the development process [7]. However, these methods do not specify detailed procedures for a practical
implementation. At this time, there is no suitable systematic approach available to build process chains for CFRP structures and its manufacturing processes in early product development stages.

**Product Development Method**

In the research project “High Performance Production of CFRP Structures” (HP CFK), a methodology is being developed for structural design, materials, and manufacturing technology to interact more efficiently throughout development and production of CFRP structures. In this context, a new procedure for the interaction of product development and production planning at an early design stage was developed. This procedure is based on the classical product development approach described in VDI 2221 [8] and the production planning phases described in [9] (see Fig. 1).

**Conventional**

<table>
<thead>
<tr>
<th>Product development</th>
<th>Production planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Rough planning</td>
</tr>
<tr>
<td>Conceptual design</td>
<td>Detailed planning</td>
</tr>
<tr>
<td>Embodiment design</td>
<td>Manufacturing</td>
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<tr>
<td>Detail design</td>
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**HP CFK**

<table>
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<td>Planning</td>
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<tr>
<td>Conceptual design</td>
<td>Specific design</td>
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<tr>
<td>Preliminary design</td>
<td>Detailed planning</td>
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<tr>
<td>Embodiment design</td>
<td>Manufacturing</td>
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<tr>
<td>Detail design</td>
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</tr>
</tbody>
</table>

Based on VDI 2221

**Figure 1:** Product development procedures: Conventional and HP CFK approach.

In this new procedure, the embodiment design phase is split into a preliminary and a specific design phase. These phases enclose the rough production planning phase, in which the here presented planning method is applied. The rough planning consists of several steps (see Fig. 2), where the first three representing the here described planning method for creating process chains.

**Figure 2:** Steps of the rough planning phase highlighted the presented steps.

Input of the method is a preliminary design of a structure, which at this point of time does not include all geometrical details and assume the best available material quality without any further imperfections. The structure could be an assembly or a single part. The information of the structure are stored in an in house developed data model which holding information about product structure, part geometry description, and materials. The method uses this information to build up all possible process chains, hand them over to the following process time and cost estimation of the rough planning phase. With the here estimated costs and estimated impact on structural mass promising solutions are identified and hand over to the subsequent specific design phase. The embodiment design will then be finalized through a structure optimization with respect to defined requirements and manufacturing restrictions derived from selected process chains.
Planning Method

The method consists of three steps. The first step is the evaluation of the process suitability in context of the given preliminary design. Sub process chains for each sub component are created out of suitable processes in the second step. At this time, there are only thermoset technologies available but this can be advanced to other material technologies easily. In the last step, the sub components and its sub process chains are combined using different joining methods to complete the process chain. These steps have been mainly implemented in python™ and integrated in the overall development process and will be explained in the following.

Evaluation of the Process Suitability. Before the actual process chain creation can be conducted, the suitability is evaluated for each possible combination of structural component and process. Multiple exclusion criteria are used for this evaluation, describing process-specific geometric restrictions. There are quantitative criteria like e. g. the possible part length and width that can be compared directly and there are qualitative criteria like e. g. the capability of a process to produce a hollow structure or an undercut. Economic criteria are not applied here, because the production costs and time are evaluated for the entire structure and suitable production scenario subsequent to this evaluation.

Geometric process restrictions are defined within the preliminary design and cannot be changed through the specific design phase. Processes that do not fulfill an exclusion criterion are assumed not suitable for this component. Because these criteria excludes processes at an early development stage, the criteria have to be chosen carefully so no possibly promising process is excluded. The part size, for example, is assumed as package dimensions around the component, which can be derived from the data model. This is compared to the possible part size of available machines that can perform the process. If the size of a component is bigger than the possible part size of the process, this combination is excluded from further considerations.

All further process restrictions are addressed in the specific design phase, because these restrictions can cause a design change in the specific design phase, but they do not make it impossible to manufacture a component with the specific process. The result of this planning step are lists of suitable processes for the production of every single component of the structure.

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. A sub process chain is complete if all five fundamental procedural steps to manufacture a composite component are included. These procedural steps for composites with thermoset matrix material are impregnation, layup, forming, consolidation and curing. Necessary preparation processes like e. g. vacuum bagging have to be added afterwards, because they could possibly effect more than one component of the structure. Processes, which are added to shorten the lead time or improve the economic efficiency are treated likewise.

Each process is capable to cover one or more procedural steps (see Table 1). Some processes, which are covering multiple steps, are able to perform one of their steps separately (for example the manual draping process) whereas other have to perform all steps together (for example the autoclave process). In this example, the amount of processes is limited to achieve clarity.

The automated fibre placement (AFP) process and automated tape laying (ATL) process are widely used in the aerospace industry and known for achieving high fibre volume content. The manual draping is also commonly used in aerospace industry, mostly for complex parts. These three processes are capable to perform the layup step direct into the final geometry or produce a flat laminate for a following forming process. The prepreg production is normally done by a supplier and prepregs are purchased as semi-finished products. For the impregnation of large complex structures, typically with low quantities, the vacuum assisted resin infusion (VARI) process is an appropriate process. In contrast to this, the resin transfer moulding (RTM) process is normally used for high quantities and smaller structures. The consolidation and curing are simultaneous performed by the autoclave process.
Table 1: Capability of considered processes to cover procedural steps and allocation to process routes.

<table>
<thead>
<tr>
<th></th>
<th>Layup</th>
<th>Forming</th>
<th>Impregnation</th>
<th>Consolidation</th>
<th>Curing</th>
<th>Process route</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFP</td>
<td>●,○</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>Prepreg</td>
</tr>
<tr>
<td>ATL</td>
<td>●,○</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>Prepreg</td>
</tr>
<tr>
<td>Manual draping</td>
<td>●,○</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>Prepreg/Infusion</td>
</tr>
<tr>
<td>Forming</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prepreg/Infusion</td>
</tr>
<tr>
<td>Prepreg production</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td>Prepreg</td>
</tr>
<tr>
<td>VARI</td>
<td>●</td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td>Infusion</td>
</tr>
<tr>
<td>RTM</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
<td>Infusion</td>
</tr>
<tr>
<td>Autoclave</td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>Prepreg/Infusion</td>
</tr>
</tbody>
</table>

● possible procedural steps of the process
○ single step possible

The procedural steps occur in two sequences. One is utilizing prepreg technologies and the other one is utilizing infusion technologies (see Fig. 3). An equivalent set of steps and process routes is applicable for thermoplastic matrix materials.

**Prepreg sequence**

1. Impregnation
2. Layup
3. Forming
4. Consolidation
5. Curing

**Infusion sequence**

1. Layup
2. Forming
3. Impregnation
4. Consolidation
5. Curing

Figure 3: Possible procedural steps sequences for CFRP with thermoset matrix material.

The processes can fit in one or both of the sequences. They are assigned starting with the last procedural step. For each sequence, the sub process chains are created independently. If, for example, curing is to be done via an autoclave process, the steps of curing and consolidation are prearranged and so the next step to assign will be the infusion or forming step, depending on the choice of material. This will continue until the assigned processes in the sub chain cover all five procedural steps.
Lists of possible sub process chains for each component are the result of this step. With this set of the here mentioned processes, theoretically every component has at most ten possible sub process chains, if all considered processes are evaluated as suitable. Each of them is able to represent the complete manufacturing process of the component.

**Process Chain Combination.** It is more reasonable to evaluate the production costs on the scale of the whole structure, so that shared productive resources and idle times can be taken into account. This becomes even more important if the scenario specifies to set up a production for only a single structure and due to the exclusiveness of the machine, idle times could not be utilized for producing components of other structures. Accordingly, without sharing resources this would lead to unrealistic scenarios with highly unused resources. Therefore, it is important to build the structures complete process chain for the cost estimation.

### Sub process chains of two components

**Component A**
- Prepreg production
- AFP
- Forming
- Autoclave

**Component B**
- Prepreg production
- AFP
- Forming
- Autoclave

### Possible process chain combinations

**Joining with rivets**
- Prepreg production
- AFP
- Forming
- Autoclave
- Riveting

**Joining with adhesive bonding**
- Prepreg production
- AFP
- Forming
- Autoclave
- Adhesive bonding

**Joining with co-bonding**
- Prepreg production
- AFP
- Forming
- Autoclave
- Autoclave

**Joining with co-curing**
- Prepreg production
- AFP
- Forming
- Autoclave
- Autoclave

Figure 4: Example for resulting process chains from a combination of two sub process chains using different joining methods.

Normally, a structure is defined as an assembly without specifying a certain joining method. Therefore, the components and their sub process chains can be combined by using different joining methods. Depending on the used joining method, the shape of the resulting process chain differs (see Fig. 4). The order and pairings of possible combinations are defined within the preliminary design and represented in an assembly tree, which is part of the in house developed data model.
Four joining methods are considered in this method so far. Riveting is the state of the art joining method in the aerospace industry, it requires that both components are fully cured. For a joining with adhesive bonding both components also, have to be fully cured. In contrast to this for co-curing both components, have to be in a pre-cured state. The components sharing the curing process and form one rigid part. In this case vacuum bagging as a necessary preparation process has to be shared as well. For co-bonding two parts, one component has to be in cured state whereas the other one is still pre-cured. Because the curing state of the components can be switched, the resulting process chain can have two different shapes.

The method combines all possible sub process chains and joining methods in a full-factorial pattern to generate all possible process chains of the structure. The suitability of a joining method is evaluated during the combination process and considers only the curing state. Geometrical restrictions of the methods are addressed in the specific design phase.

The above mentioned example structure consisting of only two components, each with possibly ten sub process chains and five joining methods would lead to a list of at most five hundred possible process chains for this structure. This maximum number of possible process chains n depends on the number of sub process chains s, the number of components m and the number of suitable joining methods j for the m minus one connections (see Eq. 1).

\[ n = (s_1 \cdot s_2 \cdot \ldots \cdot s_m) \cdot (j_1 \cdot j_2 \cdot \ldots \cdot j_{m-1}) \] (1)

Just in case of all components have the same number of sub process chains and all joints have the same number of suitable joining methods the quantity of possible process chains can be calculated as shown in Eq. 2.

\[ n = s^m \cdot j^{m-1} \] (2)

Thus, the number of possible process chains raises exponential with the number of components and proportional with the quantity of possible sub process chains and the number of suitable joining methods. This leads to a relatively large number of process chains even for small structures with a few components. To reduce complexity and calculation effort in the following design phases, it is necessary to further develop exclusion criteria and referring to the design to reduce the number of individual components, e. g. by using common parts or part families with a similar geometry.

Conclusions

The integration of product development and production planning reduces costly, late iterations between each other. The overarching development procedure presents a structured way for this integration. One mayor key for this integration is the presented method, which allows a systematic development of possible process chains based on a preliminary design. This information is used to further optimize the structure with regard to manufacturing and process chain restrictions and allows a more accurate estimation for the mass and the mechanical performance of the structure.

The reasonable process chains are the input for the calculation of production cost in the next steps of the rough planning phase. This makes it possible to find the best compromise between cost and structural performance according to given preferences for the overall solutions of design and production. Further steps in development are a complete implementation of the rough planning phase in python™ and a systematic approach for the handling of the amount of possible process chains.

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References


