ECONOMIC POTENTIAL OF SINGLE- AND MULTI-STEP PREFORMING FOR LARGE-SCALE PRODUCTION OF COMPOSITE STRUCTURES

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Abstract

The use of fiber reinforced plastics (FRP) has great potential to reduce the overall weight of automotive structures. Yet, FRP are currently not economically competitive with conventional materials from a production point of view. The production of highly integrated textile preforms for FRP components is responsible for up to 40% of the overall part costs, as state of the art preforming process chains are predominantly based on manual and semi-automated operations. The combination of innovative single-step and multi-step preforming processes is a viable approach to realize a cost effective preform production and establish FRP in large-scale automotive applications. Single-step preforming refers to the production of non-crimp fabrics (NCF) which feature locally adjusted properties. The term multi-step preforming represents the production of complex, near net-shape textile structures in a sequence of automated process steps.

At the Institut für Textiltechnik (ITA) of RWTH Aachen University, Germany, the economic potential of this approach was evaluated. The objective was to show that the combination of single- and multi-step preforming is economically reasonable. Two different process chains for the production of the textile preform of a characteristic automotive FRP hardtop were designed. The process chains were then evaluated with a focus on cycle times and costs per unit, using the in-house developed software tool “EcoPreform”. The validation was carried out successfully using the machinery available at ITA.

Technological Background and Requirements

The objective of the research carried out at ITA is to increase the level of automation in the production of FRP parts using automated preforming technologies. The focus lies hereby on the processing of fibers, i.e. rovings and textiles. The semifinished product of the regarded processing steps is the textile preform. In Figure 1 the scope of the processing steps regarded in this work are shown. The injection or infusion of the preform with resin is not part of this research project and is therefore not considered here.

Figure 1: Schematic overview of the production of FRP parts using preforming technology. The processing steps regarded in this work are marked red

1 Here, large-scale production is defined as having a production rate of roughly 100,000 parts per year [5].
2 A roving is a long and narrow strand of (usually several thousand) fibers.
In previous work conducted, different technologies were developed at ITA, which have the potential to be adapted in large-scale production scenarios of textile preforms. The benefit of these technologies has only been validated for demonstrators with simple geometries and without specific applications. In order to prove the applicability of the innovative technologies within the large-scale production of a realistic FRP part, a complex demonstrator was chosen. Its design and configuration is similar to the metallic roof segment of a BMW 3 series convertible (see Figure 2) and is therefore very close to a real-live automotive part. All textiles and rovings used are carbon fiber based, thus the final CFRP (carbon fiber reinforced plastic) part features mechanical properties similar to the metallic original.

![Figure 2: Use of the roof segment in a BMW 3 series convertible [2]](image)

**Single-step Preforming**

The core of the single-step preforming process is the multi-axial weft insertion machine. It is designed to connect and fix several layers of rovings using warp-knitting yarns by means of loop formation. The product of this process is a multiaxial non-crimp fabric (NCF), whose individual layers are created by inserting rovings in different orientations. An NCF with locally adjusted characteristics like thickness and drapability\(^3\) is referred to as Tailored NCF. Its advantages are the reduction or elimination of subsequent processing steps, e.g. placement of reinforcements and handling operations.

For the research performed, the multi-axial weft insertion machine Copcentra MAX 3 CNC by LIBA Maschinenfabrik GmbH, Naila, Germany was used. In its standard configuration, it features three weft insertion units and one pillar thread device (see Figure 3). The rovings are fed from the creel to the weft insertion units and the pillar thread device, where they are positioned in different angles. The different layers are then knitted to create a multi-axial NCF. The stitching type can be changed online during the production.

\(^3\)Drapability is the adaption of laminar semi-finished material on curved three-dimensional surfaces [1].
In order to achieve the integration of all these functions, the machine has been modified for the purpose of this research. Different modules were developed and implemented at ITA, as it is shown in Figure 4. The reinforcement placement unit incorporates different methods to position and fix additional fabrics with the aim to locally change the thickness of the Tailored NCF. In order to adapt the knitting unit to the varying thicknesses, an adaptive pillar thread bar with a spring-damper-system was developed. The cutter unit allows creating the final shape of the preform, including cut-outs, using an ultra-sonic blade. The semifinished products are temporarily stored using the stacking unit, which places the preforms on top of each other while considering their individual shapes.

Process steps which cannot be incorporated in the single-step preforming technology have to be performed subsequently. Thus, additional machinery may be required for the finalization of the preform. In the case of the roof segment, the integration of inserts and stringers (see Figure 6) is realized using a robotic system.
Multi-step Preforming

The entire automated multi-step production of the textile preform of the FRP roof segment is carried out at the ITA-Preformcenter (see Figure 5). It consists of an industrial robot by KUKA Roboter GmbH, Augsburg, Germany, mounted overhead in a manufacturing cell by Keilmann Sondermaschinenbau GmbH, Lorsch, Germany. Furthermore, a variety of end-effectors can be mounted to the robot. This allows performing sequences of different operations with the same robot. The end-effectors can be deposited on a dedicated storage and can be changed automatically. A needle and a vacuum gripper are used for the handling and positioning of parts and components. The joining of textile layers is carried out using either one-sided sewing, tufting or binder technologies. The binder is a thermoplastic glue which is at first applied to the textile and thermally activated in a second step. The final contour of the three-dimensional preform is established using an ultra-sonic blade to trim the edges of the preform and/or to create cut-outs.

The ITA-Preformcenter can process any kind of textile material, i.e. either standard (non-crimp) fabrics or specifically produced Tailored NCF. The textiles can be cut into the specific size and shape using a CNC cutting table (Turbocut 2501 CV) by Assyst Bullmer Spezialmaschinen GmbH & Co. KG, Mehrstetten, Germany. It is a separate machine but is placed inside the reach of the robotic arm, allowing an integration of the cutting table into the production process chain.

![Diagram of ITA-Preformcenter](image)

*Figure 5: Drawing and photography of the ITA-Preformcenter [4]*

**Description of the Demonstrator**

The demonstrator consists of different components, which are adapted from the original metallic roof structure. The roof shell is the basis of the preform, as all other sub-preforms\(^4\) (i.e. stringers and inserts) are mounted onto it. Additionally, reinforcements are placed under the inserts in order to reduce the local stresses due to forces acting on mounted components. As glass fibers are cheaper and feature similar processing properties compared to carbon fibers, glass fiber based materials were used for the manufacturing of the demonstrator. The overall configuration of the preform is shown in Figure 6.

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\(^4\) Several sub-preforms are joined in order to create a complete preform. A sub-preform consists of at least one layer of fabric.
The automotive roof segment that serves as a complex demonstrator. Left: exploded view drawing of the unfolded roof shell (1) including reinforcement layers (2), stringers (3) and inserts (4). Right: photography of the completed demonstrator inside the mold (see Figures 7 and 9).

The stringers are each made up of a rigid foam core made from Polymethacrylimid (PMI) and a carbon fiber draping. The foam core defines the shape of this component. The inserts serve as metallic attachment points for external components like the locking and guidance mechanism of the roof. Both stringers and inserts are sub-preforms consisting of an NCF and a further component. Therefore, the final preform is a hybrid structure, as it incorporates more materials (i.e. PMI and aluminum) apart from carbon fibers and auxiliary materials.

The roof shell consists of eight layer of fabric, while the reinforcements are made up of four additional layers. Furthermore, the stringers have an eight-layer and the inserts a four-layer carbon fiber draping. The thickness of four fabric layers is 0.75 mm (0.0295 in). Therefore, the local total thickness varies between 1.5 mm (0.059 in) and 3 mm (0.1181 in). The configuration of the layers is quasi-isotropic and contains an equal number of fibers oriented in the directions 0°, 90°, 45° and -45°.

**Development of Process Chains and Practical Implementation**

Two different process chains were designed and compared using the four-step-methodology described in [5]. This methodology is a systematic and iterative approach to find a technologically feasible and resource efficient production process chain. Its four major steps are:

1. collecting data to create a decision basis,
2. identifying and connecting the relevant process modules,
3. development and selection of technological sequences,
4. development and selection of a detailed production sequence.

In this work, an extensive database with empirically collected knowledge was already available. It consists of results from previous research, such as performance data of the machinery and feedback from the industry. Furthermore, both process chains were tested in part, ensuring the feasibility of key process steps. This also allowed validating, extending and possibly correcting the existent knowledge database.

In both process chains, the manufacturing of the sub-preforms is not considered. The stringers and inserts are regarded as available for the integration into the roof segment.
Process Chain 1: Multi-Step Preforming

The first process chain exclusively utilizes the ITA-Preformcenter. All processing steps are performed using the robot and the cutting table. Furthermore, a deposition mold is required to create the desired curved shape of the roof segment. In order to reduce the number of handling operations, available standard quadraxial NCF are used. A possible layout of the production system is shown in Figure 7.

The non-crimp fabrics and auxiliary materials are stored on the left and are transported to the cutter table, where the desired blanks are cut. The robotic arm of the ITA-Preformcenter on the right can pick up the layers either directly from the cutter table or from the intermediate storage. The preform is built up in the mold, by positioning the NCF layers, stingers and inserts. The end effectors are stored nearby and can be changed at any moment. In the end, the completed preform is placed in the final storage. Additionally, two workers perform preparatory tasks and ensure the material supply for the cutter table and the ITA-Preformcenter.

![Diagram of production system](image)

Figure 7: Example of a possible layout of the production system for process chain 1

The cutter table and the ITA-Preformcenter work independently and do not have to be synchronized in their work cycle. Hence, two parallel sub-process chains are created (see Figure 8). The cutting of individual fabric layers takes place in the upper sub-process chain, while the entire handling and joining is done in the lower one. The entire process chain consists of 36 process steps and the full cycle time is 20.8 min.
Process Chain 2: Combination of Multi-Step and Single-Step Preforming

The second process chain was developed taking into account the results from process chain 1. All process steps which could be integrated into the single-step preforming on the multi-axial weft insertion machine were outsourced from the ITA-Preformcenter (see Figure 9). As it is shown in Figure 4, only the positioning and joining of stringers and inserts cannot be integrated and remain like in process chain 1.
The necessary rovings and reinforcement fabrics are fed to the multi-axial weft insertion machine and processed to semifinished textile products. These feature the roof shell, the local reinforcements and the final contour of the roof segment. They are then placed in an intermediate storage inside the ITA-Preformcenter. Like in process chain 1, the robot mounts both inserts and stringers to the Tailored NCF. The preform is then stored in a final storage.

Like in process chain 1, the production is separated into two parallel working sub-process chains (see Figure 10). The multi-axial weft insertion machine works with a cycle time of 2.5 min, while the second sub-process chain lasts 8.3 min. This defines the total cycle duration of the process chain, which consists of 17 process steps.

![Diagram showing process chain](image)

**Figure 10:** Gantt chart of process chain 2, created using the software tool EcoPreform. Sub-process chain “Multi-axial weft insertion machine” is shown on top, sub-process chain “ITA-Preformcenter” is shown underneath.

### Economic Evaluation

The economic evaluation of the production costs was performed using the software tool EcoPreform. The possible revenues could not be considered as no data on selling prices were available. Several assumptions and simplifications were made in order to reduce the complexity of the calculations. The production is examined for one year periods, assuming that the machinery is linearly depreciated over ten years and exclusively used for the production of the demonstrator. The costs of the sub-preforms, which are economically considered as readily available vendor parts, were estimated. All values are regarded as an annual mean, without considering disruptions or learning curves.

As part of the evaluation, the cost distribution between material, labor and machinery was determined. In the case of full production capacity utilization, the material costs make up a major part of the total costs: 93.6 % and 95.9 % for process chains 1 and 2 respectively. Therefore, only a small portion of the costs can be reduced by using the presented technologies.

The cost for an individual preform depends on the ratio between the annual production rate and the total annual production costs. At full capacity, a total of 13,752 preforms per year can be produced with process chain 1, costing 9,237,301 USD/a. When using process chain 2, a maximum of 34,372 preforms per year can be produced for a total cost of 22,206,280 USD/a. The resulting costs per unit are 98.58 USD and 590.25 USD for process chains 1 and 2 respectively.
However, the full capacity of the production system is not always used, depending on the number of produced preforms. In the following diagram (Figure 11) the dependence of the cost per unit on the production volume is shown, assuming that the production system is exclusively used for this purpose. When the target production volume exceeds the capacity of the existing machinery, a further production system has to be employed, leading to fluctuating cost per unit. It is obvious that the unitary costs vary more for process chain 2, which is due to the higher investment costs per production system (2,823,030 USD compared to 742,644 USD). On the other hand, the cost per unit is constantly higher for process chain 1 for a large-scale production.  

![Diagram showing cost per unit vs. annual production volume](image_url)

*Figure 11: Development of the cost per unit of the completed preform over the annual production volume*

**Conclusion and outlook**

Concluding, it can be said that process chain 2 is more suitable for the large-scale production of a complex textile preform like the regarded case study. It contains fewer process steps and is therefore less complex, compared to process chain 1. This leads to a higher stability of the production system as a whole, as each connection between elements is a potential risk. The cycle time is 60% shorter, allowing a higher annual production rate with the same number of production systems. Despite having 280% higher investment costs, the unitary cost of the preform is 8.33 USD lower. However, the capacity and investment cost of a production system for process chain 2 limits its flexibility to adapt to varying target production volumes.

The potential of the technologies was not yet fully exhausted within this project. Further iterative development cycles can lead to a better layout of the production system, a shorter cycle time and a better utilization rate of the machinery. Additional modifications and enhancements of the used machinery, like a multi-gripper for stringers, could reduce both cost and cycle time. Moreover, the execution of a limited number of full production cycles could reveal weaknesses and make use of learning curves to optimize certain parameters.

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5 See footnote 1.
Bibliography


