DeMaCo
Design for Manufacture of Composites

Public report

10th Joint CORNET Call for Transnational Collective Research Projects

IWT  project 100729
AiF  project 53 EN
# CONTENT

<table>
<thead>
<tr>
<th>1</th>
<th>Executive Summary</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Goal of the initiative</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>Summary of the project results</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Funding</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>Partners</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>Project Coordinator</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2</th>
<th>Description of Consortium Partners</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Sirris</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Forschungskuratorium Textil e.V. (FKT)</td>
<td>5</td>
</tr>
<tr>
<td>2.3</td>
<td>Institut für Textiltechnik of RWTH Aachen University (ITA)</td>
<td>5</td>
</tr>
<tr>
<td>2.4</td>
<td>Institute of Polymer Materials and Plastics Engineering of Clausthal University of Technology (PuK)</td>
<td>6</td>
</tr>
</tbody>
</table>

| 3 | Users Committee | 7 |

| 4 | Research Approach | 7 |

<table>
<thead>
<tr>
<th>5</th>
<th>Results</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Project management</td>
<td>9</td>
</tr>
<tr>
<td>5.2</td>
<td>Generic Design Specifications and Case Selection</td>
<td>10</td>
</tr>
<tr>
<td>5.3</td>
<td>Selection of Preforming Technologies</td>
<td>13</td>
</tr>
<tr>
<td>5.4</td>
<td>Systematic Approach for Matrix Selection</td>
<td>14</td>
</tr>
<tr>
<td>5.5</td>
<td>Choice of Molding Process and Tooling</td>
<td>14</td>
</tr>
<tr>
<td>5.6</td>
<td>Efficient Post-Processing</td>
<td>18</td>
</tr>
<tr>
<td>5.7</td>
<td>Integrated Cost Assessment Tool</td>
<td>19</td>
</tr>
<tr>
<td>5.8</td>
<td>Decision Tool</td>
<td>23</td>
</tr>
<tr>
<td>5.9</td>
<td>Dissemination</td>
<td>24</td>
</tr>
<tr>
<td>5.10</td>
<td>Follow-up after the completion of the project</td>
<td>27</td>
</tr>
</tbody>
</table>

| 6 | Further Information | 28 |
1 Executive Summary

1.1 Goal of the initiative

Composite materials offer unique opportunities in part and product design. Their high specific strength and stiffness, high chemical resistance and other distinctive properties make them the materials of choice for an ever increasing range of applications. Today’s growth prospects are very positive for composites, thanks to their adoption by the aerospace and wind industry and – upcoming recently – the automotive industry. This creates unique opportunities and possibilities: carbon fiber is now widely available for industrial use, newly developed resin systems are tough and yet straightforward to process, closed mold processing techniques become more robust and automated production solutions are increasingly available.

Nevertheless, there is still a threshold for small and medium enterprises (SMEs) to implement these composite solutions, as the design and economical production of such products is considered being much more difficult than of traditional metallic products. The aim of the project “DeMaCo” was to develop “design for manufacture of composites” (more specific for liquid composite molding processes) guidelines which support SMEs during the development of composite products.

The objective was to develop guidelines and tools which lead designers towards the right mix of product geometry, materials and production processes including considerations for preforming processes and finishing operations.

By means of these guidelines, designers and production managers should be able to:

- Select the most suitable production process steps for a composite design
- Consider the relation between the material choices and the production steps
- Select appropriate tooling solutions, such as mold material, mold type and consumables
- Select the right finishing operations
- Roughly calculate the cost for the part produced in fiber reinforced composite materials

1.2 Summary of the project results

Based on literature research, industrial partners, laboratory research and case studies, a decision tool for liquid composite molding processes and a cost estimator tool were developed. The scope was limited to three processes: vacuum assisted resin infusion (VARI), resin transfer molding (RTM) and RTM-light.

In a first step, performance specifications dedicated to the design of composite components were derived. These performance specifications remained central throughout the project, and its attributes were linked to the distinct steps of the decision tool. Dependencies between process selection, selection of materials, tooling design and part design were sought. They led to key specifications which were integrated in the decision tool.

In a second step, three demonstrators were defined in collaboration with the industrial users committee. The chosen demonstrators were: a dinghy in VARI, a tram nose in RTM-light and an automotive control arm in RTM. The aim of these demonstrators was

a) to undergo the complete design process from idea to small scale production,

b) to extend the consortiums knowledge on design and processing of complex parts by a design of experiment (DOE) exercise,

c) to demonstrate the selected liquid composite molding processes to the users committee during hands–on workshops,

· to document and facilitate the dissemination of the results.

Following conceptual and process design, the demonstrator and their molds were designed. Where necessary, mold production was outsourced. Where possible, manufacture was done in–house in order to incorporate hands–on knowledge in the guidelines.
Third, a series of lab experiments was performed. For example, a methodology was validated to simplify the relationship between resin viscosity and the permeability of the textile. Similarly, a draping test was defined which quantifies the drapability of a textile for further use in the decision tool. These experiments were supported by literature surveys.

Forth, a DOE exercise was prepared based on the lab experiments. The aim of this exercise was the validation of the lab experiments in a semi-industrial production process. Subsequently, a series of 10 prototypes was manufactured for the three demonstrators.

In parallel, a cost model was developed. This cost model incorporated cost for material and preforming, tooling and consumables, post-processing as well as depreciation of equipment. The cost model was programmed in Excel and provided with a graphical users interface.

Finally, the results were collected, processed and integrated in the decision tool. Following fine-tuning and layouting, these guidelines will be published as a handbook in autumn 2013 and distributed via a print-on-demand service.

1.3 Funding
10th Joint CORNET Call for Transnational Collective Research Project
Funding is granted by
- IWT (Flanders)
- AiF (Germany)

1.4 Partners
- Sirris (Belgium)
  - Sirris Leuven–Gent Composites Application Lab (SLC-Lab)
  - Advanced Manufacturing
- Institut für Polymerwerkstoffe und Kunststofftechnik of TU Clausthal (Germany)
- Institut für Textiltechnik of RWTH Aachen University (Germany)
- Forschungskuratorium Textil e.V. (Germany)

1.5 Project Coordinator
Markus Kaufmann, Sirris, markus.kaufmann@sirris.be, +32 498919491
2 Description of Consortium Partners

2.1 Sirris

Sirris is the collective R&D center of the Belgian technological industry, and the coordinating association of DeMaCo. Sirris was founded under the name WTCM-CRIF in 1949 by Fabrimetal (now Agoria, the Belgian federation of technology industries). Sirris advises and supports companies, from small companies to large industrial groups, on the implementation of technological innovations. Services offered are technological advices, the organization of innovation projects, shared R&D projects, shared capacity (access to infrastructure) and knowledge transfer in the fields of product design, materials, production techniques and process organization.

The internal organizational structure combines a local presence with a stronghold in the industrial networks of Brussels, Flanders, and Wallonia. Sirris has six branches spread across the country: Brussels, Leuven, Ghent, Hasselt, Liege, and Charleroi. This enables Sirris to take the optimal sensitivities and the specific legal requirements of each of the three regions into account.

Sirris works in collaboration with universities, research centers, companies, associations, and institutions in Belgium and across Europe (e.g. VLOOT, FMTC, IMEC, VITO, BIL, Flanders' DRIVE, Flanders InShape, Flamac, KMO–IT, KU Leuven, Ocas). It exchanges collaborators, knowledge and methods with these partners.

Research related to composites is performed by the Sirris Leuven–Gent Composites Application Lab (SLC), a joint initiative between Sirris, KU Leuven and University of Ghent. SLC-Lab is recognized as the link between composite research and the industry. It ensures that materials and process knowhow is translated into tangible end products. SLC-Lab provides the environment where companies and composite experts together develop innovative applications with composite materials.

Beside research, the transfer knowledge transfer is the other core competence of Sirris. With more than 5000 industrial interventions, more than 2000 different Belgian companies are supported per year. Sirris employs 120 technology experts and has already carried out more than 100 European research projects.

2.2 Forschungskuratorium Textil e.V. (FKT)

The Forschungskuratorium Textil (FKT) encompassed the Central Confederation of the German Textile and Fashion Industry as well as 15 regional and trade associations with the aim of promoting and coordinating collective research projects. This network of associations acts on behalf of 1.300 textile companies employing almost 150.000 people in Germany.

Research projects supporting the value-added textile chain are implemented together with the partner organizations from related operational areas such as textile machinery, synthetic fibers, dyeing and textile services. In cooperation with 16 textile research institutes nation-wide, the FKT carries out industrial collective research projects within the working group of the German Federation of Industrial Cooperative Research Associations ”Otto von Guericke” (AIF – Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V.) and with the support the Federal Ministry of Economics and Technology (BMWi).

2.3 Institut für Textiltechnik of RWTH Aachen University (ITA)

The Institut für Textiltechnik (ITA) belongs to the faculty of mechanical engineering at RWTH Aachen University. The institute works on the improvement and construction of new textile machinery as well as on the development of new textile structures. ITA has expertise in mechanical engineering and textile application technology.

The research of ITA lies in all areas along the textile chain. ITA develops products and processes for the areas of staple fiber processing, man–made fiber technology, textile machinery, fiber reinforced composites, technical textiles and medical textiles. Design and prototyping are used for machine development within these areas. Using simulation and testing equipment, machinery and processes are improved. In
The past, focusing the research on textile machinery has led to the development of new methods and technologies for the technical textiles and fiber reinforced composites. The 3-D braiding technology for the production of net-shape preforms with a continuous textile fiber pattern is already in industrial use. For the assembly of complex textile preforms, the one-sided ITA stitching technology allows to join large textile structures while reducing fiber damage. Besides the development of entirely new methods, such as the one-sided ITA stitching technology, analysis, modeling and optimization of existing procedures and processes are a major field of research at ITA.

New developments and the adaptation of passive to active machinery components lead to innovative textile products. The combination and coordination of single process technologies and materials, especially in the context of new fiber materials, is supported by ITA’s existing knowledge on the use of high performance materials for textile machinery and their subassemblies.

ITA is member in several research networks, for example Zukunftinitiative Textil NRW (ZiTex) with over 330 participating companies and the Aachener Textil Zentrum.

2.4 Institute of Polymer Materials and Plastics Engineering of Clausthal University of Technology (PuK)
The Institute of Polymer Materials and Plastics Engineering (PuK) at Clausthal University of Technology was founded in 1998 and was under the guidance of Prof. Dr.-Ing. G. Ziegmann until 2011 and is currently led by Dr.-Ing. Dieter Meiners. The PuK is responsible for education and research in the field of polymers and processing techniques as well as composite technologies. At the moment the institute consists of 20 scientific co-workers and seven technicians, who are working in the following main areas of research:

- Development of highly-filled polymers and processing techniques to produce structures via melt processes (extrusion, injection molding, press forming)
- Development and simulation of micro injection molding processes
- Development of special polymers (electrical conductive, magnetic properties etc.)
- Research on natural fiber composites as well as high-performance composites and designs for the aeronautic industry
- Throughout characterization and modeling of material properties for simulation purposes.
- Simulation of injection molding and LCM processes
3 Users Committee
A Flemish and a German users committee were established. According to Cornet rules, these committees would meet separately. For the first, third and fourth meeting, however, it was decided to combine the two groups into a transnational committee. This allowed good discussions and networking across the borders.

The users committees were composed of a carefully selected group of companies. For example, a material supplier of liquid composite molding equipment, a material producer of sandwich core materials, OEMs from the automotive and transport industry, the boat industry and sports are represented. These companies will had full access to the obtained results and were regarded as priority valorization partners.

4 Research Approach
Composite design is traditionally a strongly interlinked, iterative and multidisciplinary task. The challenge at this stage was to develop a tool which is not overly complex in its use, and that can be developed within the available project time frame. Thus, the starting point was the study of the compatibility of the chosen liquid composite molding (LCM) processes in combination with available materials (resin and fibers), shapes, tolerance and its relation to process efficiency. In a second step, the compatibility with the envisaged tooling technology was studied, followed by the relationship with geometric part design.

In order to tackle the problem most efficiently, it was decided to split the preform, resin and process selection into different work packages. Hence, the research groups will work separately on systematic approaches to choose the materials and processes as a function of the specifications. The connecting threads were the use of a generic performance specification, the work on three demonstrators, the development of a cost assessment tool, and the synthesis of the results into “design for manufacture” guidelines.

Not only primary shaping processes were considered. Finishing operations, surface treatments and assembly added considerable complexity to the “design for manufacture” strategy; they were included as a separate work package.

The resulting guidelines tackled the selection of processes, materials, tooling and part geometry based on performance specifications, whereas knowledge from literature research, knowledge from industry, lab experiments and the work on three demonstrators were collected and synthesized. This approach is illustrated in the following figure.
The challenge was to follow an approach where the decision process was studied from different, well-separated but potentially conflicting perspectives (compatibility of process and performance specification) and then re-synthesized into a balanced selection strategy. The work on the three demonstrators helped to fine-tune the approach and mitigate the risk. The benefits of the demonstrator studies were multipurpose:

a) to pass the complete design process from idea to series production,

b) to extend the consortiums knowledge on design and processing of complex parts by design of experiment (DOE) exercises,

c) to demonstrate the selected liquid composite molding processes to the users committee during hands-on workshops

d) to facilitate the dissemination of the results.
5 Results
The main objective of the project was the development of guidelines which facilitate decision taking in the design of composite parts. The generated tools should lead the industry systematically to the subject of design for manufacture and indicates possible concepts for the manufacture of composite components. The single selection steps of the guidelines were directly linked to the technical work packages. They were:
- the selection of the reinforcement material (Work package 3)
- selecting the appropriate resin system (WP 4)
- the selection of the tooling technology (WP 5)
- the selection of technologies for post-processing (WP 6)
- a cost estimating tool for Liquid Composite Molding processes (WP 7)

5.1 Project management
Despite the geographical spread of the project consortium, face-to-face meetings and hands-on workshops were a substantial part of the collaboration. Besides the regular meetings, a series of phone conferences were organized in order to coordinate the work of the strongly interlinked work packages. The phone conferences were intensified in the second year of the project. The following list gives an overview of the activities performed in work package 1:
- Overall management regarding all administrative, financial and contractual tasks
- Documentation and reporting to the national funding authorities
- Coordination of the technical activities
- Preparation of the following consortium–internal workshops and meetings
  - Kickoff Hasselt 13/14 June 2011
  - Meeting Wuppertal 25 August 2011
  - Cost workshop Aachen 16 September 2011
  - Meeting Duisburg 8 November 2011
  - Workshop Clausthal 23/24 February 2012
  - Workshop Leuven 19/21 September 2011
  - Workshop Leuven 9 October 2011
  - Workshop Leuven 3 December 2012
  - Meeting Aachen 1 February 2013
  - Manufacturing workshop Leuven 14 February 2013
  - Manufacturing workshop Leuven 18/19 April 2013
  - Guidelines Meeting 4–6 June 2013
- Preparation and meeting minutes of the following users committee meetings
  - Kickoff meeting Aachen 11 October 2011
  - Belgian meeting Leuven 8 May 2012
  - German meeting Obertshausen 11 May 2012
  - Workshop and network event Leuven 17/18 October 2012
  - Final workshop Leuven 5 July 2013
5.2 Generic Design Specifications and Case Selection

A list for generic performance specifications was tailored to the design of composite structures (economic requirements & functional requirements). In addition, relevant requirements were identified and translated for use in the decision tool:

- Selection of requirements for the design of composite products
- Structuring of requirements in logical groups
- Classification in rigid and flexible requirements
- Classification in dominating and subordinate requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Economic</th>
<th>Rigid</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection of requirements for the design of composite products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structuring of requirements in logical groups</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classification in rigid and flexible requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classification in dominating and subordinate requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outgoing from a range of proposals from several sectors, three demonstrator cases were defined in collaboration with the industrial users. These demonstrators were used in the continuation of the project to feed, evaluate and enhance the decision tool.

Particular important for the definition of the demonstrators was:
- They were representative for the needs and typical applications in the target industry
- They covered a wide range of specifications (small, mid and large series; different geometrical complexities; different functionalities; etc.)
- They were tailored for the three processes RTM, RTM-Light and Vacuum Infusion

The following figures show the key features of the three demonstrators, as well as the discussed alternatives and the final component.
After the definition, a detailed performance specification was made for each of the demonstrators. These specs formed the requirements for the conceptual and detail design in work package 5.
5.3 Selection of Preforming Technologies

A strategy was derived to identify the most suitable fiber material (glass, carbon, natural fibers) for a given case. In particular, the strategy supports the pre-selection of materials with respects to the performance specification and available material datasheets.

Based on that, methods for the characterization of textile reinforcement were developed and validated. They served as the basis for the development and elaboration of methods for application-specific selection of textile structures. These methods were also applied for the design of three demonstrator parts and their validation. Subtasks were as follows:

1. A database for reinforcement textiles was created. This database included the following information for each textile: name, photographic image, fiber material, binding/stitching, weight, approximate price, and source of information.

2. A methodology for characterization of reinforcement fabrics for draping was developed. The approach made it possible use a simple test bench for the characterization. The test bench consists of standard polystyrene balls of different diameter, on which the textiles are draped. The subsequent analysis extracts angles and radii from photos. From these values, a characteristic value was derived, which allowed the comparison of different textile fabrics as the basis for selection with regard to draping.

3. A strategy was developed to identify the most suitable textile structure (for a given part geometry and specification). Criteria taken into account were the areal weight, fiber orientation, fiber crimp, bending stiffness/drapability, permeability, cost and surface aspects.

For the process chain of the preforming process, a knowledge-base was developed covering the available technologies. In particular, a multi-step methodology for the process chains was presented to the users committee, consisting of cutting, handling, draping, joining/fixation. Boundary conditions included parameters such as available machinery, number of operators, budget, production quantity, complexity, required reproducibility.
5.4 Systematic Approach for Matrix Selection

In a first subtask, the matrix-related parameters in the performance specification were screened and related to relevant matrix properties. Typical parameters were performance, cycle time, thickness and shape tolerances, surface aesthetics and application temperature.

The compatibility between preform and matrix is related to the permeability of the textile, and the viscosity profile of the matrix throughout the curing process. In this task, the correlation between the permeability and the flow behavior was studied, supported by permeability experiments, rheometer and DSC measurements. Selected resin systems during were unsaturated polyesters, vinylesters and epoxies and a resin database for typical matrix systems was created.

Further, a combined tool for the detection of the maximum flow length of a resin system was developed. This tool was based on Darcy’s law and allowed to determine the permeability of a fabric used in the tool with the help of a replacement fluid (vegetable oil), from a sectional approximation of the resin viscosity. For the validation of the tool, comparative measurements were carried out with the existing PuK permeability tool. Using low pressure gradients, flow lengths up to 6m for UP and VE systems, and up to 10 m for epoxy systems could be derived.

Further, industrial knowledge (“rules-of-thumb”) were translated into processing guidelines. These processing guidelines were integrated in the work on the three demonstrators.

5.5 Choice of Molding Process and Tooling

A systematic approach for the choice of the liquid composite molding process and tooling solution was developed. In particular, the “best fitting” technologies for a given composite product design were sought with respect to the performance specification and cost-efficient manufacture. The three processes in scope were vacuum assisted resin infusion (VARI), resin transfer molding (RTM) and RTM-light.

In a first step, the three processes were analyzed and described in detail. In particular, a differentiation was made with respect to resin compatibility (e.g. viscosity, preheating and curing temperature, injectable process time), preform compatibility (compaction behavior, permeability), dimensional product attributes (volume, section thickness, surface area ranges, thickness tolerance ranges and surface roughness), etc.

Available tooling solutions were classified, including rigid tooling solutions (machined from solid billets, rapid tooling,...), semi-rigid and flexible tooling solutions (silicon sheets, rubbers,...) and removable tooling inserts. During the subsequent work, it was concentrated on rigid tooling and the link of its technological limits to the performance specification.

A literature study with regard to a) the process/tooling compatibility, b) geometrical design guidelines (e.g. demoldability) and c) an economical evaluation (cost for equipment and tooling, operator level and efficiency and the degree of automation) concluded the theoretical part of this work package.
Based on the performance specifications and the ongoing work with work packages 3–5, the three demonstrators were designed. In particular, the components and molds were dimensioned and the process windows were defined. In order to accelerate the design, the prototypes were not optimized for every aspect, such as structural performance. Features to be integrated were:

- geometrical process and tooling limits (e.g. minimum corner radii, maximum tapering ratios and demolding angles)
- requirements such as dimensional tolerances, surface aspects and production quantities

For each demonstrator a dedicated tooling solution was designed. Mockups and molds were manufactured by third parties where necessary. The composite molds and countermolds of demonstrator A and B, however, were produced within the consortium in order to gain practical experience with mold manufacture.

For the validation of the developed methodology, a design-of-experiment exercise was carried out. Different process variants, mold filling strategies, consumables, fiber/resin systems, and the opportunity for automation were explored in theory before different configurations were manufactured and validated against each other.

**Demonstrator A (sailing boat)**

The mockup of the sailing boat was milled externally in PIR foam. The targeted production quantity and the specification required a gelcoated polyester tooling which was produced in-house.

The mold was finished in October 2012, just in time for the third users committee workshop. During this workshop, a first dinghy was produced together. Subsequently, a series of 8 sailing boats was produced, using

- different process parameters
- different infusion strategies
- different fiber/resin systems
- different stiffening strategies (rigid honeycombs, infusible 3D-core honeycombs, stiffeners)
- different consumables
**Demonstrator B (tram nose)**

The mockup of the tram component was milled from a casted block of Ebaboard 105. Targeted production quantity (100 – 200 pcs) and the specifications required a composite mold and countermold. Both were produced within the research consortium.

The mold was finished in February 2012. Subsequently, a series of 10 tram noses were produced, using
- different process parameters
- different infusion strategies
- different gel coats
- different fiber/resin systems
- different core materials (monolithic/no core, combi mats, infusible Soric honeycombs)
Demonstrator C (control arm)

The design of the RTM mold was challenging. First, it was a rather complex shape in combination with a complex shaped core. Second the included bushings (using Teufelberger’s T-igel inserts) needed an additional set of tooling inserts in order to keep the longitudinal tolerances at a minimum. Third, the consortium decided to design the part “net-shape”, avoiding post-processing such as trimming of the part. As the investment for the tooling was quite substantial, a flow simulation was carried out in order to verify the infusion strategy. Several design iterations led to quite some delay in the milling of the tooling. Therefore, the first of the 16 prototypes were produced as late as April 2013.

From the beginning, structural design was limited in order to accelerate the design. This was clearly communicated with the users committee, although there was the wish for a structural evaluation of demonstrator C. Due to the delay in production, three prototypes will be tested outside the project and the results communicated to the committee afterwards.

After manufacture, an evaluation was made in terms of production times and costs. This evaluation included material costs (incl. material waste), depreciation of equipment, tooling costs, labor, etc. The result was used to validate the cost models within work package 7.
5.6 Efficient Post-Processing

In this work package, various techniques for material removal (trimming, machining and drilling) were evaluated via experiments on a selected number of composite materials. The compatibility between product design attributes and the various techniques were addressed as well.

Second, a literature studies on design for assembly and on surface finish were conducted. The results were applied to the three demonstrators.

Post-Processing Operations

Within a first subtask, trimming and drilling operations were examined using mechanical and non-mechanical material removal techniques. This was done in the labs of Sirris Advanced Manufacturing via experiments. Of particular interest were

- the use of robots
- contouring by conventional milling
- contouring by water jet, laser milling or sawing

Parts were decomposed in a series of features and included in the decision tool. In addition, a link to the performance specifications was made by integrating tolerances, roughness and accuracy in the tool:

Design for Assembly

Design for assembly was treated by a literature study. Hereby, mechanical assembly (riveting, direct threading), adhesive bonding as well as novel bonding technologies (expanded bonded bushing) were treated and included in the handbook.

Surface Aesthetics

An overview of applicable surface treatments was made in form of a literature survey. Of particular interest were:

- gel and top coating
- thermoformed surface layers
- grindable gel coats or primers combined with paints
- in-mold coating techniques for low pressure molding

By literature studies, component design was considered with relations between geometrical design attributes, the surface requirements (e.g. class of surface quality, scratch resistance) and the available surface coating techniques.
Demonstrator A was designed and manufactured using
- in-mold insert technology
- gel coats
- trimming operations

Demonstrator B was designed and manufactured using
- adhesively bonded onserts and clips
- gel coats
- trimming operations

Demonstrator C was designed and manufactured using
- Teufelberger’s t-igel technology and appropriate bushing holders
  (green and blue tooling inserts in the figure below)
- removal of the flash only (net-shape part)

5.7 Integrated Cost Assessment Tool
In this work package, a simple-to-use cost estimator tool was developed. Starting point for the development of this tool were Sirris’ “Sandwich Selector”, ITA’s “Ecopreform” tool and Ashby’s cost estimation methodology. Based on previous experience, Excel was chosen as the environment.

The cost-relevant process steps were identified in a work breakdown structure. For each item of the WBS, cost model was programmed according to Ashby’s cost model. This cost model was split up into a share of material contribution, tooling contribution and a mixed term for equipment, labor and overhead.

\[
C = \left[ \frac{mC_m}{1-f} \right] + \frac{C_t}{n} \left[ \text{ceiling} \left( \frac{n}{n_t} \right) \right] + \frac{1}{n} \left( \frac{C_c}{L_t} + \hat{C}_{oh} \right)
\]

- Material contribution
- Tooling contribution
- Capital overhead & production rate
Material contribution
- Materials cost $C_m [€/kg]$
- mass $m [kg]$
- scrap fraction $f [-]$

Tooling contribution
- Cost of tooling $C_t [€]$
- Actual production quantity $n [-]$
- maximum production lifetime of the tooling $n_t [-]$

Capital overhead & production rate
- Cost of equipment $C_c [€]$
- productivity factor per tool $L [-]$
- capital depreciation time $t_{dep} [a]$
- labor rate including overhead for administration, rent $C_{oh} [€/hr]$
- production rate $n [1/hr]$

First, this basic equation was rewritten into cost shares on product, project and investment level. Special consideration was given to the shape complexity of the component. Experience showed that both the tooling cost and the cycle time were strongly dependent on the complexity. Different means of complexity definitions were reviewed, such as an analytical geometry analysis, CAD supported curvature analysis, etc. None of these means where robust enough with regard to different cases. Therefore, the consortium decided to include a series of examples in the handbook and the cost estimator tool.

The tool was developed in Visual Basic for Applications and Excel. In parallel, the tool was documented as part of the handbook. By means of the three case studies, the tool was validated and demonstrated to the users committee. Feedback regarding the layout user friendliness was incorporated. The final release will be published and distributed online in parallel with the publication of the handbook,
Screenshots from the graphical user interface of the cost estimator
5.8 Decision Tool

The results of the project were condensed in a decision tool. In consultation with the users committee, it was decided to publish the decision tool in form of a handbook. This handbook should contain the basic principles of the envisaged composite processing, the decision tool as such, and the three, well documented demonstrator case.

An important request from the users was a structure and layout which was as interactive as possible. Dealing with a multi-criteria decision tool, a series of didactic means were tested throughout the project. Tested didactic means were Ashby plots, spider charts, flow charts, compatibility matrices and others. Finally, the consortium decided to use multi-criteria decision matrices. In particular, the researchers identified criteria, scores and the weighting as part of the technical work packages.

By doing so, the user of the decision tool simply has to mark the criteria which apply to the project/product and to sum up the total of all relevant scores. The option with the highest total would be taken further in the subsequent evaluation steps. This approach proved to be

- reliable over a wide range of applications, as a series of more than 20 cases were used for the fine-tuning of the scores and the weighting
- very robust, as the same options were prevailing for different users of the tool
- simple enough to be printed in a handbook

<table>
<thead>
<tr>
<th>Selection step</th>
<th>Flag</th>
<th>Weighting</th>
<th>Option1</th>
<th>Option2</th>
<th>Option3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Criterium 1a</td>
<td>yes/no</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Criterium 1b</td>
<td>yes/no</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Criterium 1c</td>
<td>yes/no</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
<td></td>
<td>7</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Criterium 2a</td>
<td>yes/no</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Criterium 2b</td>
<td>yes/no</td>
<td>7</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterium 2c</td>
<td>yes/no</td>
<td>7</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 3</td>
<td></td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Criterium 3a</td>
<td>...</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Criterium 3b</td>
<td>...</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 4</td>
<td></td>
<td></td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 5</td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Percentage</td>
<td>(of max total)</td>
<td>12+23+</td>
<td>12+8+</td>
<td>15+39+</td>
<td>67% 45% 100%</td>
</tr>
</tbody>
</table>
During a final workshop a series of cases was discussed with the member of the users committee. The provided feedback allowed further fine-tuning of the guidelines and its documentation. Tasks to be completed after the project were review tasks, layouting, publication and distribution of the handbook. Estimated period of publication is September 2013.

In order to reduce handling and shipping of the handbook after the project, the users committee agreed to distribute the book via a print-on-demand online bookstore. This allowed reducing the risk of printing too many or too few copies (see Amazon’s [www.createspace.com](http://www.createspace.com) or Bol’s [www.bravenewbooks.nl](http://www.bravenewbooks.nl)).

5.9 **Dissemination**

Subject of work package 9 "dissemination" was the communication of the results among the users committee and the broader target industry. The dissemination was structured in four phases:

**Phase I: Active participation of users committee in workshops**

Internal dissemination activities were necessary in order to inform the users committee about the project progress. A half yearly meeting sequences was defined to create a good follow-up of the project and to fulfill the requirements specified in the Cornet rules. From the beginning of the project, it was chosen to actively involve the users committee. Instead of an ex-cathedra dissemination of the results, the industry partners were working hands-on in the lab.

In that sense, the members of the users committee were part of the following workshops:

- decision on the demonstrators
- layup and infusion of a service tray, a sailing boat, a tram part and the control arm
- case studies in order to validate the decision tool
Phase II:  Dissemination of intermediate results to the industrial users committee

Besides the regular presentations for project review, the following documents and files were presented and distributed among the members of the users committee:

- Generic performance specification (Excel template)
- Overview on LCM processes (PowerPoint presentation)
- Viscosity and fabric permeability (PowerPoint presentation)
- RTM mold design (PowerPoint presentation)
- RTM-light mold design (PowerPoint presentation)
- VARI mold design (PowerPoint presentation)
- Overview on preforming and drapability (PowerPoint presentation)
- Overview cost estimator (PowerPoint presentation)

These documents stay available to the member via an ftp-server and direct contact with the researchers.

Phase III:  Publication of project results and final guidelines to the industrial community

The following documents will be distributed among the users committee upon layouting and publication:

- LCM cost estimator (Excel sheet)
- Guidelines (handbook)

At the end of the project, the book still needed to be layouted (foreseen in August/September 2013). Via a print-on demand online bookstore the guidelines will be distributed across a broad industrial community.

Before the publication of the handbook, project results were already disseminated to a broader industrial community. Dissemination activities included:

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Target group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Since 2011</td>
<td>Distributing of DeMaCo flyers at Sirris and SLC-Lab during guided tours and visits to customers</td>
<td>Belgian industry</td>
</tr>
<tr>
<td>8/2011</td>
<td>Article “Softwaretool voor duurzame en haalbare materiaalkeuze” on Sirris Technilne network</td>
<td>Belgian industry</td>
</tr>
<tr>
<td>12/2011</td>
<td>Article “Additive manufacturing van oplosbare matrijzen en modellen voor composietstukken” on Sirris Technilne network</td>
<td>Belgian industry</td>
</tr>
<tr>
<td>Since 2012</td>
<td>Distributing of DeMaCo flyers at the Institute of Textile Technology (ITA) of RWTH Aachen University during guided tours and visits to customers</td>
<td>Composite professionals as well as non-specialists</td>
</tr>
<tr>
<td>Since 2012</td>
<td>Project profile on the website of the Institute of Textile Technology of RWTH Aachen University (<a href="http://tinyurl.com/ita-demaco">http://tinyurl.com/ita-demaco</a>)</td>
<td>Composite professionals as well as non-specialists</td>
</tr>
<tr>
<td>Since 2012</td>
<td>Use of results within teaching activities of ITA and PUK, as well as company trainings at SLC–Lab</td>
<td>Students in different fields, as well as industrial non-experts</td>
</tr>
<tr>
<td>03/2012</td>
<td>Distribution of DeMaCo flyers at JEC Composite Show in Paris 2012 and 2013</td>
<td>International experts in the field of composite technology</td>
</tr>
<tr>
<td>03/2012</td>
<td>Article “Nauwkeurig microbiwerkingssprocede van composietmaterialen” on Sirris Technilne network</td>
<td>Belgian industry</td>
</tr>
</tbody>
</table>
Phase IV: Publication of project results and final guidelines to the academic community

Parts of the final guidelines were already published at the following industrial and academic conferences:

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference paper</td>
<td>M Kaufmann, DC Berg, C Greb, M Cetin, B Waeyenbergh: „Design for Manufacture for Liquid Composite Molding“. Proceedings of Composite Week@Leuven, Leuven (Belgium), 18 September 2013</td>
</tr>
</tbody>
</table>

Phase IV: Bilateral projects with industrial partners

A range of bilateral projects and interventions were established as a result of project DeMaCo. These bilateral projects contain a broad range of activities:

- company visits and advices
- brainstorm session
- practical training in liquid composite molding
- production of a demonstrator on a DeMaCo mold
Parallel Spillover activities
Spillover activities are activities and projects which appeared in the periphery of Cornet DeMaCo.

- Use of a demonstrator mold for SBO project “self-sensing composites” (see www.selfsensingcomposites.be). The aim was the proof-of-concept of optical fiber sensor technology with state-of-the-art RTM processes

- Setup of AO–NIB project „Generation Composite“ in which RTM and RTM–light were defined as two of the key enabling technologies for fast, green and flexible composite production. Within “Generation Composite”, a large, integrated demonstrator will be designed and built. For more information see www.generationcomposite.be.

5.10 Follow-up after the completion of the project
As mentioned above, the layout, publication and distribution of the handbook will be done after the end of the project. Distribution channel will be Amazon’s or Bol’s print–on–demand service. The price of the final 120 page book will be 30–50 euro, which is the cost for production and distribution.

During the coming years, the guidelines will be presented as part of workshops to reach many SMEs in a hands–on design session. These workshops are open for external participants and contain the presentation of the decision tool, an exhibition of the demonstrators. Further advertising of the project and the handbook will be done

- at scientific and industrial conferences
- via mailings and direct customer contact
- via material suppliers
- during future workshops (e.g. the master classes of NIB project Generation)

The methodology will be used in Sirris’ technical advisory service and future collaborative research programs. Thus, the Sirris Leuven–Gent Composites Application Lab (SLC–Lab) will take the lead to disseminate the results within its industrial projects. In Germany, the Aachen Composite Engineers (ACEs) will use the results as well in its advisory service. The seminars and newsletters of the “Industrievereinigung verstärkte Kunststoffe Deutschland” (AVK) is another channel to disseminate the results to the German industry.
6 Further Information

For further information on the project, the guidelines and the cost estimator tool, please contact the project coordinator.

**Markus Kaufmann**
Phone  +32 (498) 91 94 91
Mail  markus.kaufmann@sirris.be
info@slc-lab.be

**Address**
Sirris Leuven–Gent
Composites Application Lab
Celestijnenlaan 300C
3001 Heverlee

For a route description click [here](#).