4.1 Final publishable summary report

4.1.1 EXECUTIVE SUMMARY

The present project fills the gap existing in the European market concerning energy efficient and lightweight composite parts and tooling. For that aim, the recent but emerging Tailored Fibre Placement (TFP) is supposed to be a very interesting technology because it allows inside a composite component to have the carbon fibres where they are really needed and adjusted to principal stress fields. Besides, self-heating technology combined with TFP offers to the composites industry a faster response and energy efficient heating system for composites manufacturing processes. However, these technologies still need more optimization and industrialization in order to have a wider utilization in many industrial applications such as aeronautic, wind energy or automotive.

All over the project, the key issues have been in one hand the finding and developing of interesting applications where self-heating concepts combined with TFP technology can be very useful and in other hand, the improvement of some features of that technology. The applications which have been carried out along the project have improved the energy efficiency in rigid tooling and flexible membranes/vacuum bags for composites manufacturing processes and increased the productivity of preforming, infusion and RTM operations.

In parallel, it has been matured the TFP machine technology towards a higher process robustness, productivity, quality and reliability without a tremendous price increase of the technology itself. Therefore the research during the project was concentrated on two topics, firstly the further automation of the deposition capabilities and secondly the monitoring of the process. The last issue considered during the project has been a computer tool in order to exploit another outstanding feature of the TFP, which is the steering of the reinforcing fibre, allowing the manufacturing of ultra light components, where fibre is, at each point, oriented according to the stress field, which means an optimum material usage.

The success of such interesting developments could only be done if the qualification of the consortium was high. So, the project was planned at the European level forming a consortium able to meet the project needs and formed by 6 SMEs willing to obtain final products or improvements on their manufacturing processes and 3 RTD institutions experts in manufacturing components in composite using TFP technology and self-heating concepts.

In order to carry out this work, the project has been organized in 4 workpackages plus two additional workpackages for management and dissemination issues: WP1: Development of self-heating concepts based on TFP embedded layers, WP2: Monitoring and automation of the TFP technology, WP3: Advancements in fibre steering, WP4: Development of prototypes, WP5: Final evaluation, dissemination strategies, training and exploitation, WP6: Management and coordination. EMBROIDERY project has lasted 2 years, starting on 01/01/2011 and ending on 31/12/2012, and at the project end all the **goals** of the project have been **fulfilled, fact that make all partners consider it a success**. The following table resumes obtained results:

Result Nº	Description
1	Automated heating membranes for aircraft repair
2	Self heating reusable flexible membranes for vacuum bag and infusion processes
3	Self heating reusable flexible membranes for preforming applications
4	Self heating composite rigid tooling and thermal simulation tool
5	Composite components with thermal built-in function
6	Monitored and automated stitching head
7	Computer algorithms accounting for fibre steering

Table 1.- Obtained results

4.1.2 SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

Composite materials are starting to be used extensively in many industrial applications (automotive, rail, aeronautic, marine, wind energy, construction, etc.) with higher production needs than the yielded by current manufacturing technologies. A trend towards automation and liquid moulding technologies is noticeable nowadays. However, still some drawbacks exist:

- The preforming step of the dry fibre is a very time consuming hand labour process, accounting for an important ratio of the cost of the final product.
- The productivity is limited by the long heating/cooling cycles required to bring the laminate to the curing temperature (the whole mass of the mould has to be heated).
- In the case of the infusion process, a major limitation is the long time required to lay up the disposable vacuum bag and the impossibility of heating the laminate side in contact with the bag.

Tailored Fibre Placement (TFP) is a recent but emerging technology that was developed in the mid-90s and is based on embroidery machinery used in the garment textile industry. The machines have been adapted to deposit and stitch fibre rovings onto a base material. The relative movement between stitching head and carrier material forms the roving path. The following figures show a TFP machine in use and an example of preform.

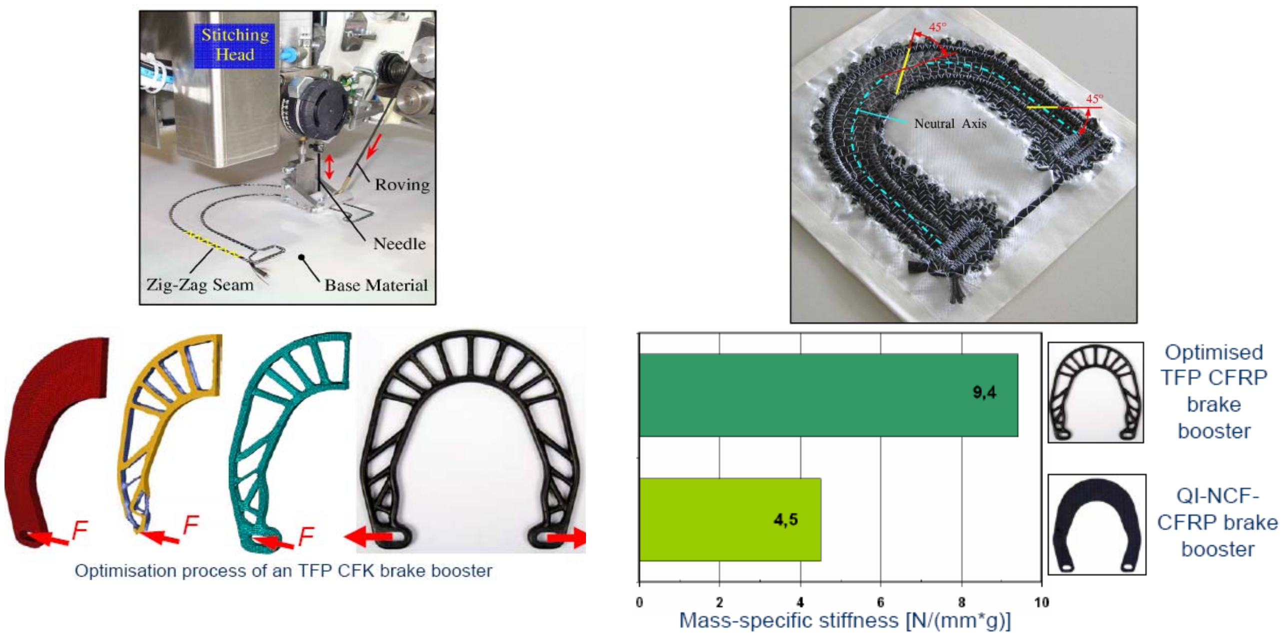

Figure 1.- TFP process and example of optimised preform (MTB brake booster). Source: IPF and IFB

The main benefits coming from TFP technology are:

- Fibre orientation can be adapted to principal stress fields within the component, fully exploiting the load carrying capacity of the fibres.
- Local reinforcement of preforms in highly stressed areas is possible.
- Near net shape production reduces material waste.
- Automatic deposition ensures high accuracy and repeatability of amount and orientation of fibres.
- Multifunctional preforms with structural and thermal capabilities.

In order to solve the drawbacks mentioned before, TFP will be used to manufacture a carbon fibre based layer able to be embedded within either rigid composite laminates or elastomeric materials. **This layer will act as heating layer**, bringing out the following benefits:

- Increasing productivity in ***infusion and preforming*** operations, by reducing heating/cooling time.
- Decreasing energy demand and increasing productivity in ***RTM process***, by placing heat just where needed.

In addition, EMBROIDERY aims at solving a limitation of current manufacturing techniques, which make use of standard fabric materials for building a laminate. This means that, within a layer of material, it is not possible to vary the fibre orientation along the geometry. However, TFP technology provides the ***fibre steering potential***. That means that in the preform, the fibre orientation at each point can be oriented according to the stress field of the component, exploiting the full capabilities of the reinforcing fibre and optimising the material usage. However, in practice this potential is not exploited yet due to the lack of a computer commercial software package which takes into account the fibre steering feature. Therefore, a second focus of this project will be put on developing computer algorithms which account for steering potential. The final objective is the implementation of such algorithms into commercial software for composites analysis.

A third focus of the research will be put on the **automation and monitoring of the TFP technology** itself. In this part of the project, three topics have been addressed, further automation of the deposition capabilities, the monitoring of the process and the influence of the design quality on the deposition process. One important goal of EMBROIDERY was to reduce the manufacturing costs of the process to make it attractive for a wider range of applications and industry fields. This could be achieved by increasing the overall machine speed or to use reinforcement fibres types with a higher weight per length, so called Heavy Tow material. Heavy Tow material is a roving which has more than 50 000 filaments in case of a carbon fibre and was not able to be placed in a productive way before this project, due to the small spool the machine uses in the standard configuration. To solve this issues a development for an external feeding device to increase the deposition capabilities started in EMBROIDERY.

For aerospace and automotive application it is important to have a process documentation capability for quality reasons. Without it the TFP process would not find acceptance as a manufacturing technology. Therefore it is important to know the behaviour of the important machine and process parameter during manufacturing and a possibility to document them. During this project the capability to measure and document the sewing thread tension and the roving spool thickness was established.

The third focus of this part of the project will be put on a design quality study to increase placement robustness. From the experience of the partners it was obvious that the fibre pattern design for the TFP process has an influence on the productivity and the quality of the process itself. Therefore a quality study was performed to figure out the influence of different machine parameter settings on the laydown behaviour of different reinforcement fibre thicknesses.

The following table summarizes the quantified expected objectives from the proposed research in terms of cost reduction, energy reduction, time reduction and weight reduction. Obviously, these benefits are interrelated, a time reduction of the moulding process implies a reduction on the manufacturing cost. However, in the table below each parameter is considered to be independent for make the analysis easier.

Overall objective	Ref	Potential application	Targeted markets	Benefits (%)				
				Cost reduction	Process energy reduction	Process time reduction	Weight reduction	Quality control
Development of a embeddable carbon based heating layer by means of TFP technology	1	Elastomeric membranes for aircraft repair	Aeronautics	20	-	-	-	
	2	Elastomeric membranes for infusion process	Wind energy, aeronautics, construction, transport	-	40	10	-	
	3	Elastomeric membranes for preforming applications	Aeronautics, transport	-	40	40	-	
	4	Self heated composite tooling	Wind energy, aeronautics, construction, transport	-	40	20	-	
	5	Self heated composite components	Aeronautics, wind energy, transport				5	
Development of algorithms for exploiting the fibre steering capabilities if the TFP technology	6	Ultra light components	Transport, space, aeronautics-	-	-	-	25	
TFP machine, optimisation and monitoring	7	Monitoring and automation of TFP machine	General composites industry					YES

Table 2.- Quantified expected benefits from the research

And the following table compiles some industrial applications where these results could be applied:

Industry sector	Specific segment	Current issues	EMBROIDERY approach
Automotive/ transport (medium-high volume composite parts)	Body panels and structural lightweight chassis structures	Limitation of productivity and cycle time of composite processing technologies	Reduction of curing cycle time due to the use of fast and energy efficient self heated tools
Aeronautic composite structures	Heavy loaded composite components and with additional functionalities (de-icing, etc)	Manufacturing costs, further weight reduction and additional functionalities of composite structures	Self heated composite structures with resistive embedded preforms and tailored local fibre reinforcements
	Composite repairs	High intensive labour costs of heating blankets and thermal control limitations	Automated manufacturing of heating circuit by TFP with tailored thermal power areas
Windmill sector	Composite blades	Manufacturing costs and additional functionalities of composite structures	Self heated composite moulds/ membranes for infusion with resistive embedded preforms
General composite structures	General purpose fibre preforms by TFP	Lack of optimization design tools and process robustness and automation	Specific design tools for structural fibre preform optimization and fibre laying process monitoring capabilities

Table 3.- Potential applications

4.1.3 DESCRIPTION OF THE MAIN S&T RESULTS/FOREGROUNDS

Six work packages (WPs) **completed in two years** were identified to achieve the objectives stated for the project. The final results obtained are those which are resumed in Table 1.

In order to carry out this work, the project was organized according to the following scheme: **WP1: Development of self-heating concepts based on TFP embedded layers, WP2: Monitoring and automation of the TFP technology, WP3: Advancements in fibre steering, WP4: Development of prototypes, WP5: Final evaluation, dissemination strategies, training and exploitation, WP6: Management and coordination.**

In the next paragraphs, the main results obtained in each of those work packages are resumed.

WORK PACKAGE 1 has provided the first developments and small samples to show the reliability of self-heating concepts based on TFP embedded layers. The main objectives of this WP were the following:

- To develop carbon fibre or metallic wire based resistive heating layers by means of TFP technology.
- To develop self-heating flexible membranes for composite repair, infusion and preforming processes by embedding the heating layers inside the membranes.
- To provide the heating system to composite rigid tooling by embedding the heating layer.

The first task of these WP has been the selection of the applications where the SME participants have detected an important room for improvement which can be solved by the proposed technology. Then, each SME has set the requirements that must be fulfilled by the heating system in terms of maximum temperature, cooling/heating rates, total power output, power density, durability, adaptability to complex geometries, etc.

There are three different types of applications depending on the interest of SMEs. First of all, there were selected **self heated flexible membranes** for preforming or repairing tasks. In this case, for example, the SME dedicated to the fabrication of repair membranes manufactures the heating layer manually and then they embedded it between silicone membranes. TFP technology could provide an automatically manufacturing of the heating layer and that is the reason why it has been selected. The following figure shows the final repairing membrane and manually manufactured heating layer.

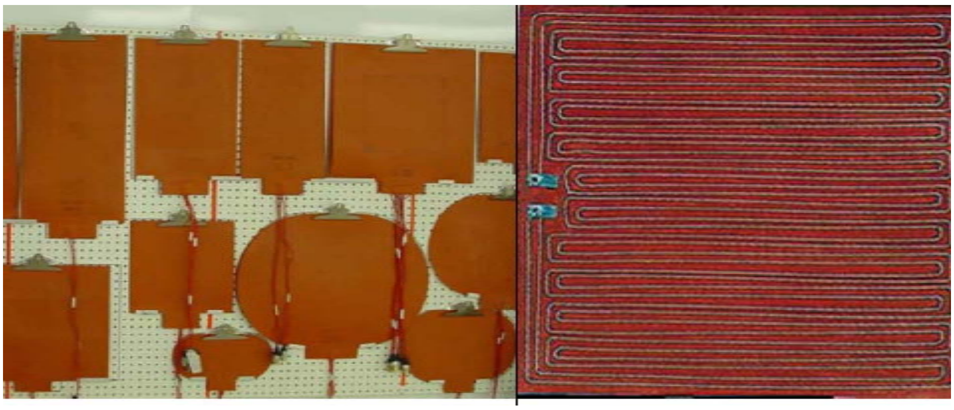

Figure 2.- Various heating blankets and manually manufactured heating layers

Another type of application selected has been the developing of **self heated rigid laminates** for tooling and also developing of specific software/codes for resistive heating thermal simulation. The main aim was to make easier and more efficient the design of complex heating structures.

Finally, **self heated rigid laminates for multifunctional components** have been carried out. The SME interested in this application wanted to develop multifunctional components, which mean structural laminates with embedded thermal capabilities (for example de-icing applications). Additionally and recommended by the officer of the project, all partners have found some **general public applications** where this technology could be of interest.

After selecting the applications to be carried out, the selection of raw materials has been done in order to use the most suitable materials for the technological trials. In one hand, the materials to manufacture the heating layers by TFP technology have been selected, such as the fabric supports where the resistive materials are stitched, stitching yarns or resistive materials. Some carbon fibre rovings and metallic wires have been chosen and then they have been used depending on mainly the power output of each application.

In the other hand, silicone membranes for the fabrication of reusable heated membranes have been selected and tested. Several paste silicones and precured silicone sheets have been evaluated and a precured silicone sheet has been selected for self heated flexible membranes because it makes the embedment of heating layers easy and it has very high temperature resistance and high mechanical properties in terms of tear strength and elongation. Other approaches evaluated have been the using of commercially available thermally conductive silicones and the doping of thermally insulator paste silicones in order to enhance the thermal conductivity of the flexible material. These tests have offered some good results but this option has not been considered in the final prototypes.

For the manufacturing of self heated rigid laminates, some prepeg materials have been chosen and tested because of an easier embedment of the heating layer. Apart from that, a liquid laminating resin and a surface gel coat have been selected for the study.

Another task carried out has been the way how the resistive circuit is connected to the current source. The carbon fibres and metallic wires used as heaters are brittle and it is needed to connect the resistive circuits ends to a more robust metallic strips along the mould/membrane and then leave these robust strips from the prototype for connecting to the power source. The following figure shows a simple draft of the suggested connection approach.

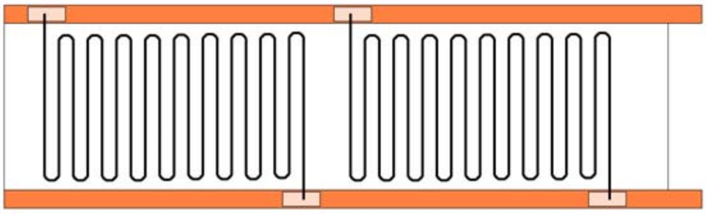

Figure 3.- Suggested connection approach

In order to support the technological tasks, some heat transfer simulations have been carried out. The aim of this task is to determine the best configuration of self heated rigid laminates in order to have the best homogeneous thermal distribution on the surface of the RTM mould and also the evaluation that basic irregularities found in RTM mould do have in the thermal distribution of the mould surface. Regarding the best configuration of the self heated rigid laminate, the best position of the heating layer in the through thickness direction and the influence of the mould materials to get the best energy efficiency and homogeneous thermal distribution on the surface of RTM moulds have been evaluated. In the evaluation that basic irregularities have in the thermal distribution, the temperatures at the surface along edges and corners have considered of special interest, mainly because manufacturing limitations would not allow extending of the heating layer perfectly into these zones.

Apart from previous simulations, some tools have been developed for the simulation of the thermal behaviour of moulds and membranes for composite manufacturing. The main aim of these tools is to make easier the calculation of the required power densities in the heater in each application and also the features (circuit sizing, number of branches, type of resistive material, distance between circuit lines and so on) that the heater would have to reach the required power density. The following figure shows the developed 1D mathematical model to calculate the required power density of the heater:

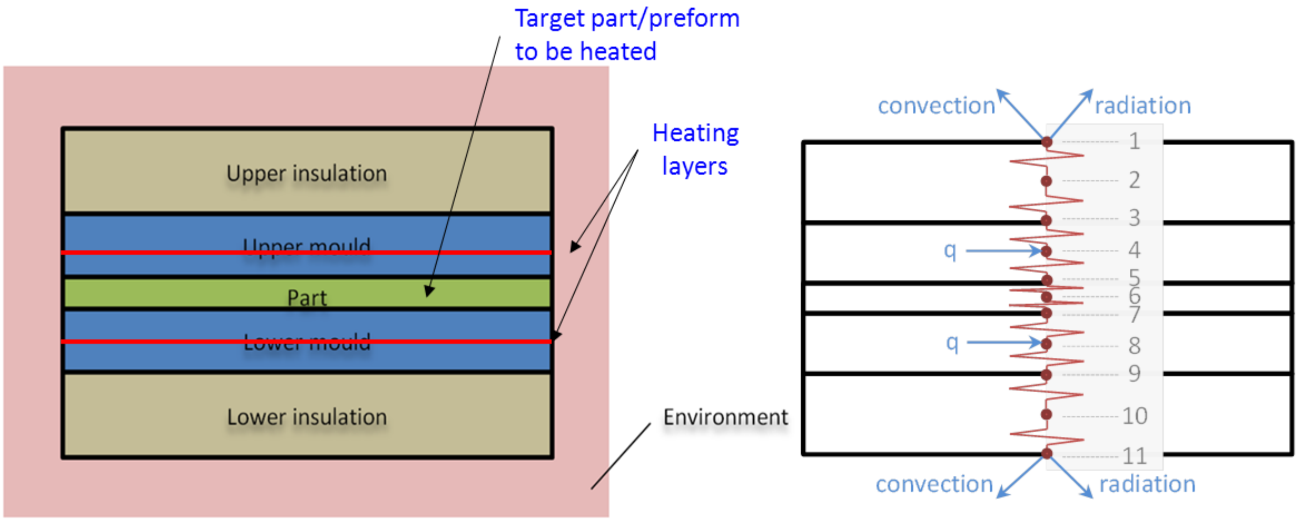

Figure 4.- Closed mould model

The next step in this WP has been to define a Validation Plan in order to test and validate previously selected materials, heating layer embedding procedures in flexible membranes and rigid laminates and also the simulation tools developed for sizing the heaters. Besides technical issues, those trials were important also to demonstrate the economic feasibility of proposed technology and if it can be applied to the targeted industrial sectors (manufacturing of composite components).

Regarding the manufacturing of heating layers, it was concluded that both carbon fibre rovings and metallic wires could be stitched by TFP technology. Two different support fabrics were used depending on the final application. For self heated flexible membranes, an open support material was used because it guarantees the contact between both silicone membranes in the embedment. But, for self heated rigid laminates, a light glass fibre was used because it makes the stitching of the resistive material easier. The following figure shows a heating layer made by carbon fibre roving:

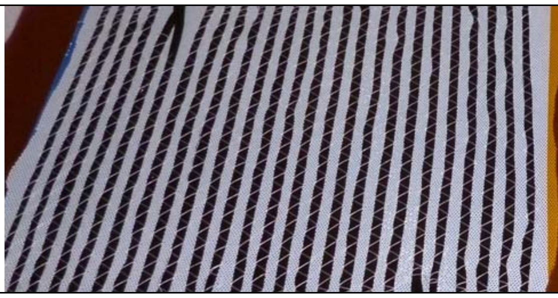

Figure 5.- Carbon fibre stitched on support material

In the previous figure it can be observed an electrode integration method used to connect the resistive circuit to the current source.

Then, some embedment trials have been done to validate selected flexible membranes and prepeg materials for rigid laminates. Then, all of them have been heated by a programmable power source for the evaluation of their heating ability. The heating of the specimens was measured using a thermal camera and reached maximum temperature and thermal gradients on the sample surface were assessed.

The electrical and thermal performance of manufactured specimens was completely satisfactory and it was demonstrated that the proposed technology and materials were suitable to fulfil the requirements of selected final prototypes. Moreover, some carbon fibre laminate preforming and prepeg material curing trials have been done using manufactured self heated specimens in order to validate the final aim of these items. The following figures show manufactured omega shape self heated membrane, preformed carbon laminate and the recording of the thermocouples fixed to the membrane.

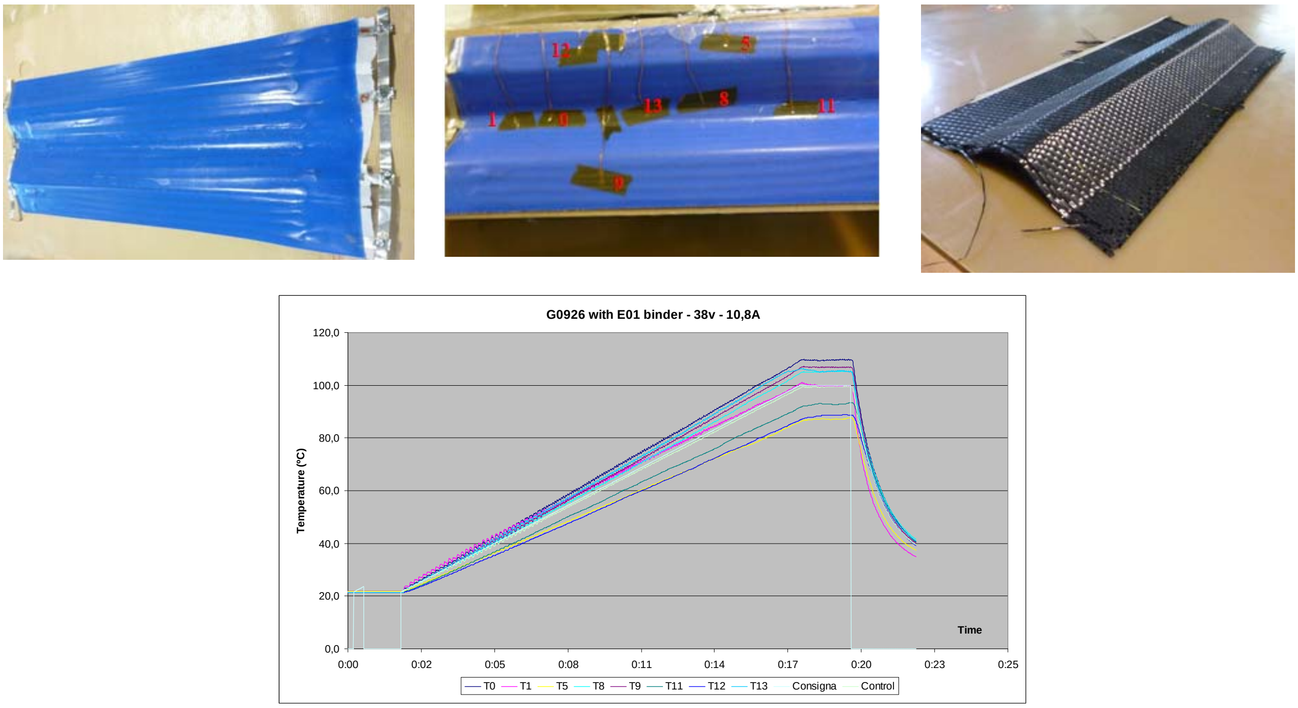

Figure 6.- Manufactured self-heated membrane, preformed carbon laminate and the temperature recording of the thermocouples

Then, the self-heating concepts based on TFP embedded layers developed in WP1 have been used to manufacture some representative prototypes defined by participant SME´s. Some self heated flexible membranes and rigid tooling for multifunctional components have been carried out. In the following lines one of the self heated flexible membrane manufactured for aircraft repairing is presented.

The proposed self heated membrane has a square shape with 500mm side. This membrane must reach 180-200ºC and it must have two zones, the inner and the outer having 10% more power density for lightening edge effects. Moreover, the thermal gradient allowed in each zone is ±5 ºC. By using calculations tools developed during the project, it was defined the power density and resistive circuit size needed in each zone of the heating layer in order to reach required temperatures on the surface. The resistive circuit to be used is a metallic wire and the circuit design is shown in the figure below. Then, the heating layer has been manufactured in an open support fabric, and after doing electrical connections it has been embedded between two silicone membranes. The final self heated membrane is shown below.

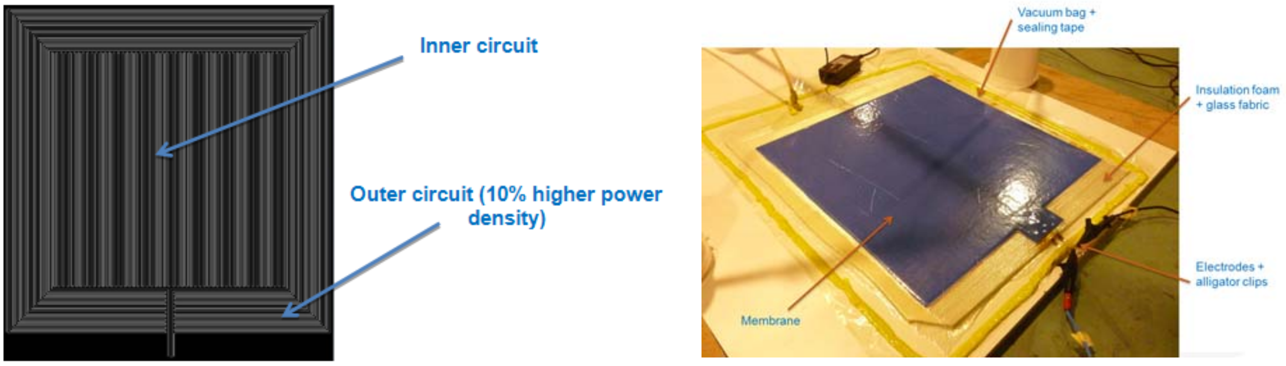

Figure 7.- Designed resistive circuit and final self-heated membrane

The manufacturing of the membrane has been satisfactory and then it has been heated and validated by an infrared camera. The figures below show the heating of the membrane and a graph where it is demonstrated the accurate thermal distribution in each of its zones.

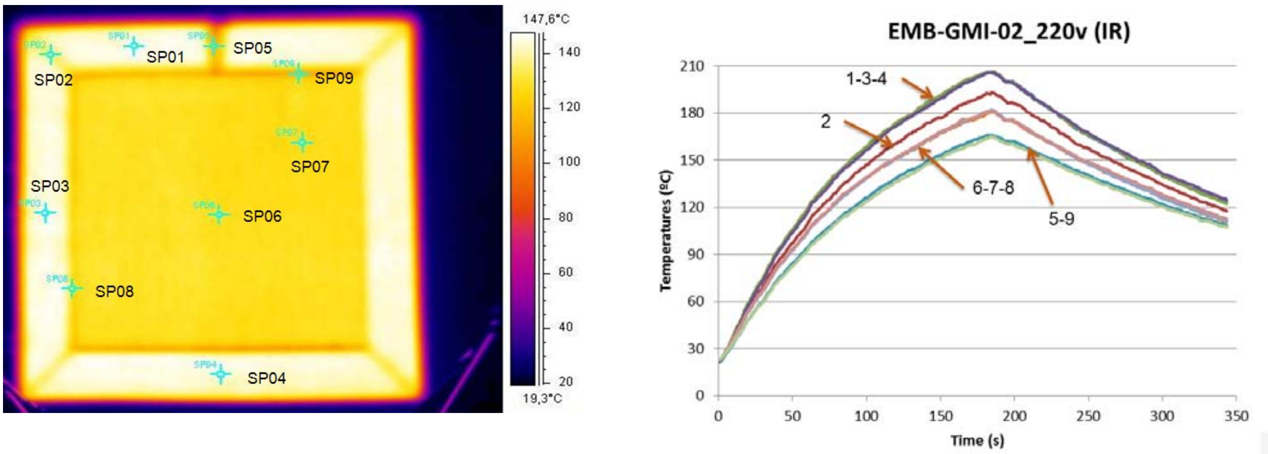

Figure 8.- Position of the temperatures plotted in the graph on the left and temperature recording of infrared camera on the right

Using the same procedure detailed for the aircraft repairing membrane, the other proposed prototypes have been manufactured and validated. The results obtained in all of them have been completely satisfactory and it has been demonstrated that the proposed technology is capable of fulfilling the requirements demanded by SME´s.

WORK PACKAGE 2 aimed at selecting the most suitable monitoring and automation system for the TFP process to enhance preform quality and process robustness. The main objectives of this WP were the following:

- Selection of the most suitable monitoring and automation system for the TFP process to enhance preform quality and process robustness
- Developing of concepts for the prototype realization examined in the TFP environment

Below, the concepts developed by IFB are summarized:

Monitored stitching head and I/O board

With the thread tension measurement device developed in EMBROIDERY, it is possible to measure the thread tension during the stitching process. This enables the operator to monitor the stitching process and to control the thread tension consistent according the best settings for the TFP process. A storable documentation of this information is available for quality assurance proposes. In the picture of the sensor device the attachment point at the machine is illustrated. It was important to place the measurement device as close as possible to the needle position to secure realistic tension values.

In cooperation with the developed I/O board by Tajima GmbH it is now possible to stop the machine in case of a tension value out of the defined thread tension range. This allows an absent operator while machine running which offers a big cost potential.

However, the I/O board is not only important for the monitoring system or the external feeding device developed during EMBROIDERY, but also to connect different other external devices like an automated frame changer which already exists.

Endless feeding device

The endless feeding device enables the use of reinforcement fibres without rewinding them onto special embroidery spools. By the usage of the original spools from the fibre manufacturer the time consuming process step of rewinding is eliminated. Additionally the necessary change of empty fibre spools is reduced up to 90% percent, due to the usage of bigger amount of fibre material.

Because of special monitoring capabilities integrated in the endless feeding device additional functions are available. For instance a laser distance sensor is integrated, monitoring the diameter of the fibre spools. This is necessary because the fibre were pulled from the spools. To adjust the pull speed which depends on the spool diameter it is necessary to know it. Knowing the spool diameter enables the control unit to calculate the amount of fibre length left on the spool.

For the external feeding device different concepts were developed. The specifications for the feeding device were the following:

- Use of original spools up to 8 kg in weight
- Use from 12K up to 50K of carbon fibre roving material
- Head rotation up to 360° in both directions (720° rotation in total)
- Equal placement result compared to state of the art system
- Assembly on the Tajima TCWM series

This was realised during EMBROIDERY developing a fibre feeding concept fulfilling all the specifications mentioned before. The roving fibre spool is storage behind the machine. Using a controlled spooling system, the spools will be unwound according the deposition speed of the placement process.

The reinforcement fibre is guided through guiding elements. To realise the 720° rotation of the head some of the guiding elements are connected by a small chain. This chain is hold and moved by the head using a modified sprocket. All guiding elements are made out of PTFE to minimise friction losses.

Deposition tests with the new external feeding device, using carbon fibre with 3300Tex, show good placement quality and only a slight reduction in the placed fibre width compared to the state of the art TFP-technology.

Some pictures show the developed external feeding device.

Deposition head of the external feeding device

Thread tension measurement device adapted at the TCWM machine

Back view of the TFP machine with the developed external feeding device

Figure 9.- Developed external feeding device

WORK PACKAGE 3 deals with developing methods and tools to generate mechanical appropriate finite element models, which help engineers to construct light weight parts with a maximum performance. Thus, another outstanding advantage of TFP is exploited, which is the possibility to use the anisotropic properties of the fibers to transfer the load in fiber reinforced plastic structures effectively, resulting in lightweight components.

The results in this part of the project consist of two major parts, a theoretical foundation and a numerical implementation. The first part considered the theoretical analysis of variable axial fiber structures, which are typical for the TFP technology. Due to the high flexibility of TFP the fiber layouts no longer are limited to a constant fiber distance and orientation for each layer of fibers. This allows for very high performance while also inducing a significant complication to create realistic FEA models. The thickness of the fiber layers usually varies strongly.

Using a simplified description of the roving paths in terms of lines inside the stitching plan, it was possible to derive fully analytically the continuous thickness distribution for any given stitch pattern. For the resulting formula the material properties like roving cross-section area and lay-up width are used as input parameters. The second step, the numerical implementation, is essential for any exploitation of the results for the benefit of SME's. For this purpose many file exchange format issues had to be resolved. As the final objective of this work package was to develop industrial deployable software, the development of peripheral file exchange tools was an important task. In Figure 10 and Figure 11 the thickness distribution of an optimized brake booster layout is shown. The local thickness is shown as a color plot in position space. And the profile of a cross section along the green line in the left picture is shown in Figure 11. Different rovings are marked with different colours.

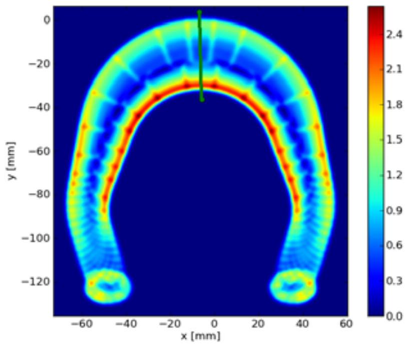

Figure 10.- Colour plot of the thickness distribution

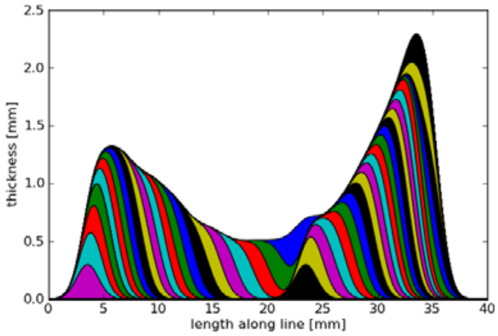

Figure 11.- Cross-section along the green line in

A theoretical extension of the derivations for the thickness distribution yielded a locally averaged fiber orientation. This information is the second step to create mechanical appropriate FEA models. Using a macro scaled approach, i.e. using reasonable fine meshes and not modeling on a filament basis, the local geometry and also the fiber orientation is needed, due to the anisotropic material properties of composite materials. Figure 12 shows the schematic diagram of the FEA model construction. The process to generate these models was worked out as follows. A 2D geometrical model, e.g. defined by the boundary of the part, is meshed in ANSYS or similar FE tools and coordinates of all mesh nodes are exported. A numerical tool computes the thickness for each node and each layer as well as the fiber orientation angle for each element. This data, exported back to the FE tool using an appropriate exchange format allows to compute all relevant mechanical properties of the part.

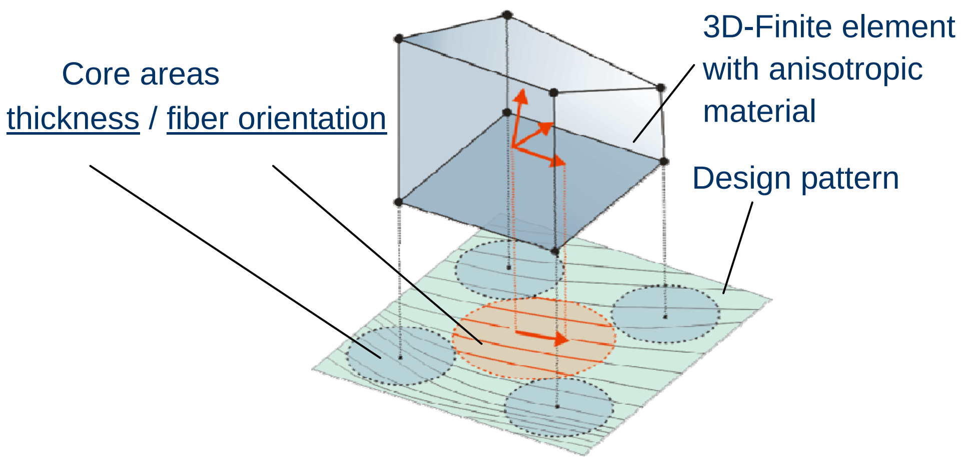

Figure 12.- Schematic diagram of the FE-model construction

The results were verified with preliminary experimental data for comparison, see Figure 13. All deviations between numerical and experimental results are within the experimental variations.

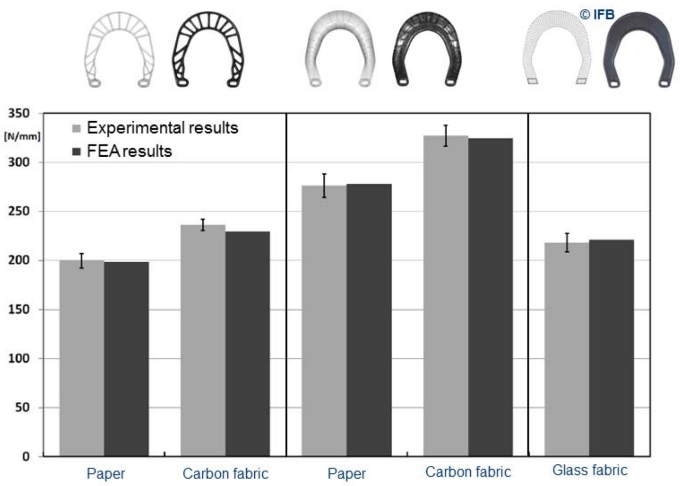

Figure 13.- Stiffness results for three different brake booster geometries. The experimental results are marked in light grey and the numerical results are shown by the dark bars for various base materials

The state of the art 3D failure criteria proposed by Puck as well as Cuntze were implemented in the finite element analysis (FEA) software ANSYS. Both criteria are recommended by The World-Wide Failure Exercise [N.N., Hinton, M. J.; Kaddour, A. S. & Soden, P. D. (Eds.) Failure Criteria In Fibre Reinforced Polymer Composites: The World-Wide Failure Exercise. Elsevier 2004, Amsterdam: Elsevier, 2004] and considered of comparable quality. It turned out that the implementation of the Cuntze criterion within ANSYS with help of the APDL macro language results in a much faster calculation than the Puck criterion.

With this implementation the newly created FEA models could be investigated for failure analysis. However, for certain extreme cases, where single rovings constitute a whole fiber layer in some areas, meshing problems were observed. Most models with a more uniform distribution of rovings can be modeled for strength analysis with the current tool set. The results were tested for bolted joint specimens. Especially for fiber failure the results agree with experimental results, although the effects of the stitching and other sources of error during production amount for much larger deviations in comparison to the predictions for the stiffness.

The same specimens were also used to verify and evaluate different optimization criteria such as load path and principal stress optimization. From this analysis we recommend the principal stress optimization for further investigation as well as a basis for a variable axial fiber design for applications, because the resulting laminates have much more homogenous thickness compared to load path optimization and the possible improvements based on the failure analysis are much easier to accomplish.

For the definition of guidelines for simplified patterns, different versions of optimized fiber layouts were analyzed numerically. For the comparison the principal stress optimized layout for a bolted joint sample was used together with an intuitive optimization consisting of straight lines and semi-circles and radial fibers. The intuitive optimization implemented almost the same amount of fibers. Especially in terms of strength both designs showed significantly different results. The intuitive design, which is a very good example for a simplified guideline approach, resulted in failure strength of only half the value compared to the principal stress optimized version. However, the industrial deployable AOPS design tool was developed as a standalone software tool to assist engineers with the optimization process. With the AOPS tool it is very easy to generate exactly optimized fiber layouts. For this purpose a fiber path generator algorithm has been derived and implemented to follow the principal stress directions for a given isotropic simulation result.

Furthermore, the software tool implements exchange formats to standard CAD and FEA software such as DXF, ANSYS coded database, and NASTRAN bulk data format. Using the AOPS tool it is possible to generate principal stress optimized fiber layouts, define a stacking sequence for production, generate and export the corresponding FEA models, and also evaluate the expected thickness distribution as well as export the thickness data as an IGES file to construct infiltration tools.

For prototypes two samples were proposed by the SME's. From IDEC an aircraft fitting component was proposed. Due to the high complexity of the part and the isolated region of import a subcomponent was selected to demonstrate the tools and optimizations. A reference design made of a quasi-isotropic laminate and two optimized layouts, load path optimization and principal stress optimization, were modeled numerically and analyzed for strength. For verification purposes the three different types of specimens were produced by resin transfer moulding process, see Figure 14. The tool surface was constructed with the help of the thickness calculation tools developed for AOPS. For each type at least 6 samples were produced. The experimental failure analysis proved (Figure 15) to be challenging as many different failure modes with various impacts on the characteristics of the specimen needed to be distinguished. For fiber failure reasonable agreements were found.

Figure 14.- Test specimens

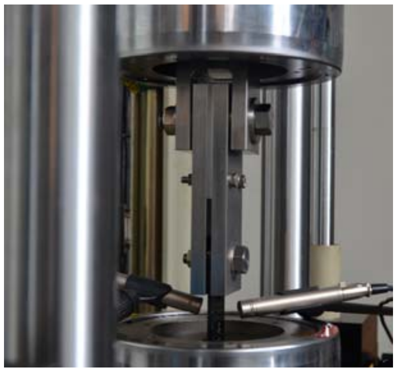

Figure 15.- Experimental setup – special fixture was used for testing the bearing strength of the samples. The microphones on either side were used for acoustic measurement

Additionally AVANA proposed a landing gear application. The objective was to construct a replacement for a steel solution. The design was analysed numerically and, using topology optimization, was modified to fit the extremely high load requirements. An optimized fiber layout was developed and a numerical FEA model was created. However due to a very high thickness of the part the model exceeded the capabilities of the hardware currently available at the IPF.

4.1.4 THE POTENTIAL IMPACT (INCLUDING THE SOCIO-ECONOMIC IMPACT AND THE WIDER SOCIETAL IMPLICATIONS OF THE PROJECT SO FAR) AND THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION OF RESULTS

4.1.4.1 The potential impact

The project has been consistent with the objectives specified in the Call Work Programme (FP7-SME-2010-1), research for the benefit of SMEs. The EMBROIDERY project has shown the tremendous potential of TFP and it has contributed to strengthen the innovation capacity of European SMEs and in consequence to improve their competitiveness. They have expanded their existing markets or have created new ones. The industrial competitiveness across Europe will be also increased due to the proposed automation and optimization, thus reducing labour cost contribution in the production cost. Thus, European companies could compete in a better position face to emerging countries.

The Table 4 shows the intended direct use that each SME participant pretends for their corresponding results. The table clearly shows the expected market for the new product/process/service, the provided benefits and the implications that these benefits do have in the business of each participant. We have assumed two different approaches, which are quantified in the table:

- A cost reduction of the currently manufactured products (heating membranes, composite components, etc).
- A sales growth due to the improved performance of the products

SME	Results	Description	Market	Benefits	Impact
GMI	1	Automated manufacturing of improved heating blankets	Aeronautics	Variable heat distribution and automated manufacturing	Membrane cost reduction (20 %), sales growth (20 %)
MANDI	2	Self heating reusable membranes for infusion and OOA processes	Marine Wind energy Construction	Manufacturing time reduction (10%) and energy reduction (40%)	Manufacturing cost reduction (20)
IDEC	3	Self heating reusable membranes for preforming	Aeronautics	Manufacturing time reduction (40%) and energy reduction (90%)	Manufacturing cost reduction (10%)
	7	Computer algorithms accounting for fibre steering	Aeronautics	Weight reduction (25%)	Sales growth (5 %)
QPOINT	4	Self heating composite rigid tooling	Whole composite industry	Manufacturing time reduction (10%) and energy reduction (40%)	Sales growth (20%)
AVANA	5	Composite components with thermal built-in function	Aeronautics Transport	Weight reduction (5%)	Sales growth (5%)
	7	Computer algorithms accounting for fibre steering	Transport	Weight reduction (25%)	Sales growth (5%)
TAJIMA	6	Monitored and automated stitching head	Whole composite industry	Increased quality and productivity Cost reduction	Sales growth (20%)

Table 4.- Direct expected impact for each SME participant

Regarding developed **self-heating concepts based on TFP embedded layers**, different prototypes/demonstrators have been done for each SME. In case of GMI Aero, self heated heating blankets have been carried out. With the participation in this project GMI Aero has further developed its expertise in the area of heating aircraft structures and will be able to develop new heating products with better controlled thermal distribution, specifically adapted for complicated repair cases. This ability of the heating element will significantly improve the quality of the repair, by enabling "tighter" temperature tolerances (i.e. staying well inside the usually specified +/- 5 ºC margin) as well as by making possible the minimization of thermally induced stresses in the surrounding materials. GMI expects an increase of 20% in selling equipment, due to the increase of application cases and consequently number of repairs. Furthermore, the project will definitively contribute to help GMI Aero to improve its productivity in the manual manufacturing of shaped multi contoured heating mats.

IDEC also expects to have big benefits from the technology researched during the project. They are owner of self-heating membranes for preforming applications and co-owner of computer algorithms for fibre steering. The direct application for self-heating membranes for preforming applications is cost reduction (because of reducing of power consumption), due to the curing process of one of the parts manufactured is carried out in a big oven. The power consumption of a preform done in an oven and using the reusable self-heating membrane has been compared, with these interesting results:

	Oven	Self heated membrane	% power reduction
Estimated power consumption (Wh)	63000	1617	97.4

Table 5.- Estimated power consumption

The benefit of the researched technology for Qpoint Composite GmbH is that they can offer more qualitative and innovative heatable composite tooling for the production of composite parts, providing an important sales growth (up to 20%) taking into account that it is the core business of the company. The proposed product has the ability to lead to manufacturing process more efficient and cost effective. This could provide a manufacturing system for the production of composite parts on an industrial scale. A process cost reduction of 25% is estimated and an overall cycle time reduction of 20% is estimated. Apart from that, it is expected to improve the quality of heatable tooling by homogenizing surface temperature and allowing free geometry of the heating structure.

Mandi and Avana also expect that the developed technology would have a great impact in their manufacturing processes. In case of reusable membranes for infusion processes of Mandi, they will benefit from an improved manufacturing process, where both time (curing) and cost are reduced (estimated cost reduction up to 20%). Self heated de-icing composites parts manufactured for Avana are very promising although some more tests in icing tunnels are necessary to validate the technology. But the laboratory scale tests reveal a uniform and high level heating capacity of the specimens.

The developed **external endless feeding device** shows good potential for its use in the composite market. Especially for medium volume production using heavy tow material, as the 50K roving tested during the project. This addresses especially the machine industry and automotive industry were the SME Tajima wants to achieve a bigger market penetration in future. It has been calculated that the missing rewinding process would mean around 20 minutes more time for the operator and the reduction of the amount of spool changes leads to 90% time saving and reduction of machine downtime.

To address a bigger range of application also the wire placement technology could be addressed, as there are TFP machines already in the market, producing seat heating elements for the automotive industry. Furthermore the results of EMBROIDERY show that this market could be of bigger interests in future.

Finally it could be stated with the EMBROIDERY results a big step in the technology readiness level of the TFP technology is achieved. Due to the developed machine equipment, the new application fields in heating elements and the important software solution.

The last issue of the project was to exploit the **fiber steering** capability of TFP by creating some specific tools. In contrast to many preliminary applications where TFP was mainly used to apply uniform patches on conventional fabrics, the full capabilities of the fiber material can now be exploited with the tools developed within this project. This allows designing of structural components with a much higher performance in terms of mechanical properties compared to the weight of the structure. Energy saving due to weight reduction is one of the most important consequences.

Furthermore, the TFP technology together with appropriate design tools is well suited to strengthen European companies in the composite market. Their production facilities profit from high precision and high performance technologies to compete against manufacturing technics which require a lot of manual labor.

The high flexibility of the technology enables the possibility to combine aesthetic and mechanical design. As a result much more organic structures can be produced. Delicate truss-like shapes are well suited for materials with strongly anisotropic characteristics such as carbon fibers. These fibers need to be oriented along the loads inside the part, which also means along the branches of the structure. There is no other technology that offers such a flexibility to design structures such as the CFPR stool application produced as a public demonstrator for this project.

4.1.4.2 Main dissemination activities

The Dissemination strategy of the Consortium partners addresses the increase awareness among European industries and the promotion of the use of results, leading to the eventual marketing of the products through seminars, workshops, fairs…

Furthermore, in order to support the dissemination level and visibility to general public of EMBROIDERY project, it was decided to further develop two demonstrators which would be attractive for the general public. In this context, an outdoor self heated chair and a lightweight carbon stool were manufactured using TFP technology.

The main dissemination activities conducted during the project have been the following:

- Embroidery Consortium created at the beginning of the project a **project web** (http://www.embroidery-project.eu/) for public dissemination combined with a private area (extranet), which serves as repostary for project documentation (deliverables, presentation, meeting-minutes, etc.).

- **Description of TFP technology** together with **a reference to the EMBROIDERY project was included in Wikipedia** (http://en.wikipedia.org/wiki/Tailored_fiber_placement).

- A 2 min **project video** was prepared in video format for dissemination in several events like JEC exhibition in Paris 2012.

- Publications in conferences: **4 technical publications** have been submitted in total including 1 at SAMPE/ SEMAT 12 conference and 3 at the 13th textile conference in Chemnitz, Germany.

- **Fairs and exhibitions**. A technical presentation was presented in JEC 2012 Automation Forum. Also project posters were presented both in JEC 2012 and also in the Composite Engineering Show 2011, in Birmingham UK.

- The general public (self heated chair and lightweight stool) demonstrators developed will be presented in future events including exhibitions like JEC 2013 in Paris (April 2013) as well as in specific magazines from the composite market like JEC Magazine during 2013.

The next figures show some posters prepared and presented during the project:

Figure 16.- Examples of the project posters prepared and presented

Additionally, a final open seminar dissemination event was organized on the 14th December 2012 at Tecnalia facilities for any company interested in the developed technology. The call had a great success and very relevant companies like GAMESA EÓLICA, AERNNOVA, AIRBUS SPAIN or MTORRES took part in the open seminar. The goals of the event were to disseminate the results obtained during the project, present the main activities developed by the different partners, present the main applications developed and also to show and test the prototypes/demonstrators manufactured during the project.

As it has been mentioned before, some prototypes have been manufactured to present to general public the benefits of TFP technology and self-heating concepts. Two different prototypes have been manufactured, a self heated chair to demonstrate the benefits of TFP and self-heating concepts and a structurally optimized stool to demonstrate the fibre steering capabilities of TFP.

The self heated chair is designed for outdoor applications and it has integrated a heating circuit made with carbon fibre rovings. Then, this heating layer has been embedded within a fibre glass laminate and it has been infused with a matrix. The chair is fed by a 24v battery. Next figures show the heating layer, the final prototype and the validation by infrared camera of the heating ability of it.

Figure 17.- Manufactured self-heated outdoor chair

The second public demonstrator carried out was a lightweight stool. This item from the day-to-day life can intuitively illustrate the capabilities of the developed technologies. Applying topology optimization to design proposals worked out together with Dresden University of Applied Science (HTW Dresden) the structurally optimized CFRP stool is obtained. The design is well suited for the TFP-technology as it can be composed of flat surfaces by draping. For the prototype about 300 g of 24K carbon fiber roving were used. The infiltration was done using the vacuum assisted process with a one sided infiltration tool. The final prototype is shown in Figure 18.

Figure 18.- Prototype of the TFP-CFRP stool

4.1.4.3 Exploitation of results

Important achievements have been obtained during the EMBROIDERY project. Each SME is the owner of its corresponding result/s and will exploit it by taking advantage of the competitive position face to the competitors that the generated knowledge will provide. Taking into account that most of the R&D activities have been carried out by the RTD performers, it was of major importance for the exploitation of the results, that these research activities were spread within the SME participants. For ensuring full transmission, specific seminars/ sessions have been hold, each of them dealing with one of the main activities (WP1, WP2 and WP3 developments) and the corresponding SMEs.

Self-heating embeddable layer will be used in various composite manufacturing processes. The developed technology will be used internally by the SME participants in WP1. The intended use for MANDI and IDEC is the production of self heated membranes for their internal production. GMI will implement automated manufacturing to the heating circuits required for the repair membranes. In that way, they keep their competitive position face to the competitors. AVANA will be able to produce components with de-icing capacity for the aircraft they produce. Finally, QPoint will offer the self-heating technology for the composite rigid tooling they supply to third parties.

On the other hand, it is also foreseen to obtain revenue to the invested money from licensing and selling property rights to third parties. Specifically, Tajima has patented and will exploit the updated TFP machines with endless feeding device and process monitoring.

In terms of the result of WP3, both IDEC and AVANA will receive licenses of the AOPS developed software for their internal use. However, provided that essential background by the IPF was required for the development of the software, the IPF will retain the rights to exploit the software to third parties. In this context, it is foreseen that the IPF will undertake negotiations with a FEA software provider, in such a way that the capability of fibre steering is included in commercial FEA package and available through the entire composites community.

With reference to the self-heated outdoor chair and lightweight composite stool some exploitation actions have been carried out, contacting directly potential customers or showing them in events. In case of the chair, some companies have visited TECNALIA facilities in order to know the technology used to manufacture and heat the chair.

Apart from the previous exploitation activities, developed technology has been disseminated by several ways as it has been explained in the chapter "Main Dissemination Activities".

The possibilities identified concerning IPR activities protection are summarized in the next table. For Tajima it was a successful project with promising results. First of all due to the external feeding system and the monitored stitching head and secondly due the developed software capabilities which improves the level of technology readiness dramatically. So it is expected that this will increase the potential customer range significantly. The monitoring system developed in EMBROIDERY is already commercial available. For the external feeding device a patent is forthcoming to protect the innovative ideas therein. Tajima is very interested in putting the prototype onto a commercial technical and saleable level. In addition, for the designed software by the IPF within WP3 (advancements in fibre steering) software licenses will be distributed between the owners of this activity (AVANA and IDEC).

Main Achievement	**WP related**	**Possibility identified for IPR protection**
Technological tasks (optimal resistive materials, embedding process developed, materials with enhanced thermal properties)	WP1 (Self heated concept based on TFP)	-
- Thread tension measurement device - Continuous carbon roving feeding device	WP2 (Monitoring/ Automation of TFP)	Endless feeding device will be patented
Design tool/ software	WP3 (Advancements in fibre steering)	Software licenses

Table 6.- IPR activities

4.1.4.4 Address of the Project Public Website

The publication of the web-site was the first step in the exploitation and dissemination activities. The EMBROIDERY website can be found at the following web address: http:// www.embroidery-project.eu.

Project coordinator: Mr. Riccardo Mezzacasa (e-mail: ricardo.mezzacasa@tecnalia.com)

The project web page has been constructed organised into two areas: **public** and **private**.

- The homepage provides access to the public area, presenting an overview of the project, the project objectives and the partners involved.

- The private section is a protected area with level of access (username and passwords) just for partners, which can be defined according to specific users. This section is useful to consult and share general information and documents: work plan, tasks activities, deliverables, meeting minutes, task actions, etc.

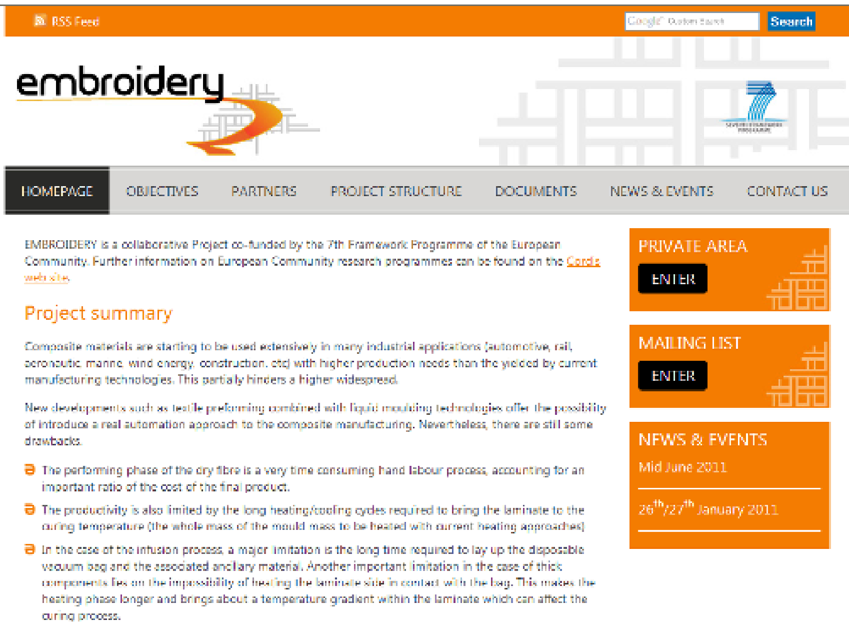

Figure 19.- Homepage of Embroidery web page

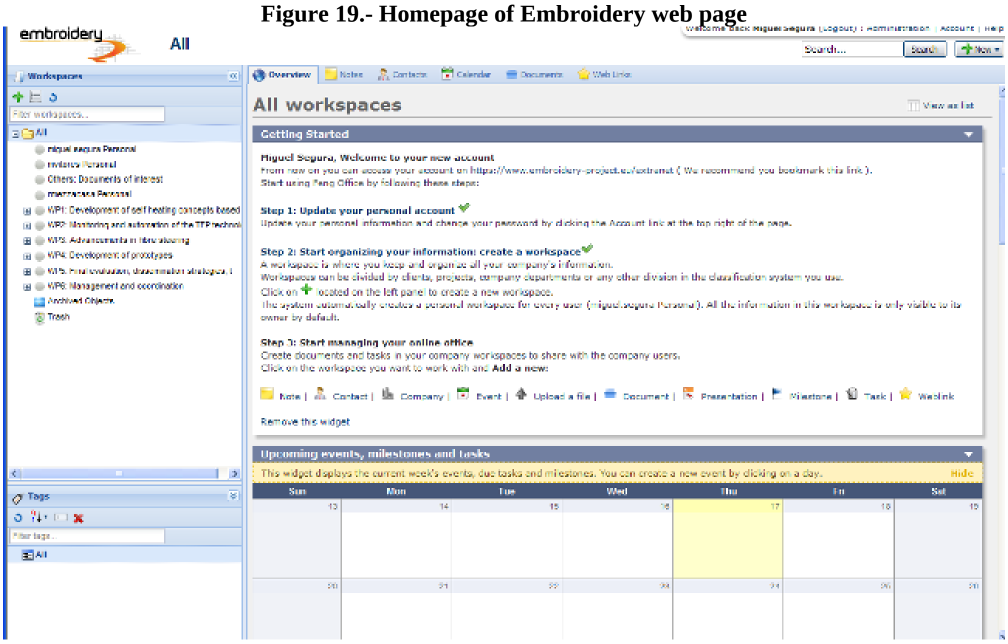

Figure 20.- Main page of the private area