# PROJECT FINAL REPORT

Grant Agreement number: **314003**

Project acronym: **LOCOMACHS**

Project title: **LOw COst Manufacturing and Assembly of Composite and Hybrid Structures**

Funding Scheme: **Collaborative Project Large-scale integrating project**

Period covered: **from 1st September 2012 to 31st August 2016**

Name, title and organisation of the scientific representative of the project's coordinator:
**Maria WEILAND, SAAB AKTIEBOLAG, SE-581 88 Linköping, SWEDEN**

Tel: **+46 (0) 13 184158**

Fax: **+46 (0) 13 181401**

E-mail: **Maria.Weiland@saabgroup.com**

Project website address: [www.locomachs.eu](http://www.locomachs.eu)

**Project co-funded by the European Commission within the Seventh Framework Programme**

This document has been produced under the EC FP7 Grant Agreement 314003. This document and its contents remain the property of the beneficiaries of the LOCOMACHS Consortium and may not be distributed or reproduced without the express written approval of the LOCOMACHS Coordinator, SAAB.

# Table of Contents

List of acronyms ..... 5
1 Executive summary ..... 8
2 A summary description of project context and objectives ..... 9
3 Description of the main S&T results / foreground ..... 13
  3.1 The LAWiB demonstrator Design Architecture & Build Philosophy ..... 13
  3.2 Design ..... 13
  3.3 Manufacturing ..... 17
  3.4 NDI/NDT ..... 24
  3.5 Assembly ..... 29
  3.6 Design recommendations for cost reduction & Cost models ..... 36
  3.7 Virtual demonstration ..... 38
4 Potential impact ..... 40
  4.1 Rated global LOCOMACHS achievements ..... 40
    4.1.1 Objectives and scope ..... 40
    4.1.2 Methodology ..... 41
    4.1.3 Results and recommendations ..... 42
    4.1.4 Conclusions ..... 43
  4.2 Dissemination ..... 44
    4.2.1 LOCOMACHS Dissemination Events ..... 44
    4.2.2 LOCOMACHS Communication Kit and Presentation Material ..... 47
    4.2.3 Scientific publications and presentations in key journals and aeronautic conferences. 48
5 Public website and contact details ..... 49

# Table of Figures

Figure 1. Lean Assembly Wingbox (LAWiB) ... 10
Figure 2. More Integrated Wingbox (MIWiB) ... 10
Figure 3. Reference Wingbox (ReWiB) ... 11
Figure 4. LOCOMACHS partners on the European map ... 11
Figure 5. Work plan structure ... 12
Figure 6. The design architecture and build philosophy for the demonstrator object LAWiB (Lean Assembly Wingbox) in LOCOMACHS. ... 13
Figure 7. ANATOLEFLEX implementation on LOCOMACHS use case a) LAWiB, b) ReFus ... 14
Figure 8: Current State of the Art (SoA) vs. LOCOMACHS LAWiB Design ... 15
Figure 9. Physical Upper Cover ready for Shipping to MTC (left). Upper Cover in Assembly at MTC (right) ... 15
Figure 10. Major design adaptions ... 16
Figure 11. Major design adaptions ... 16
Figure 12. Sensor Based Active Process Control ... 17
Figure 13. The design architecture of the demonstrator MIWiB ... 18
Figure 14. Front spar concept ... 18
Figure 15. MIWiB upper cover ... 18
Figure 16. MIWiB rib assembly ... 19
Figure 17. Sequence of online monitoring with us-sensors ... 20
Figure 18. Ultrasound sensor application ... 20
Figure 19. Flow front detection ... 21
Figure 20. Composite panel with cocured skin, stiffeners and shear clips ... 21
Figure 21. LOCOMACHS Rear Spar with cocured hinge attachment ... 22
Figure 22. Laser system ... 22
Figure 23. FESEM images of CFRP specimen showing that fibres were not damaged after laser treatment with optimum parameters (@266 nm) ... 23
Figure 24. Principle of processing sacrificial material supported by Adaptive Machining. ... 24
Figure 25. Electrocapacitive ECT transducers ( 50-800 kHz) ... 26
Figure 26. Focused piezo-composite PCT transducers: 200 kHz and 400 kHz ... 26
Figure 27. Demonstration of the ACUT set-up on MITO, AGI, Nantes (FR) ... 27
Figure 28. Close-up view of the PCT transducer set-up in transmission on MITO ... 27
Figure 29. Set of Daisy matrix probes by AGI for countersink inspection ... 28
Figure 30. DASSAV’s linear Array ... 28
Figure 31. 32x32 matrix probe and UT generator ... 28
Figure 32. DASSAV’s edge inspection system ... 28
Figure 33. Comparison of Balance ... 30
Figure 34. Rate (shipsets per month) ... 30
Figure 35. DEE operation in the Advanced Aerostructure Technology Forum-2016 public video ... 31
Figure 36: Rear View of end effector vision activated to derive pin position ... 31
Figure 37. Integrated tool and product development process ... 32
Figure 38. Rib Hexapod installing the Rib 3 and the two lower Hexapods positioning the Front spar 33
Figure 39. Forced curing at LaWib ... 34
Figure 40. KIMS low cost image metrology setup based on standard cameras and a Gobo projector. It provides 10 um repeatability within a volume of 500 x 600 x 100 mm3 ... 35

Figure 41. Composite cost model flow and hierarchy........................................................................ 37
Figure 42. Different production method costs with increasing annual production volume................. 37
Figure 43. Assembly cost of different LAWiB assembly scenarios ...................................................... 37
Figure 44: Assembly costs of LOCOMACHS innovations. ..................................................................... 37
Figure 45. View of the wing factory in the software 3DEXPERIENCE.................................................. 38
Figure 46. The Handling of the wing is simulated throw the production line...................................... 38
Figure 47. Robot access and reach abilities are studied ..................................................................... 39
Figure 48. Operator ergonomics are also considered within the simulation....................................... 39
Figure 49: Goals of Flightpath 2050 (Kallas & Geoghegan-Quinn, 2011)............................................. 40
Figure 50: LOCOMACHS HLOs .............................................................................................................. 41
Figure 51: Sensitivity analyses in LOCOMACHS..................................................................................... 41
Figure 52: Flightpath 2050 and the ACARE SRA2 and LOCOMACHS HLOs........................................... 42
Figure 53: Partners which have been interviewed............................................................................... 42
Figure 54: Results of the TRL assessment ............................................................................................ 43
Figure 55: Finding new Friends in LOCOMACHS .................................................................................. 43
Figure 56: Plenary sessions during the LOCOMACHS NDI/NDT Workshop.......................................... 44
Figure 57: Guillaume Pierre (SONAXIS) presenting his Air Coupled Ultrasound Inspection technology ........................................................................................................................................... 44
Figure 58: Maria Weiland (SAAB) and Peter Helgosson (PRODTEX) at the LOCOMACHS booth at Aerodays.............................................................................................................................................. 45
Figure 59: Magnus Engström (SAAB) presenting LOCOMACHS during the “Competitiveness of Aviation Industry” session .................................................................................................................... 45
Figure 60. Guided tour of the LAWiB cell during the LOCOMACHS Final Forum ................................. 45
Figure 61. Some of the booth displays of the LOCOMACHS Final Forum: Metrology solutions (top left), Physical robot-human collaboration tasks (top right), Reconfigurable tooling (bottom left)...... 46
Figure 62. LOCOMACHS Final Forum poster displays .......................................................................... 46
Figure 63. VIPs talking during the “Industrial take-up beyond LOCOMACHS” session........................ 47
Figure 64. Initial LOCOMACHS poster (left) and double-sided bookmark (right) ................................ 48
Figure 65. Extracts from the initial LOCOMACHS presentation ........................................................... 48
Figure 66. Extracts from the LOCOMACHS booklet.............................................................................. 48
Figure 67. LOCOMACHS Public Website homepage............................................................................. 49
Figure 68. Geographical spread of connection sessions (map)............................................................ 49
Figure 69. Geographical spread of connection sessions (top 20 countries) ........................................ 50
Figure 70. Evolution of sessions (dark blue) and page views (light blue) over the project’s duration, highlighting the project’s three main dissemination events............................................................... 50

# Table of Tables

Table 1. Comparison of balance and capacity....................................................................................... 30
Table 2. Balance and capacity with two robots .................................................................................... 30
Table 3. Lessons learnt from assembly demonstrations LAWiB/MIWiB............................................. 36
Table 4: Case studies of cost sensitivity analyses of LOCOMACHS innovations ................................. 42

# List of acronyms

| Abbreviation / acronym | Description |
|---|---|
| ACU | Air Coupled Ultrasounds |
| AE | Acoustic Emission |
| AFP | Automated Fibre Placement |
| AM | Additive Manufacturing |
| ANATOLE | Tolerance analysis software developed by EADS |
| AR | Augmented Reality |
| ATL | Automated Tape Laying |
| AU | Acousto-Ultrasonic |
| AUT | Acousto-Ultrasonics Tomography |
| BW | Frequency Bandwidth |
| CAA | Component Application Architecture (Development API in CATIA) |
| CAD | Computer Aided Design |
| CAT | Computer Aided Tolerancing |
| CDR | Critical Design Review |
| CFRP | Composite Fibre Reinforced Plastic |
| CMM | Coordinate Measuring Machine |
| COG | Centre Of Geometry |
| CPD | Composite Design workbench in CATIA |
| CNC | Computer Numerical Control |
| CPU | Central Processing Unit |
| CTE | Coefficient of thermal expansion |
| DOE | Design Of Experiments |
| D.O.I. | Digital Object Identifier |
| DAP | Dissemination Action Plan |
| DL | Deliverable leader |
| DLF | Discontinuous Long Fibre |
| DMU | Digital Mock Up |
| DoF | Degrees of Freedom |
| DOW | Description Of Work |
| DP | Deliverable process |
| DSC | Differential Scanning Calorimetry |
| EE | End Effector |

| Abbreviation / acronym | Description |
|---|---|
| FC | Central Frequency |
| FE | Finite Element |
| FEA, FEM | FE Analysis, FE Model |
| FEM | Finite Element Method |
| FS | Front spar |
| GD&T | Geometrical Dimensioning and Tolerancing |
| GOM | [The name of a metrology company] |
| GPS | Geometrical Product Specification |
| H2H | Hole to hole |
| HMC | Human-Machine Collaboration |
| HMD | Head Mounted Display |
| HMI | Human-Machine Interface |
| Hw/Sw | Hardware/Software |
| IML | Inner Mould Line |
| IP(R) | Intellectual property (Rights) |
| Kc | Key Characteristics |
| LAWiB | Lean Assembled Wing Box (physical demonstrator object) |
| LC | Lower cover |
| LF | Low Frequency |
| LFW | Linear Friction Welding |
| LOCOMACHS | LOw COst Manufacturing and Assembly of Composite and Hybrid Structures |
| LUT | Laser Ultrasonics Testing |
| MAJ | Manual Assembly Jig |
| MASD | Manufacturing Assembly & Structural Design |
| MIWiB | More Integrated Wing Box (physical demonstrator object) |
| MS | Milestone |
| NC | Numerical control |
| NCF | Non-Crimp Fabric |
| NDE | Non Destructive Evaluation |
| NDI | Non-Destructive Inspection |
| NDT | Non Destructive Testing |
| NRC | Non-Recurring Cost |
| OEMs | Original Equipment Manufacturer |
| OGV | Outer Guide Vanes |

| **Abbreviation / acronym** | **Description** |
|---|---|
| OML | Outer Mould Line |
| OWA | One Way Assembly |
| PAT | Phased Array Transducer |
| PDR | Preliminary Design Review |
| PID | Process-induced distortions |
| PKM | Parallel Kinematic Machine |
| RC | Recurring Cost |
| RD&T | Robust Design & Tolerancing (a software developed by CTH) |
| ReFus | Reference Fuselage (virtual demonstrator object) |
| ReWiB | Reference Wingbox (virtual demonstrator object) |
| RS | Rear spar |
| RTI | Resin Transfer Injection |
| RTM | Resin Transfer Moulding |
| RXL | Specific type of fastener (Bombardier) |
| SP | Sub Project |
| SPC | Statistical Process Control |
| TAU | Specific robot axis configuration |
| T/E | Trailing Edge |
| Tg | (Technical) Target |
| Ti | Titanium |
| TRL | Technology Readiness Level |
| TTR | Through-thickness reinforcement |
| UC | Upper cover |
| US | Ultrasonic |
| V-REP | Virtual Robot Experimentation Platform |
| VRML | Virtual Reality Markup Language |
| WP | Work Package |

# 1 Executive summary

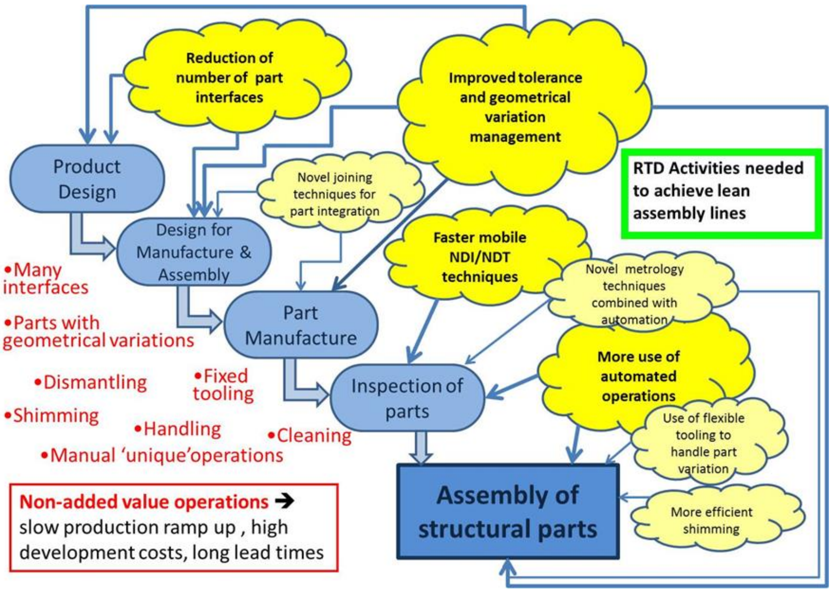
As aircraft and engine manufacturers face an ever-increasing challenge of providing more cost efficient and environmental friendly products, the use of composites in the design of aircraft structures and engine products has dramatically increased. Indeed whilst the A380 possesses only 25% of composite parts, the Boeing B787 contains 50% and the A350 will contain 52% as larger and more sophisticated assemblies are produced using Carbon-Fibre-Reinforced Polymer (CFRP) composite material. Typically, on the A350 and B787, the fuselage and wing structures are primarily made of composite.

This continued use of composite materials in the aerospace industry has been addressed in several past research projects which have focused on new design solutions and composite manufacturing processes. However an area which has been given much less attention up until now is how to achieve a time and cost effective lean assembly production system. The current airframe assembly process of composites, metals and hybrid structures is affected by an important number of non-added value operations, which strongly cause disruptions and prevents fast ramp-up and high production rates.

LOCOMACHS (LOw COst Manufacturing and Assembly of Composite and Hybrid Structures), a collaborative research and development project coordinated by SAAB AB, gathered 31 partners including European key players in the aircraft industry. The project, supported by the EC and with a project budget of 33M€, had an objective to create cost efficient part manufacturing and assembly of composite, metal and hybrid airframe structures.

Within the LOCOMACHS project, the step change is to develop missing emerging technologies and integrate them with existing ones to create cost efficient part manufacturing and assembly of composite, metal and hybrid airframe structures.

The different RTD activities of the project addressed simultaneously different areas of the product development cycle, from product design through to assembly of the structural parts.



# 2 A summary description of project context and objectives

LOCOMACHS focused on significantly reducing or totally eliminating the most time-consuming and hence expensive non-added value operations, e.g. temporary assembly to check gaps, shimming, dismantling and tool handling. The project worked on improving the design conditions which today strongly dictate the way part manufacture and assembly is performed, focusing on important step changes to dramatically improve the use of tolerance and geometrical variation management.

The project worked on integrating existing technologies with missing breakthrough technologies developed and matured within LOCOMACHS. To support the industrialisation of future assembly production lines, key innovations such as intelligent drilling, high speed non-contact hole inspection, compact automation and active flexible tooling were demonstrated.

LOCOMACHS addressed four crucial activities for the innovation of new technologies and processes with the intention of drastically reducing these non-added value operations. If dealt with in an integrated manner, these can together with breakthrough or existing technologies create a 'lean' approach to manufacturing and assembly of composite and hybrid parts:

- By implementing a better tolerance and geometrical variation management methodology using advanced simulation and SPC tools both in design, part manufacturing and assembly.
- By attempting to reduce the number of part interfaces by an intelligent use of composite manufacturing techniques to provide an accurate single part rather than many sub-parts.
- By seeking to introduce more automated operations in the inspection and assembly of parts.
- By rendering available novel NDI/NDT techniques adapted to the material properties of composite which can be used directly on the production line, in a faster and automated way.

In addition to the above mentioned most crucial activities, four other important areas were identified for the reduction of non-added value operations:

- Novel joining techniques such as co-bonding and co-curing techniques for part integration which is partly a condition for fewer part interfaces.
- Novel metrology techniques combined with automation which is a supporting technology to handle geometrical variations and control manufacturing processes.
- Flexible assembly tooling to enhance the handling and fixation of parts with geometrical variations during assembly.
- Improved shimming process, when gaps & steps cannot be avoided, to reduce lead time and improve the working environment of the operators.

To ensure coherence across the different project activities the following scientific and technical **high level objectives (HLOs)** have been defined for the project:

- **Define and validate a set of design and manufacturing rules for more complex structural parts**: A set of design and manufacturing rules were defined and validated to be used in the design phase of product development.
- **Fully integrate geometrical tolerance and variation management in a representative airframe assembled wingbox structure:** The geometrical tolerance and variation management are optimised and fully integrated in a representative airframe assembled wingbox structure.
- **Reduce by 50% the recurring costs[1] of non-added value shimming operations in structural joints by**: Reducing recurring costs of non-added value shimming operations in structural joints thanks to a better knowledge of the manufacturing process, innovative part assembly architecture and novel design of

---

[1] Compared to current techniques used by airframe structual parts manufacturers within the European Aeronautical industry in the context of the long range wide bodied passenger aircraft A350

structural joints, and the use of materials and methods requiring less curing time for more efficient shimming.
- **Reduce by 30% the recurring costs[1] of non-added value dismantling operations** with the use of one-way assembly to avoid temporary assembly operations, the development of more cost efficient measurement and verification methodology and the use of flexible assembly tooling to handle geometrical variations in airframe parts.
- **Increase the level of automation** with the development of fully integrated automated assembly processes as well as safe solutions for human-robot co-working operations.
- **Reduce the NDI/NDT lead time by 30%[1]** via more integration of the NDI/NDT operations on the in situ components, more flexible, compact and faster processing of inspection, and more automation in the handling of NDI/NDT sensors.

LOCOMACHS assessed all developments through advanced physical and virtual demonstrators to establish the reduction of 50% recurring cost of the most critical non-added value shimming operations, 30% of the non-added value dismantling operations and part joining operations and finally of the reduction of NDI/NDT lead time by 30%.

Physical demonstrations was performed on:

- The **Lean Assembly Wingbox (LAWiB)**, an assembled structure with low level of part integration. It consists of a section of a front and rear spar, four ribs, upper and lower cover and connecting parts. It will be a mix of metal and composite parts.
- The **More Integrated Wingbox (MIWiB)**, based on the same part design as LAWiB but with a much higher level of integration. It consists of a section of a wingbox with an integrated upper cover with front and rear spar, two ribs and lower cover.

**Figure 1. Lean Assembly Wingbox (LAWiB)**

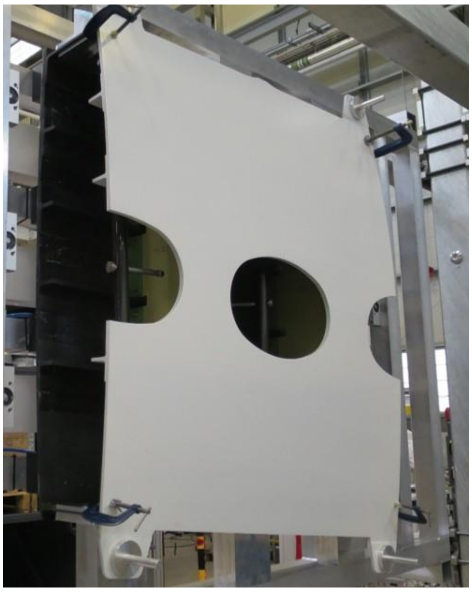


**Figure 2. More Integrated Wingbox (MIWiB)**

Virtual demonstrations, based on extrapolation of the technology feasibility test results to representative complex larger aircraft assembly units, were performed on:

- The **Reference Wingbox** (ReWiB), a complete wingbox airframe structure where the focus is on demonstrating a virtual lean production flow including both manufacturing and assembly processes in a lead time and physical handling perspective.

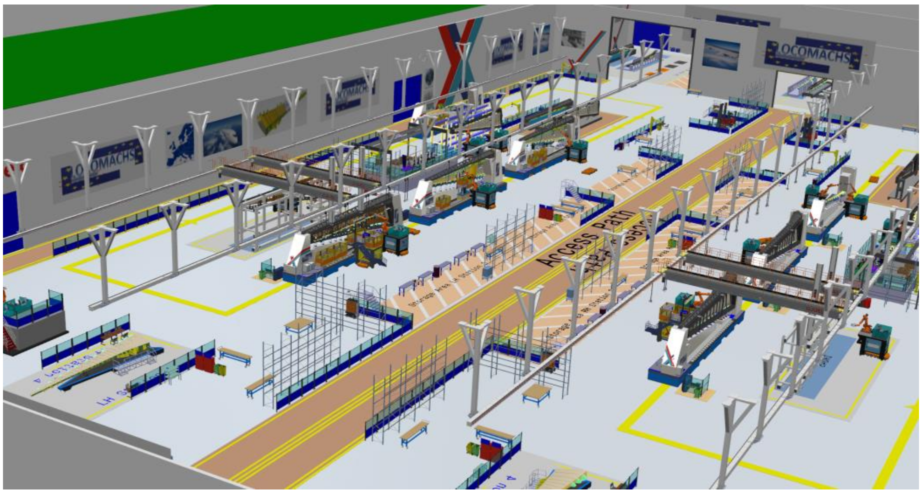


**Figure 3. Reference Wingbox (ReWiB)**

- The **Reference Fuselage (ReFus)**, to focus on computer aided tolerancing of large flexible composite parts as a tool to aid design of airframe assembly tooling and equipment to be used for assembly of these parts.

To achieve these goals, **31 partners from 10 European countries** (Figure 4) were involved in the LOCOMACHS project:

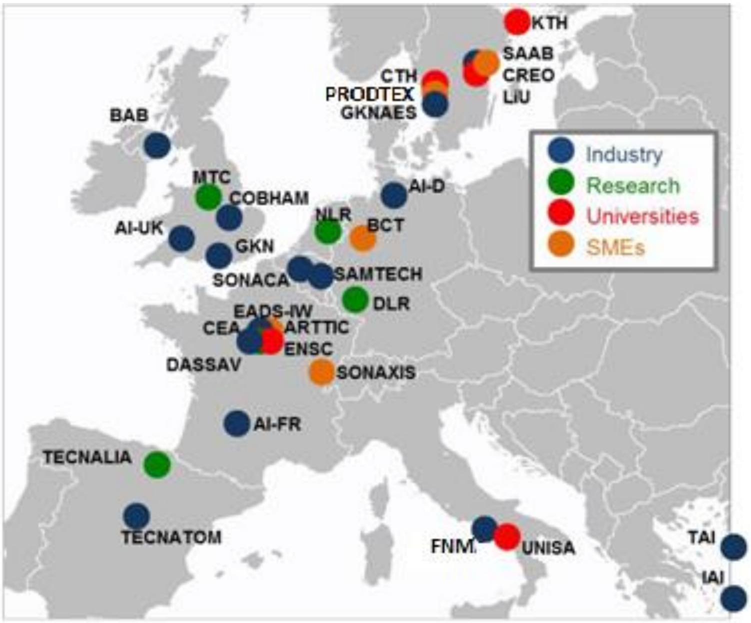


**Figure 4. LOCOMACHS partners on the European map**

The work plan for the LOCOMACHS project was organised around five main subprojects (SP) themselves organised in work packages (WP). SP1 focused on design related topics, SP2 on manufacturing of components, SP3 on assembly topics and SP4 on the combining of these topics as technical demonstrators. SP5 provides the project management, including dissemination and training.

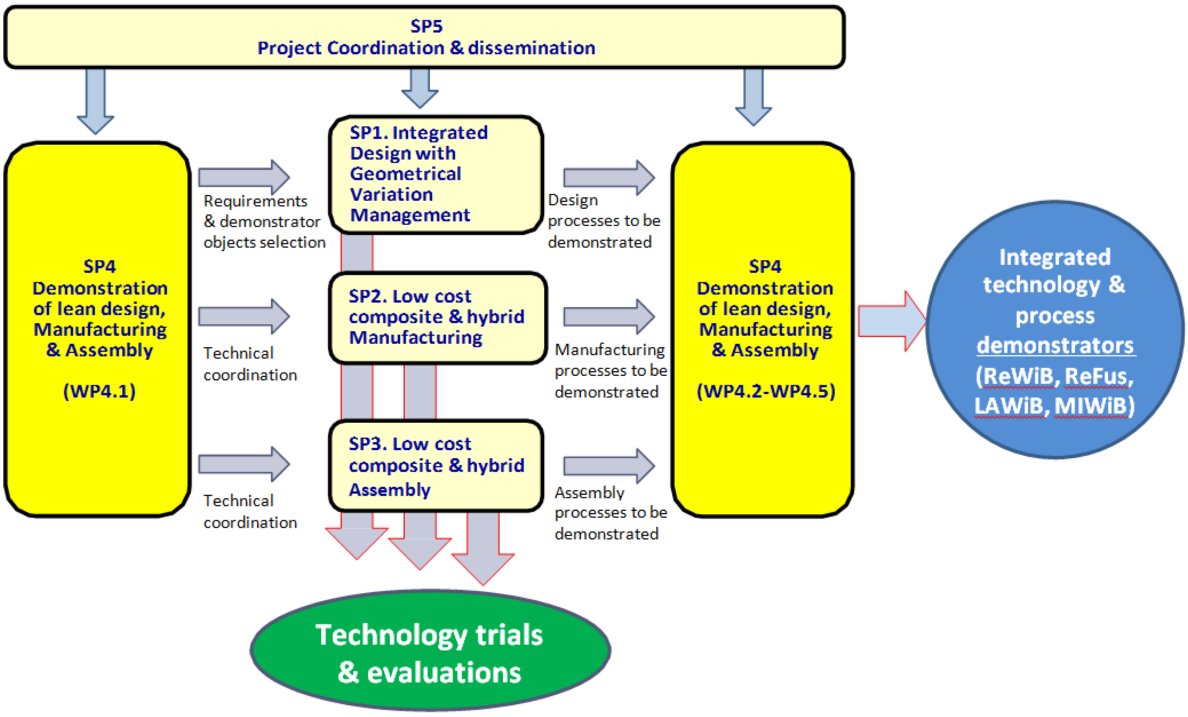


**Figure 5. Work plan structure**

# 3 Description of the main S&T results / foreground

## 3.1 The LAWiB demonstrator Design Architecture & Build Philosophy

The LAWiB design architecture and build philosophy has been a central part in the project. This has its origin from the initial approach of finding a common demonstrator object onto which a number of novel design, manufacturing and assembly technologies could be applied and demonstrated. The object should have a representative conventional design of today. It was requested that CAD-models of the object should be available for the project to avoid spending budget on conventional design work. The Bombardier Wing test box was provided and used as a baseline. The work commenced identifying design modifications and a build philosophy which would support a number of product and production requirements to answer for the market needs from today and 15 years ahead. These needs where of course reflected in the project high level objectives (HLO). A design architecture was defined with a level of part integration which together with the build philosophy had the potential to, at least theoretically eliminate or at least essentially reduce one of the most time-consuming non-added value operations in assembly – the shimming of composite parts to compensate for geometrical variations in parts caused by the nature of the material in thickness variations.

The design architecture is based on a datum strategy with fixed Leading edge and Trailing edge and an upper cover with integrated rib feet. The upper cover is aligned against the spars. A rib is best-fitted against spars and upper cover and a loose rib post between leading edge spar and the rib will consume the summarized thickness variations in the individual parts eliminating the need for shimming (see Figure 6)

<u>LAWiB Assembly sequence:</u>

1. Load Leading edge
2. Load Trailing edge
3. Load Upper cover, align to part contact in Z.
   Assemble to Rear spar
4. Measure position of spars lower flanges
5. Move out Front spar
6. Load ribs, align to part surfaces in Y(a) / Z(b) / X(c).
   Assemble to Rear Spar and Upper Cover
7. Move in Front spar. Assemble to Upper cover.
8. Load Rib posts, align to part surfaces/edges in Z / X / Y.
   Assemble to Rib and Front spar
9. Load Lower Cover (not visible), align to part contact in Z

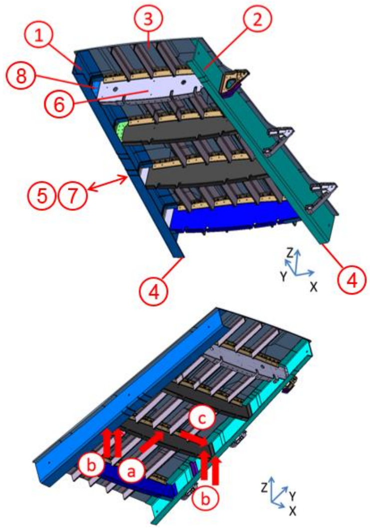


**Figure 6. The design architecture and build philosophy for the demonstrator object LAWiB (Lean Assembly Wingbox) in LOCOMACHS.**

A number of processes and operations needed new technical solutions in order to directly support the design architecture and build philosophy. Examples of these are the new assembly tooling which permits small adjustments in their positioning of parts and new manufacturing solutions to accurately integrate rib feet in the upper cover. In addition, a number of other technologies where developed, still with the common objective to reduce non-added value operations in assembly.

## 3.2 Design

### *Introduction*

LOCOMACHS, as its full title suggests is predominately a Manufacturing and Assembly project. However, with this as its focus, it was important that aspects of design were developed alongside the manufacturing and assembly demonstrations. SP1 covered this aspect of design development in support of the newly developed manufacturing and assembly technologies. Some of these technologies are highlighted in this report and include Flexible Tolerancing, Statistical Process Control (SPC) and Process Induced Deformation (spring back prediction), Integrated Part Design and 2D and 3D Simulation. There were four Work Packages (WP) 11-14, each of these is listed below:

- WP11 – Improvement of Design Process using Geometrical Variation and SPC in manufacture of structural parts.
- WP12 – Tolerance Management of Assemblies
- WP13 – Design for High Level Part Integration
- WP14 – Design Features for Simplified Assembly

### *Flexible Tolerancing of composite structure using Anatoleflex / Flex best fit of composite structure*

*Partners involved: AGI, LMS Samtech, CTH, ENS Cachan*

The aim of this work was to develop new models and solvers to simulate geometrical variations and mechanical behaviour in the same Computer Aided Tolerancing (CAT) analysis. In particular, new CAT capabilities were developed to enable flexible tolerancing for composite structure with material detailed properties.

The main result is a new software platform ANATOLEFLEX offering an integrated global approach in CATIA V5 with a continuous data workflow (CAD, MESH, Measurement). This new solution is the result of the powerful integration of ANATOLE solution dedicated to 3D tolerance analysis and SAMCEF mechanical solver within CATIA V5 workbench. End user application of such a solution could be tolerance analysis of structures, tolerance synthesis for better tolerance allocation, gap and shim prediction, and assembly process optimization with measurement aided assembly. This solution has been illustrated on LAWiB and ReFus use cases.

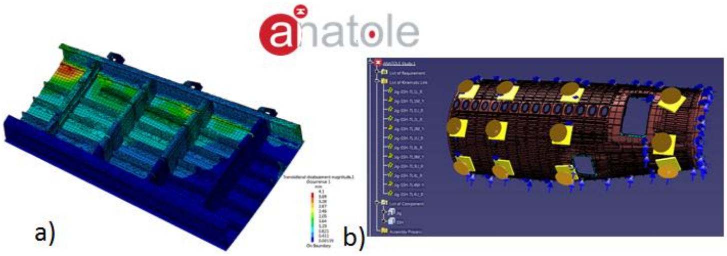


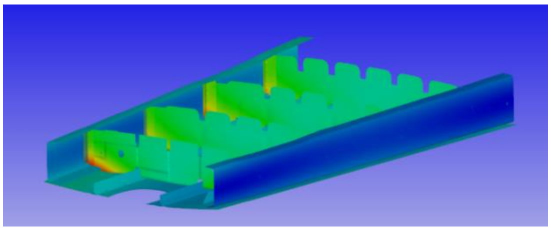
**Figure 7. ANATOLEFLEX implementation on LOCOMACHS use case a) LAWiB, b) ReFus**

### *Statistical Non-rigid Variation Simulation of Composites in RD&T (tg 12-3)*

*Partners involved: CTH, SAAB, GKNAES*

In Tg12-3, a methodology for statistical non-rigid variation simulation of composites has been developed by researchers from Chalmers. The simulation method is based on Monte Carlo (MC) simulations, combined with the Method of Influence Coefficient (MIC). The simulation method uses an assembly model, containing composite meshes of parts, definition of locating schemes and assembly methods, part tolerances, fixture tolerances, contact modeling etc. A total sensitivity matrix is implicitly defined in a FEA-based simulation model describing all mating conditions, kinematic relations and non-rigid behaviour. Using this information, the statistical distribution of critical measures on assembly level can be predicted based on tolerances and statistical distributions for the individual parts of the assembly.

For each composite part, the number of layers or plies is defined and for each ply, thickness (which can vary over the part), fiber directions and material properties are defined. This information is used as input to the MIC, together with the all mating conditions and kinematic relations. In addition to geometrical variation, simulation of variation in stress, due to part and assembly variation, are also calculated. The stress levels are presented as percentage of failure stress, using the Tsai-Hill criterion.



The methodology developed has been implemented as a demonstrator in the commercial software RD&T and resulted in three scientific papers:

A. Jareteg, C., Wärmefjord, K., Cromvik, C., Söderberg, R., Lindkvist, L., Carlson, J., Larsson, S., and Edelvik, F., 2014, "Geometry Assurance Integrating Process Variation With Simulation of Spring-In for Composite Parts and Assemblies," Proc. ASME 2014 IMECE.
B. Jareteg, C., Wärmefjord, K., Söderberg, R., Lindkvist, L., Carlson, J. S., Cromvik, C., and Edelvik, F., 2014, "Variation simulation for composite parts and assemblies including variation in fiber orientation and thickness," Proc. CIRP CATS 2014.
C. Söderberg, R., Wärmefjord, K., and Lindkvist, L., 2015, "Variation simulation of stress during assembly of composite parts," CIRP Annals-Manufacturing Technology.

The work has also resulted in a training material with tutorials for statistical flexible (non-rigid) variation simulation.

### *Integrated Part Design of Upper Cover*

*Partners involved: GKN*

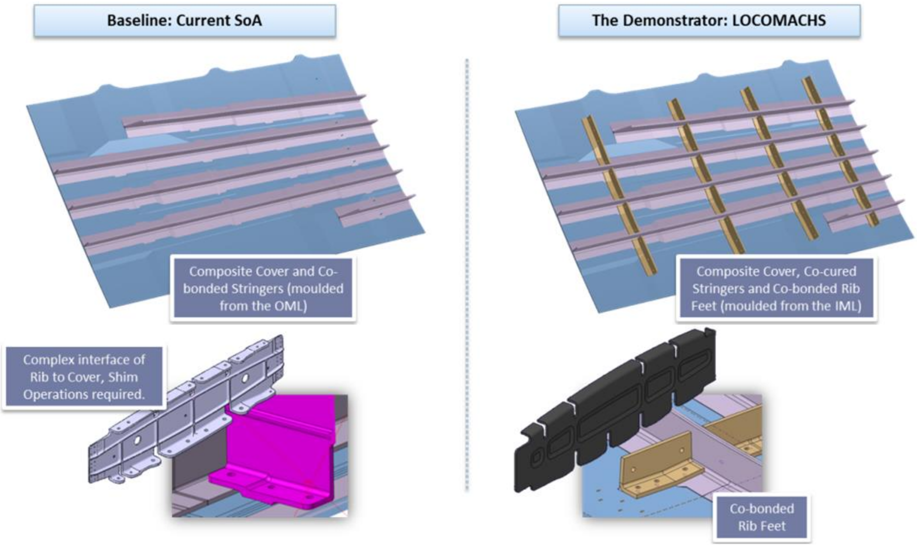


**Figure 8: Current State of the Art (SoA) vs. LOCOMACHS LAWiB Design**

The Upper Cover for LAWiB was a demonstration of co-curing/co-bonding parts during the manufacturing stages rather than assembling Skin, Stringers and Rib parts at the assembly stage. The purpose of the integrated design was to reduce the assembly operations required. This was achieved through a number of novel design approaches and innovative tooling solutions.

- Spring back Compensation to Moulding in support of a more accurate part directly out of mould.
- Part Integration in support of a reduced time to assemble.
- Inner Mould Line (IML) tooling and Thermally Stable Lightweight multi-use fixtures used together in support of maintaining a global datum system and specifically matching interfacing surfaces for greater part to part accuracy.

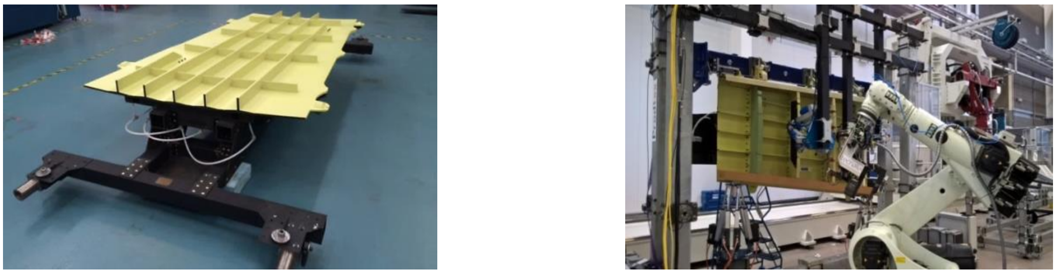


**Figure 9. Physical Upper Cover ready for Shipping to MTC (left). Upper Cover in Assembly at MTC (right)**

This demonstration of integrated design was a key output from the LOCOMACHS project and was presented at the Advance Aerospace Technology Forum and the JEC Composites Event. The Key results were:

- Achieved excellent consolidation of Upper Cover Skin and Stringers through the use of an IML tooling methodology.
- Good IML match to Forward and Rear Spar caps, with minimal requirement to shim.
- Successfully demonstrated that more accurate part Rib and Rib Foot effectively removes the need to shim between Upper Cover and Ribs.
- Contribution towards a saving in the cost of assembly through the work undertaken in SP1.

### *Verified design solutions and recommendations & 2D, 3D Simulation*

*Partners involved: DLR*

The basic nature of composite structures is that high performance reinforcement fibres are embedded in a polymer matrix. As a result there is a highly complex state of stress within the composite material which causes certain deformations. Furthermore the individual state of inner stress varies significantly with the way the composite structure is processed. To assemble composite structures in a comparable way as metallic structures are assembled it is necessary to provide comparable accuracy at least in the joining areas. In addition it makes sense to design the final structure with more tolerant joining strategies that can potentially compensate geometrical sub component deviations. Within LOCOMACHS this approach was demonstrated on the example of two composite wing ribs that were compared with machined aluminium ribs to assess competitiveness.

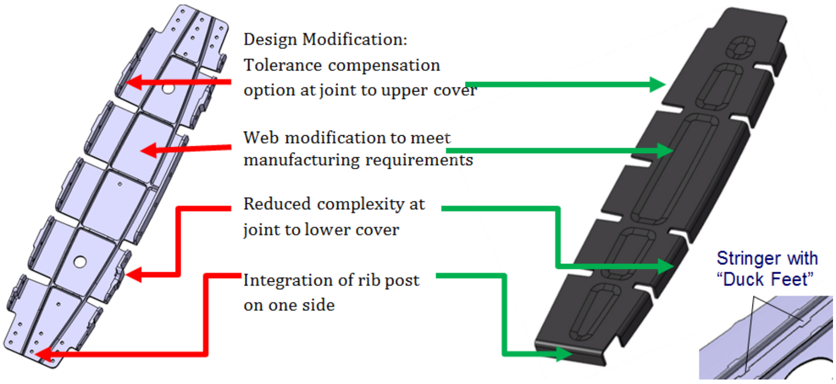


**Figure 10. Major design adaptions**

Figure 10 shows the major design adaptions that enabled an efficient composite part production and reduced tooling costs. In a second step the nominal process induced deformation of the rib was simulated on the basis of special L-coupons and a newly developed, shell element based spring-in prediction methodology.

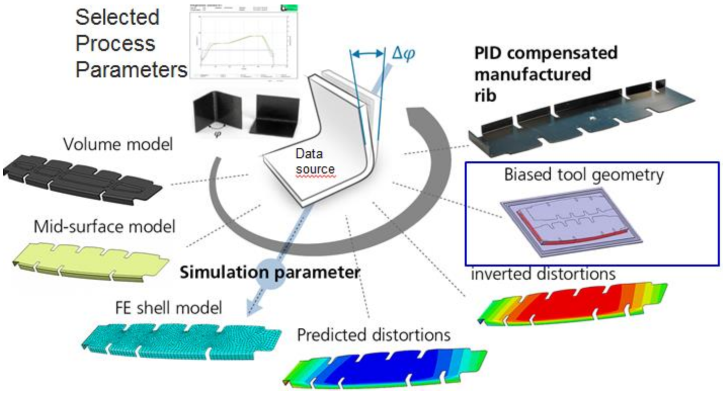


**Figure 11. Major design adaptions**

The result of the simulation was then used to create a compensated production tooling (see Figure 11). Apart from nominal process induced deformations also scatter effects like varied gelation points or varied fibre content can lead to significant tolerances in the joining areas. To address this problem a new strategy of sensor controlled processing was demonstrated within LOCOMACHS. The sensors were used to control the resin flow, the laminate thickness and the gelation of the matrix (see Figure 12).

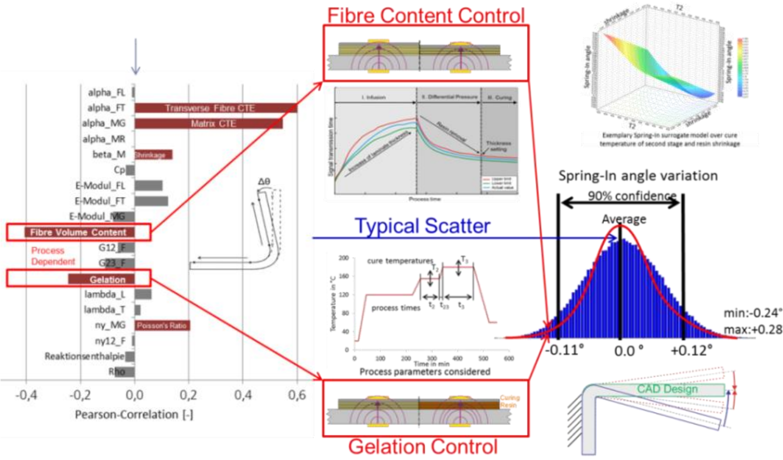


Figure 12. Sensor Based Active Process Control

By compensating nominal deformation effects and controlling process specific scatter effects it was possible to produce composite ribs with comparable geometrical accuracy as can be expected for machined aluminium ribs while still providing a significant weight advantage of more than 30%. By adapting the design also the production costs were at a comparable level even though the reduced complexity of the composite rib has to be taken into account as well.

## 3.3 Manufacturing

### *Introduction*

Manufacturing process and technology developments were developed. Processes selected as sufficiently mature were applied to part manufacture of a range of components manufactured for LAWiB and MIWib and other demonstrations. The technologies can be summarised in 3 categories and have been managed in 3 work packages described in WP21, WP22 and WP23.

**WP 21**
- Developed co-bond, co-cure technologies for more integrated structures. Part integration may provide product performance improvement in terms of weight as well as part count reduction that will reduce assembly time associated with tasks like shimming, drilling and fastening.

**WP 22**
- Developed processes to increase part accuracy to reduce assembly time, e.g. shimming.
- Manufacturing process development to speed up part manufacture

**WP23**
- Develop new solutions for NDI/NDT which can be integrated into a high rate production line
- Solve specific issues including challenges presented by more integrated structure

### *Integrated design & manufacturing process applied on MIWiB Upper Cover*

*Partners involved: IAI*

The MIWiB demonstrator goal was to develop an integral manufacture process, which combines separate parts into a single part, in order to reduce assembly effort and eliminate many of the tolerance issues which arise in conventional manufacture. The proposed manufacturing process was based on resin infusion (LRI). The design of the Co-Bonded Upper Cover Assy is based on a CAD-model earlier supplied by LOCOMACHS. This original design was modified to suit the new design architecture of the MIWiB – More integrated wing box (see Figure 13). The new design architecture of a more integrated upper cover suited the new defined build philosophy which permits a best fit assembly of the parts. This build philosophy eliminated most of the shimming which is required in common design of a composite wing box due to the nature of the composite material. The more integrated skin cover consists of the upper skin cover, stringers and a front and rear spar. The spars are cobonded to the skin, while cocuring the skin and stringers using the LRI process. Although simplified, this process manages to still eliminate shimming and fasteners between the skin and upper skin interface with less risks.

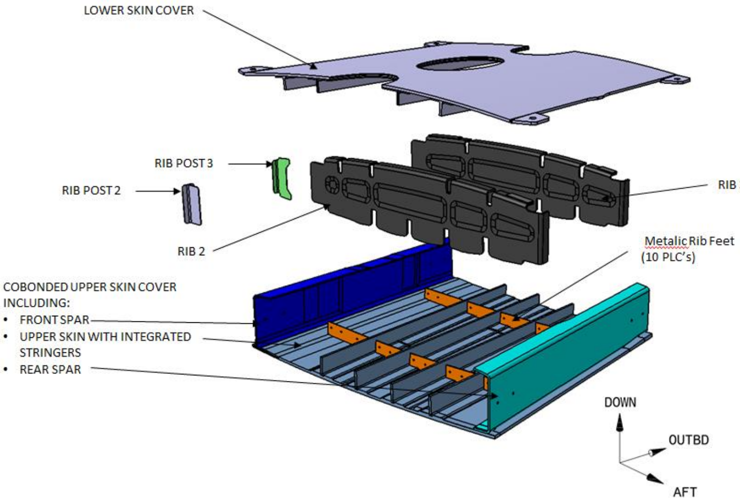


**Figure 13. The design architecture of the demonstrator MIWiB**

The parts raw material is powdered bi-axial NCF for ease of preforming and stable thickness. The fiber type is Tenax- E IMS65 E23 24K which was recommended by Saertex based on availability. The innovation of the MIWiB upper cover is that instead of manufacturing each part separately, requiring large assembly effort and shimming to gap tolerance build ups, the proposed concept eliminates shimming and fastening at each interface that is co-bonded. The economic advantages of LRI resemble the RTM advantages; additionally the use of an open tool significantly reduces tooling costs. Despite the advantages in the simplified assembly stage there are challenges to overcome during manufacturing. There is a risk of an imprint in the skin under the procured spars causing wrinkles in the skin laminate. The infusion process isn't straight forward and there is a risk of dry areas under precured parts. It is still possible to maybe prevent shimming on the fastened interfaces provided the manufacturing process is perfected. Two different approaches were attempted for the cobonding. The first approach is as proposed. The rear spar was cobonded to the upper skin on the IML. Due to the chance that during the infusion process the rear spar could sink a little into the skin and cause an imprint a second solution was proposed for the front spar. illustrates this approach where the spar was layed up on a minimal structural amount of plies and the rest of the skin was be layed up over the spar. Not only does this concept minimise the risk of the precured spar sinking into the skin but it also has an increased strength and damage tolerance due to the double shear interface.

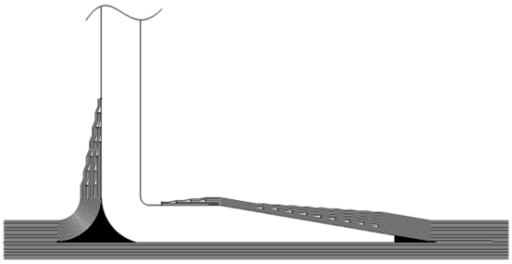


**Figure 14. Front spar concept**

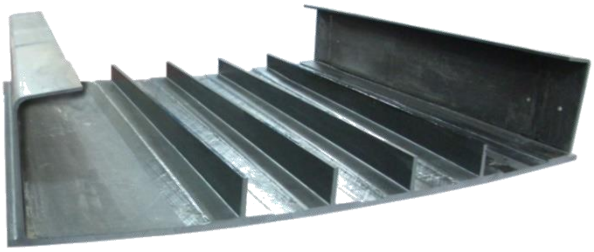


**Figure 15. MIWiB upper cover**

The part was manufactured according to internal process specifications (PS) for the LRI process. The PS outlines steps to be taken for quality control of the product which were assured during manufacture by the QC inspectors. Samples were extracted from the manufactured product for physical and chemical properties. Laminate quality was assured by thickness, microscopy and ultrasonic NDT. IAI has extensive experience with parts manufactured by LRI which also incorporates cobonding and cocuring elements/features. The process control test requirements assured that the process met all defined parameters for manufacturing the parts of high integration.

The CMM report was delivered to the MTC together with the MIWiB upper cover. The part did suffer spring in when released from infusion tool. Despite this phenomenon, the part was able to be returned to the nominal geometry of the tool with the application of reasonable force. During the assembly phase the MIWiB upper cover was be loaded in the assembly jig through the tooling holes, using reasonable force. Once located, the lower skin/spar interfaces were measured for final assembly of the ribs and lower skin cover.


**Figure 16. MIWiB rib assembly**

The ribs were loaded according to best fit philosophy as seen in . Once located and adjusted to the lower skin interface the ribs were drilled and fastened to the MIWiB upper cover. The locating of the lower skin to the MIWiB was performed using coordination holes. The interface between the spars and lower cover were mated as per design where no gap may be seen due to the control of the interface during the infusion process. Gaps may be observed between the ribs and lower cover which may be a result of spring in or thickness tolerances of the lower cover. These gaps may be resolved using shims.

**Conclusions**

In WP13 the design of a more integrated wingbox was proposed and the design was performed based on a trade-off study performed. In WP21 manufacturing trials were performed in order to validate the chosen concept. After validation the tooling was manufactured and the infusion process was defined. After the manufacturing of the 1st article quality issues were noted. Some infusion problems were expected due to the complexity of the part and usually many trials of the part are needed in order to perfect the process. The other geometrical issues (spring in, thickness variance etc…) are still being discussed in order to fully understand the LRI limits. Improvements were made in the 2nd article due to minor changes in the infusion process.

Liquid Resin Infusion (LRI) of a stiffened cover with cobonded spars has given good results and allowed to validate the build-up philosophy for the MIWiB upper cover. As a result, the assembly of the MIWiB was simplified relatively to the baseline and shows promise for future products.

- Assembly effort reduced due to more integrated parts
- No shimming on upper skin-spar interface
- Reduced shimming on the lower skin interface
- Possible interface control of lower skin/spar interface during infusion process
- Less fasteners in the upper skin
- Reduction of cost in raw materials due to use of NCF (2 to 3 times thicker than prepreg, reduces man/machine layup hours and less material wastage)
- Labour cost for assembly roughly 30% less due to less amount of fasteners and shimming
- Good condition for automated fastening in lower skin
- Solution may be certified
- MIWiB concept can be applied on other types of structures: Smaller business jet wings, tails…

### *Infusion for Thickness Adaption & US Laminate Thickness Control*

*Partners involved: DLR, Bombardier*

The following section gives an overview of the monitoring process which is involved in the manufacturing of the Rib 2 and Rib 3 for the LOCOMACHS LAWiB demonstrator. Ensuring a reproducible high product quality is a major goal for all production scenarios. In case of the ribs, geometrical accuracy was as important as the laminate quality itself and therefore a variety of measures has been investigated to actively measure and tune all quality relevant production parameters. The infusion process that has been chosen to produce the ribs is a combination of resin infusion (RTI/SLI) and autoclave technology because this combination offers a wide bandwidth of process parameter variation (see Figure 17). The whole resin infusion process is monitored by the use of ultrasound sensors which are attached on the bottom of the tool and on the laminate itself (see Figure 18). The sensor monitoring (pulse echo and transmission) refers to the flow front detection, the laminate thickness control and the degree of curing. The current status of the CFRP component can be displayed through the use of the sensors at any time. For example, the flow front measurement with the ultrasound sensors shows the same characteristics as the results of the Polyworx 2D flow simulation. The estimated filling time of 60 min could be reached and additional flow support wasn't necessary. The characteristic of the simulated resin flow front is shown in Figure 19.

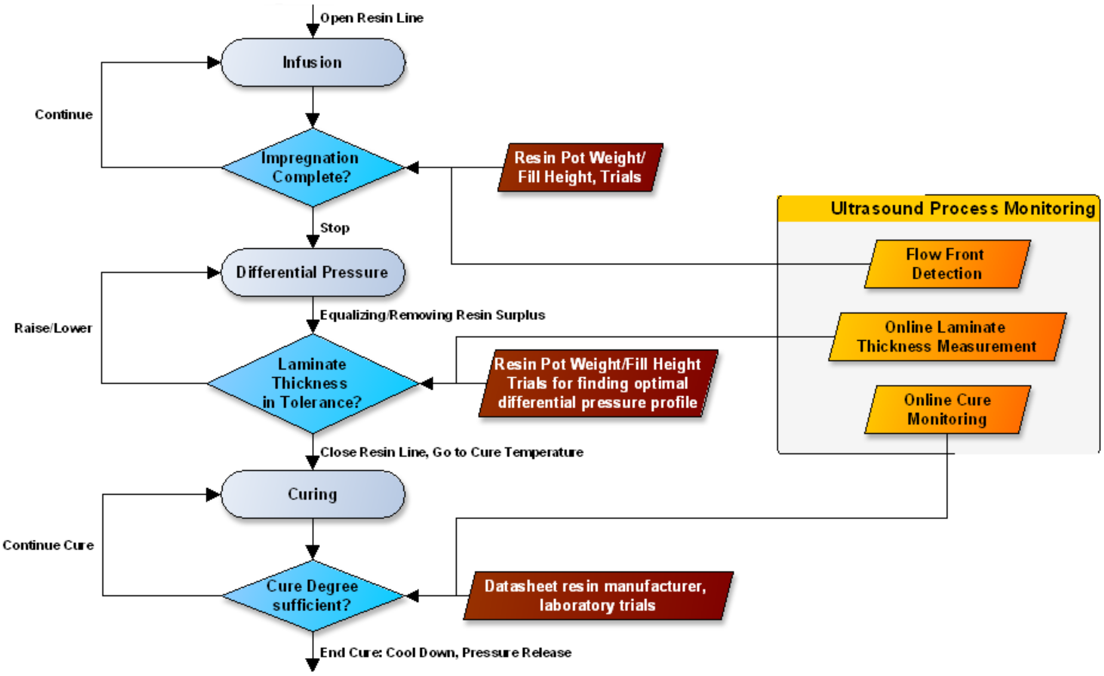


Figure 17. Sequence of online monitoring with us-sensors

The thickness adaptation due to the reduction of the injection pressure results in a maximum FVC (fibre volume content) of 60 +/- 1 %. Based on this variable pressure adaption different FVC and as well laminate thicknesses could be adjusted and an online tolerance management can be realised.

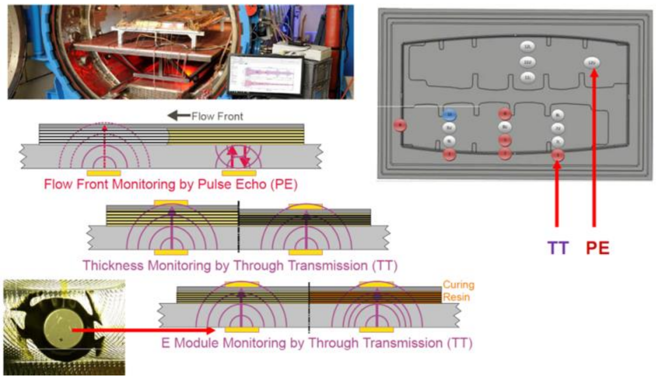


Figure 18. Ultrasound sensor application

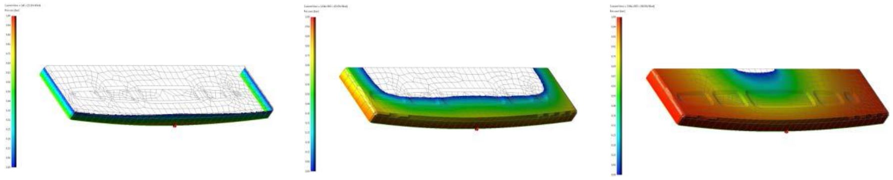


Figure 19. Flow front detection

### *Cocuring of a complex stiffened panel with integrated shear clips*

*Partners involved: SONACA*

**Figure 20. Composite panel with cocured skin, stiffeners and shear clips**

The target was to assess the feasibility of manufacturing a complex stiffened panel with hat-stiffeners cross-sections variations and integrated shear clips. In a conventional multi-step process, the skin and stiffeners are cured separately and assembled by secondary bonding; shear clips are metallic and riveted to the composite panel. Within LOCOMACHS, the selected process consisted in cocuring the skins, stiffeners and shear clips in an IML mould in autoclave. Several test articles have been manufactured with iterations of the process parameters. Although there have been some quality improvement, there were still defects like voids and their causes were not identified. All these iterations have shown the difficulty to manufacture such integrated parts by cocuring in autoclave. Closed-mold processes like SQRTM (prepreg based process) are probably more adapted for integrated parts, but such a process had not been considered due to the stiffeners cross-sections variations of the component that prevented the use of solid metallic mandrels. With the use of an autoclave process, an intermediate level of integration (skin and stiffeners only) is recommended.

### *First article of front spar for LAWiB & MIWiB*

*Partners involved: FNM (former ALA)*

The new front spar architecture was defined to fulfill manufacturing, assembly and structural design requirements through a new integrated design approach that was defined "MSA". This allowed all main requirements coming from the three disciplines to be taken into account from the very early stages of the development. They were then integrated synergically into the design and the manufacturing of the front spar. The main points are as follows:

- Lay-up analysis and simulation to predict after-cure deformation including spring back phenomenon for tool design
- Light spar webs with different thicknesses to optimize shear capability maintaining low weight
- LWR/UPR flange width increased to improve bending behavior and fastener position
- Lower flange thickness increased to improve bending behavior .
- Co-cured & re-worked pad-up which form flat interface areas allowing easy positioning of rib-post and improving bearing capability.
- Joggles in UPR/LWR flanges (representing a technological challenge for preform forming)
- Tooling designed to assure surface precision on all sides

The build philosophy target addresses the elimination of most of the shimming and other non-value added steps which are required in common composite wing box assembly due to the nature of the composite material. The search for the most promising process in terms of High Level Objectives and more specific cost containment targets was

addressed from the initial design phase and through the development of the manufacturing process. The prediction of the part deformation was experimentally proven and overall good results were achieved. The developed manufacturing process highlighted the challenge represented by joggles but solved or at least reduced the issues and led to the manufacturing of the front spar for LAWiB. The final front spar was measured with CMM and resulted within ±0.3 mm from the nominal model fully responding to the target that was set at the beginning of the research activity.

### *Spar-Hinge Attachment-Rib Post Integration*

*Partners involved: Bombardier*

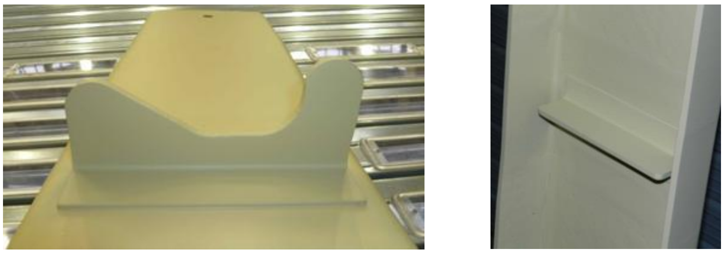


**Figure 21. LOCOMACHS Rear Spar with cocured hinge attachment**

The aim of this target was to drive further the integration of composite components by integrating a spar with rib posts and hinge attachments to be achieved via one-shot cures and qualify the viability of this approach. Component integration was expected to lead to :

a) Manufacturing parts with <u>improved accuracy</u> through datum location for assembly and the avoidance of assembly tasks.

b) Reduced in-service inspection requirement through reduced corrosion issues,

In this respect, the rear spar contributed indeed towards the LOCOMACHS programme objective of a 50% reduction of recurring costs of non-value added operations. A cost study on the economic benefits of the integrated spar revealed savings on assembly operations are possible. As the integrated spar manufacturing process is scalable in principle, but requires more complex tooling and thereby increased non-recurring spend. It has been concluded that the overall manufacturing process is negatively impacted by cost, thus negating the gains made in assembly operations. As each integration case is affected by cost differently, individual studies need to be conducted to assess their viability. Further, within LOCOMACHS, cost / benefit calculations were limited to Manufacturing and Assembly costs and did not include lifecycle cost / benefit analysis, which we recommend to fully assess the merits of increased part integration.

### *Laser surface treatment for increased bond strength*

*Partners involved: TAI*

**Figure 22. Laser system**

Development of laser surface treatment for increased bond strength was shown by morphological, chemical, physicochemical and mechanical testing. For CFRP structures adhesively bonded joints are increasing alternatives to mechanical joint. The surface preparation plays an important role in the bonding operation and is perhaps the most important process governing the quality of an adhesive bond joint. In general peel plies are used on the surfaces to be bonded and peeled off just before bonding. However, this method is not good enough especially for low temperature curing adhesives. The desired bond quality cannot be achieved by this surface preparation method. As an alternative to traditionally used peel ply method, a lab scale laser system with four wavelengths 1064 nm, 532 nm, 355 nm and 266 nm was studied and parameters were optimized to improve the out of autoclave, two-component adhesive bond quality.

It was assumed that use of such an adhesive with improved bond quality makes it possible to reduce the fasteners in the final assembly line (i.e. rib to skin joint in LAWIB) and lead to weight reduction in turn. Automation of the surface preparation method and decreasing the labor hour in this step was aimed as well. A lab scale Nd-YAG laser system with four wavelengths, 1064 nm, 532 nm, 355 nm and 266 nm were studied and their impact on CFRP surface was shown by microscopic, chemical, physicochemical and morphological analyses. From the literature and the pre-study it was derived that UV light is the most useful source for laser etching; however IR radiation is also promising to increase bond strength. For this reason laser sources ranging from UV to IR were utilised.It was shown that 1064 nm and 532 nm is not suitable for etching CFRP surface. Due to thermal effect of 1064 nm fibres and resin layer was damaged. On the other hand, 532 nm penetrates the resin and touches to fibres without any effect on the surface.355 nm was promising since it is one of the UV sources. Indeed many improvements were observed on the CFRP surface with optimum 355 nm parameters. Surface could be activated very well by increasing wettability and roughness. A good surface morphology was obtained as well. However, the expected increase in bond strength couldn't be obtained. Single lap shear strength values were found to be equivalent with those of peel ply treated specimens. In order to get a useful 266 nm light an indigenous system was designed and set up. It was obtained from the available 532 nm source using BBO crystal. The most critical parameters were defined as power, travel speed of x-y table and distance between pulses with this system. After a successful optimization, paste adhesive bond quality in terms of both mechanical strength (38.5 % increase in lap-shear strength with respect to peel-ply method) and failure mode was improved significantly without any fibre damage (see Figure 23).

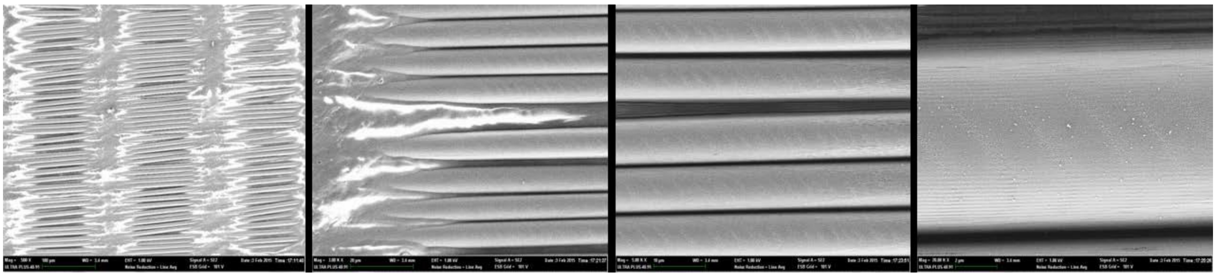


**Figure 23. FESEM images of CFRP specimen showing that fibres were not damaged after laser treatment with optimum parameters (@266 nm)**

TRL is defined as 3 at this stage. In the next step, system can be upgraded with a more powerful laser system (i.e. excimer laser) and a robotic head which make it possible to abrade sub scale parts. Cost saving compared to traditional peel ply technique was estimated as 22% with such a system.

### *Fan stand Assembly philosophy*

*Partners involved: GKNAES*

**Background:** A complex metal/composite engine component was assembled into a tight tolerance structure from several parts. In order to do this in a rational and cost efficient way there was a need for development and improvement in both the design for assembly and manufacturing processes. Assembly experiments where performed in which vanes were mounted between two rings, a hub and an outer case. This was made in order to verify the improved design solutions with the reduced need for assembly shimming and adjustable joints. As a part of this, composite guide vanes were manufactured with the objective of reducing the manufacturing time and improving the geometrical tolerances. The innovation laid in the design for manufacturing and assembly solutions.

**Results and conclusions:** The manufacturing and assembly of the AFT Fan Case assembly demonstrator at the GKN Aerospace Engine System R&T centre in Trollhättan, Sweden, was carried out successfully. The success-criteria from a manufacturing standpoint; manufacturing capability and production cycle-times, were met.

**Future developments & exploitation:** Future plans involve ideas of how to make technology insertions of this sub technology in similar products, as well as the possibilities of realizing an enhanced bandwidth of the technology to cover a wider scope of products.

### *Adaptive machining & Shimming manufacturing*

*Partners involved: BCT, FNM (former ALA), DASSAV, Bombardier, KTH*

Taking the geometry of individually shaped work pieces into consideration is one of the most significant advantages of *adaptive machining* over traditional manufacturing processes. This characteristic makes such technologies predestinated for preparing CFRP parts for the assembly process. In LOCOCMACHS optical scanning capabilities and data processing software have been integrated into the machining equipment, offering an alternative to separate external scanning methods. Based on the measurements made with the machine-integrated sensors (tactile or optical) sacrificial material sections could be processed, considering specific constraints presented by the individual applications defined by the end-users Finmeccanica (formerly Alenia, now Leonardo) and Dassault. Tests on different machines were performed simulating free-standing conditions mimicking the part shape directly after the production process as well as fixed conditions representing the part shape within a dedicated fixture system. The developments lead to an automated material removing process helping to reduce the today's shimming and alignment effort significantly.

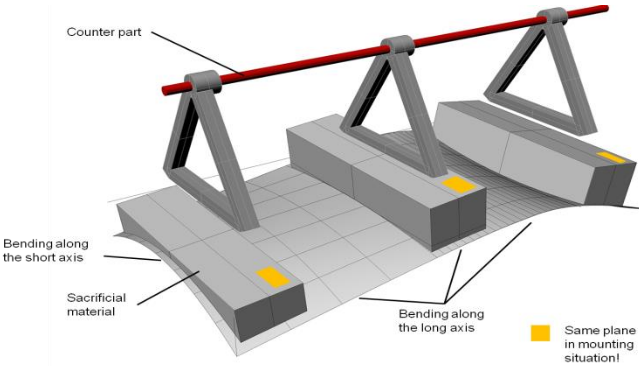


**Figure 24. Principle of processing sacrificial material supported by Adaptive Machining.**

In case that shims are used, the required geometry can be defined either by manual measurements or by a simulated assembly process based on scan data. To support the later approach developed by Airbus/KTH BCT provided a module, capable transferring the generated shim geometry directly into a milling program.

## 3.4 NDI/NDT

### *Introduction*

The work package WP23 within the LOCOMACHS project was dedicated to the improvement of NDE capabilities for modern aeronautics. The new material and more integrated and complex structures that are being implemented together with the strict requirements for cost reduction are a challenge for the NDE community.

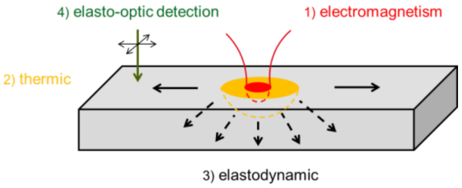
Several NDE techniques methods are available for composite materials inspection, each one having its own advantages and drawbacks; therefore the activity was focused on four different promising technologies: Laser Ultrasonic (LUT), Air Coupled Ultrasonic (ACUT), Acousto Ultrasonic (AUT) and Phased Array Ultrasonic (PAUT). These techniques were selected for their potential of both being automated and solving specific issue, they can be integrated in a high rate lean production line both at the manufacturing and assembly stages

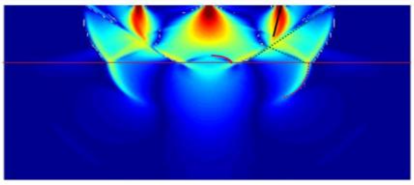
A workshop was organised aiming at demonstrating and validating the successful integration of these methods and the capability of speeding up inspection processes as well as interpretation of results.

### *Laser Ultrasonics (LUT)*

*Partners involved: Airbus Group, Dassault Aviation, Tecnatom, CEA, BCT*

The developments carried out during the project and demonstrated aimed at adapting the technology to industrial lean manufacturing and improvement of the capabilities to get a more robust diagnosis and to comply with the HLO's. The technological developments were carried out together with Laser Ultrasonic modelling conducted by CEA, in order to get a better understanding of the ultrasound generation process in composite parts and to optimize this NDT technique. The developed modelling tool has been implemented in "CIVA", commercial simulation software developed by the CEA (see Figures below).





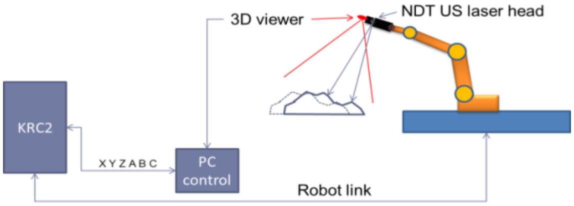
Most of the developments were carried out on the LUT platforms LUCIE (AGI, Nantes) and tecnaLUS (Tecnatom, Madrid) (see Figures below).

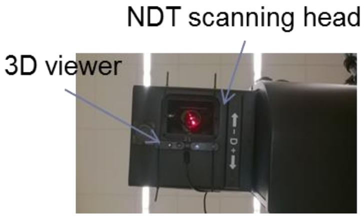
LUCIE (AGI, Nantes, FR)

tecnaLUS (Tecnatom, Madrid, SP)

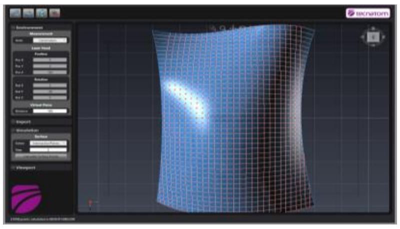
Amongst the major developments:

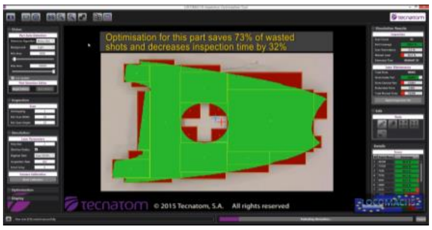
- A 3D viewer was embedded on LUCIE head (see Figures below) in order to improve the reliability of a robotic scanning system. The viewer captures in real time 3D images of the part to be inspected. The implementation of this tool has been executed successfully.





- Tools for optimizing the scanning strategy by Tecnatom
  - to help the operator to find the best poses of the robot to scan the part, so that 100% of the surface to be inspected and all the points are reachable with respect to the criteria,
  - to obtain a homogeneous inspection grid by defining equidistant point distribution over non planar surface,,
  - to save time avoiding scanning out of the part.





Optimisation for this part saves 73% of wasted shots and decreases inspection time by 32%

© 2015 Tecnatom, S.A. All rights reserved

- Automatic trajectory computation is provided by a subcontracted software which acts like an Off Line Programming Tool (see right Figure below), since it's possible to visualize the poses and the area that are reachable by the laser beams.. This permits also to check the motion of the robot and to avoid axis combination that leads to BDS (Beam Delivery System) damage. In the left figure above, the red arrows correspond to some inspection points that are out of the criteria.
- Implementation of signal processing algorithms for amplitude correction for US signal improvement and better SNR, by compensating several optical effects, the generation laser beam absorption fluctuations, the angle of incidence between the part and the laser beam, and glossy surfaces, we have some issues of repeatability.

These developments have been performed in order to achieve a leaner inspection, reducing lead time and waste in LUS inspection planning and execution, an effective lead time reduction from 17 to 42% has been obtained when the geometry of the part exhibits long curved shapes and/or large holes.

### *Air Coupled Ultrasonic Transducers (ACUT)*

Partners involved: Dassault Aviation, IAI, SONAXIS, Airbus Group, Tecnatom

The development of an advanced ACUT inspection equipment, probes and generator had the following technical objectives:

- To make the technology durable,
- Compliant with robotic inspection,
- Easier and flexible automation,
- With higher capabilities to improve aerospace composite and sandwich structures inspection.

The Technology developments concerns ACUT probes relying on two different transducer technologies were developed:

- The piezo composite technology uses a composite material made of piezo-electric ceramics embedded in a polymer matrix (see Figure 26). Focused piezo-composite transducers were developed for two different working frequencies, 200 kHz or 400 kHz, based on a shape piezo-composite element, to improve both the sensitivity and the spatial resolution.
- The electro-capacitive technology is based on the principle of a membrane which is moved in front of a cavity by an electrostatic force (see Figure 25).

**Figure 25. Electrocapacitive ECT transducers ( 50-800 kHz)**

**Figure 26. Focused piezo-composite PCT transducers: 200 kHz and 400 kHz**

A standalone UT generator with 1 to 8 multiplexed channels was developed to drive the ACUT transducers. The ACUT instrumentation interfacing with existing installations such as the robotic platforms MITO (AGI) and CESAR (DASSAV) was easy, thus enabling successful evaluation trials demonstrations.

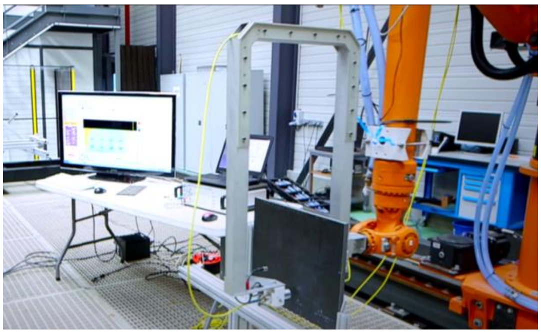


**Figure 27. Demonstration of the ACUT set-up on MITO, AGI, Nantes (FR)**

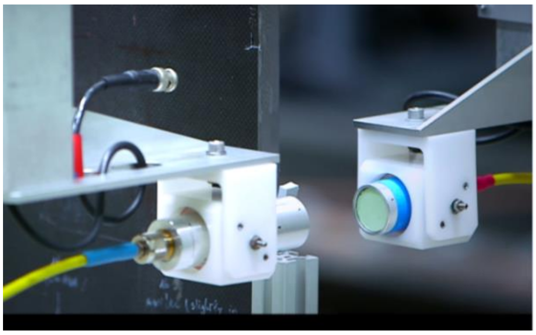


**Figure 28. Close-up view of the PCT transducer set-up in transmission on MITO**

Two families of air-coupled transducers have been developed, piezo-composite technology (PCT) and electro-capacitive technology (ECT)., they are complementary technologies in terms of applications and are performing as expected with sensitivity as good as if not better than the current and most popular air-coupled transducers in the market, which was the target. A new unique UT generator has been developed, it is able to combine these two types of transducers on a multi-channel basis for increasing sensibly the speed of inspection, a reduction factor of 7 can be obtained on the scanning time, approaching 1m² per minute.

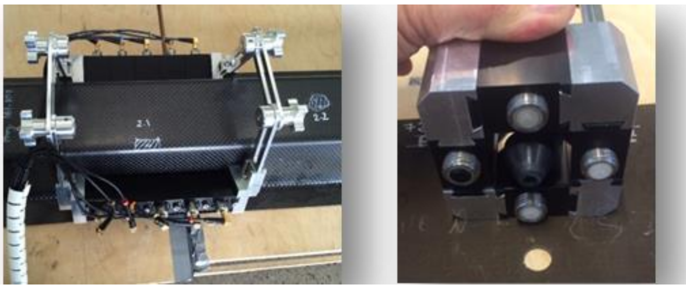
Sonaxis is now entering in the commercial and industrial phases to come up with fully demonstrated and robust equipments, the aeronautical and aerospace industries being really the prime potential customers.

### *Instantaneous imaging of structural integrity in complex CFRP parts using Acousto-Ultrasonic Tomography.*

*Partners involved: CREO, DASSAV, SONAXIS*

The quality inspection of complex integrated CFRP parts is a challenging and often time consuming task. Acousto-Ultrasonic Tomography (AUT) is a novel NDT technology that allows an instantaneous visualization of defects such as impact damage, delamination, disbonds, porosity and dry-area in CFRP structures.

The technique is based on a modular, reconfigurable sparse array of low frequency Piezo-electric probes in “hertzian” contact with the structure under inspection. Each probe generates a lamb wave propagating in the structure and pick-up by the other probes. By comparing the signals obtained for all trajectories with those obtained on a reference pristine structure of similar geometry, the system determines a damage index (DI) for all trajectories. Finally, a tomographic reconstruction of the defect position and size is performed and displayed on the user interface. The system updates at a rate of 10 Hz leading to an instantaneous imaging of the integrity of the zone within the probes. The system handles geometry variations such as radii , ply drops, bond lines or even drilled holes within the inspection area as long as the reference is acquired on a similar structure. The technology can potentially speed up dramatically the inspection process , especially for complex parts. In addition it does not require the interpretation of a complex signal which opens for its use by non-experienced operator.



### *Phased Array transducer applications (PAUT)*

*Partners involved: Dassault Aviation, IAI, SONAXIS, Airbus Group.*

The partners have developed means of inspection for drilled holes, countersinks and edges with two objectives: systems for expertise preferably manually driven and systems for production favourably to be fitted on an end effector of robot doing the drilling and milling operations. Different devices have been developed, the first one is based on a previous development done by AGI called Daisy, originally dedicated to drilled holes inspection; it is composed of a phased array ultrasonic transducer (PAUT) with a network of either hexagonal or annular elements. Specific delay lines were designed to tackle the issue of countersinks *(see 3 Figures below left*).

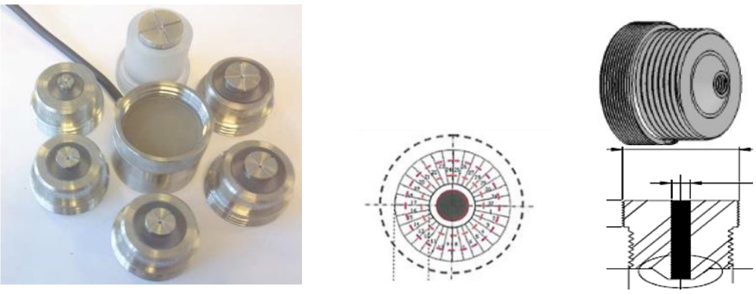


**Figure 29. Set of Daisy matrix probes by AGI for countersink inspection**

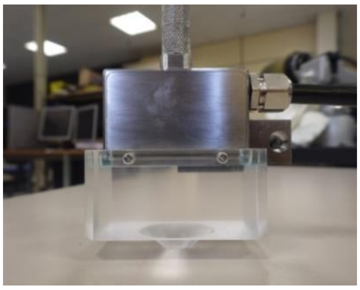


**Figure 30. DASSAV's linear Array**

The second device developed was carried out from an original idea proposed by DASSAV and is based on a linear phased array ultrasonic transducer with an encoder for mapping the inspected area around the counter sink or the drilled hole (see Figure 30). The third device developed by SONAXIS is based on an original 32x32 matrix probe providing instant inspection of the inspected area around the countersink or the drilled hole (see Figure 31).

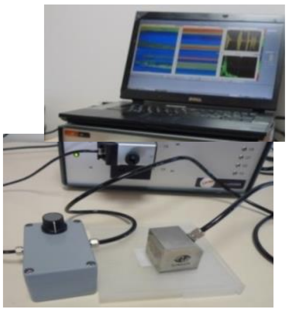


**Figure 31. 32x32 matrix probe and UT generator**

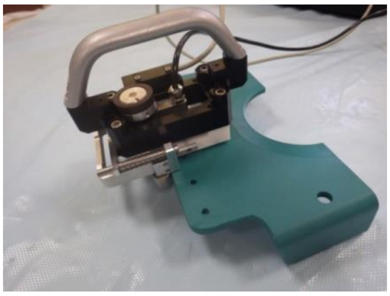
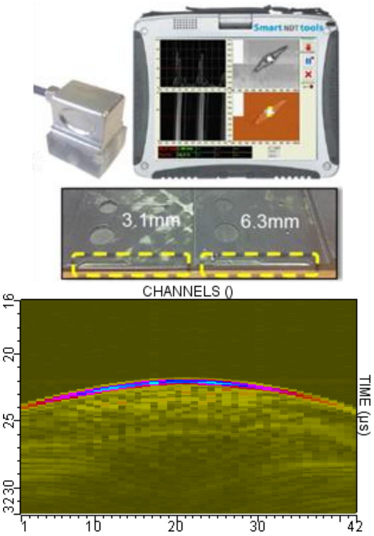
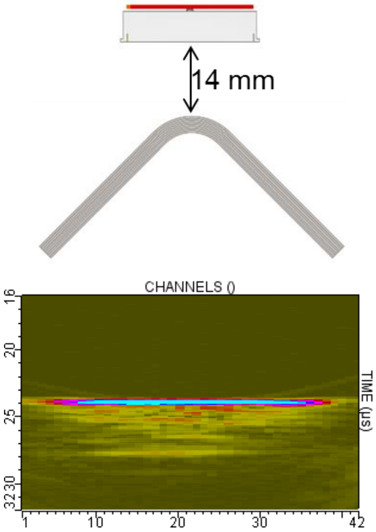


**Figure 32. DASSAV's edge inspection system**

Another case of study is the inspection of the edges of parts or large holes (Radius greater than 100mm). A specific transducer and a holding device have been developed in order to improve the edges inspection by increasing the reliability with cartography of the inspected area, thus reducing the non-inspected area close to the edges (see Figure 32). AGI developed a similar system but based on a matrix transducer (see Figure below left).





Two surface adaptive ultrasonic methods, SAUL and ATFM (Adaptive Total Focusing Method) were evaluated; they rectify the signals from complex shaped structures with parallel interfaces, in order to address a part as if it surface is flat. It is a quasi-real time correction technique (see 3 Figures above). The final case of study carried out by IAI and Sonaxis is the inspection of ply drops in composite parts for which an original 2D matrix phased array probe and dedicated test samples have been developed Several appropriate test samples were designed and manufactured with simulated defects. Most systems designs were carried out with the help of the simulation software CIVA which would remain of a great help for further optimization. Most of the experimental evaluations were successful; they comply easily with the main HLO of 30% lead time reduction. All the achieved demonstrators (5 to 6) gave good results, the technologies presented here fulfils our expectations in terms of capability of detection and simplicity of scanning. Most of them were demonstrated in Nantes and Coventry. The improvements foreseen and new probe designs are under discussion with SONAXIS.

### *Conclusion*

The numerous, comprehensive and original developments carried out on the selected NDI/NDT techniques lead to the successful completion of the three objectives which were identified:

- Inspection feasibility,
- Reduced recurring costs through increased automation by 30% (HLO),
- Reduced NDI/NDT lead time by 30% (HLO).

The availability of the developed equipment lead to a successful and fruitful demonstration of the work carried out and of the potential of the developed methods for a rapid integration in the industrial circuit.

## 3.5 Assembly

### *Introduction*

The main features for a modern and advanced assembly line for an aircraft wing, based on application of lean principles, have been established and validated. The basic requirement is the capacity of supporting 10 airplanes assembly per month in a line. Such a line is the result of the technologies developed within the LOCOMACHS project and suitable for a virtual simulation for a reference wing box named ReWiB (WP41 and WP43). In order to achieve a high production rate assembly line, that is effective in terms of quality, costs and schedule, many aspects must be taken into account, starting from an efficient design process for the different components, through manufacturing and assembly processes and finally, considering logistics (related to supply, reception, inventory, distribution of parts and tools). The design of the ReWiB assembly line has included the targeted technologies developed in SP1 for part design, SP2 for part manufacturing and SP3 for specific assembly technologies development and testing. The cost effectiveness of these choices have been estimated. Nevertheless some trade studies have been performed in order to choose an Assembly Line configuration that would result in the estimated capability of supporting high rate production. Estimation has been based on the usage of the following KPIs:

- **Capability**: maximum number of parts that a workstation is capable to produce. The number of shipsets in one month is usually calculated using a 2-shift per day basis 5 days a week, 4.5 weeks per month.
- **Parallelism**: a dimensional ***p*** value that measures *how much work is performed in parallel with respect to the total amount of work*; it is defined as 1 minus the total flow divided the total cost; it is always greater than 0 and lesser than 1. If ***p***=0 then all operations are in sequence.
- **Balancing**: a dimensional ***B*** value indicating *how operations are equally distributed among all the workstations*; it is defined as 1 minus the average value of cost differentials between all workstations and maximum cost, such value is between 0 and 1. For a perfectly balanced assembly line, ***B***=1

Using as KPIs the balancing index ***B*** and resulting capacity (s/s per month: number of shipsets that can be produced in one month) a trade study has been performed between two main configurations for the ReWiB Assembly Line:

- **Configuration R1**: Line composed of a TE subassembly and Working Stations 1-2-3 for the main line;
- **Configuration R2**: Line composed of a TE and a LE subassembly and Working Stations 1-2-3-4 for the main line.

The KPIs have been estimated and their values are shown in the following table, including number of shipsets (s/s) produced in a month:

| KPI | Line R1 | Line R2 |
|---|---|---|
| Balance (***B***) | 0.58 | 0.61 |
| Capacity (***C***) | 5.15 s/s per month | 5.67 s/s per month |

**Table 1. Comparison of balance and capacity**

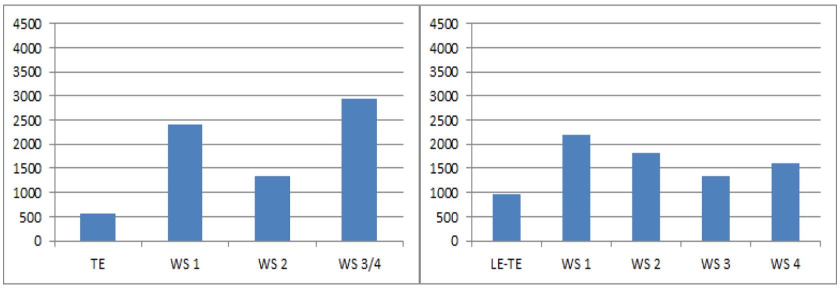
Values show that the configuration R2 is more balanced, but neither line is capable to support 10 shipset per month. Therefore working stations 1, 2 and 3 shall be equipped with two robots each, so that the following values are obtained:

| KPI | Line R1 | Line R2 |
|---|---|---|
| Balance (***B***) | 0.68 | 0.73 |
| Capacity (***C***) | 9.26 s/s per month | 10.2 s/s per month |

**Table 2. Balance and capacity with two robots**

The final choice has a line consisting of 2 subassemblies (LE and TE) and 4 main working stations (WS3/4 has been split in two). Balance and Capacity of R1 and R2 are shown.

In Figure 33 below, the y-axis represents a dimensional value proportional to the effort needed to perform the job in the relevant Working Station. Figure 34 shows that the requirements are fulfilled by the proposed Assembly Line.



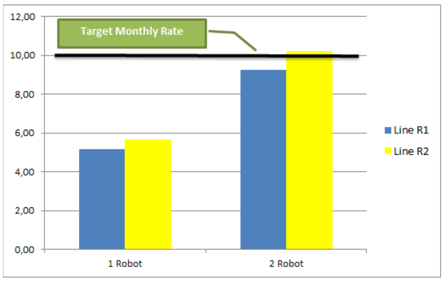
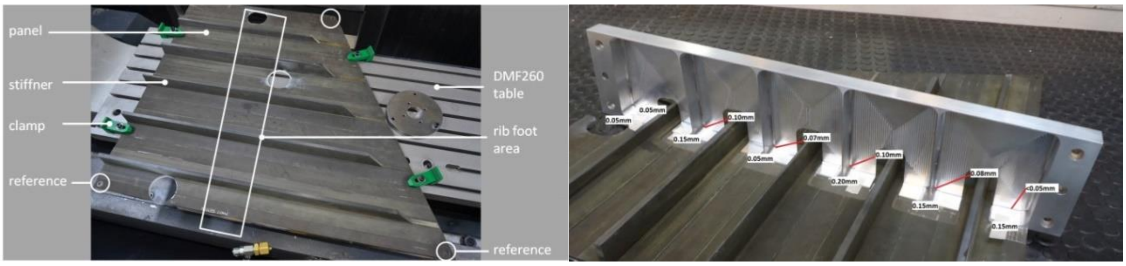


**Figure 33. Comparison of Balance** **Figure 34. Rate (shipsets per month)**

### *Sacrificial material*

*Partners involved: DASSAV*

The objective is to study the feasibility of adaptive machining to improve the assembly process, applied on a wing box example. The expected goal would be to remove any liquid shimming during sub structure assembly (gap should be <0.05mm for dry assembly criterion). A sacrificial material (glass ply stacking) is selected. It is laid on the wing skin at each sub structure assembly area. Then, it is machined with introduction of distortion (7mm difference with theoretical surface) in order to simulate a real sub structure surface with its own distortion during machining. The picture below describes the positioning and probing on the surfacing machine. The right picture indicates the result of gauging (from 0.05mm to 0.2mm) between the panel after machining and rib feet, with both parts released.



The expected criterion of 0.05mm maximum gap is not matched when parts are released. An assembly with a little coupling pressure is mandatory in order to reach such a level of gap. A cost optimisation at each step (probing, scanning, computing, machining) as well as the development of a generic software strategy are necessary to consolidate the TRL of the technology.

### *Drilling*

*Partners involved: TECNALIA, FNM (former ALA), DASSAV, EADS-IW, KTH, MTC, TAI, UNISA*

Aeronautic drilling prior to the installation of rivets is a fundamental operation to ensure the stability of the final assembly. Deficient drilling can produce delamination at the exit of the hole in CFRP plates or burr at the outlet of the titanium and aluminium alloys. The automation of this process will increase the efficiency of the process, reduce dismantling operations and improve workers ergonomic positions avoiding highly repetitive task in reduced and difficult to reach workspaces.

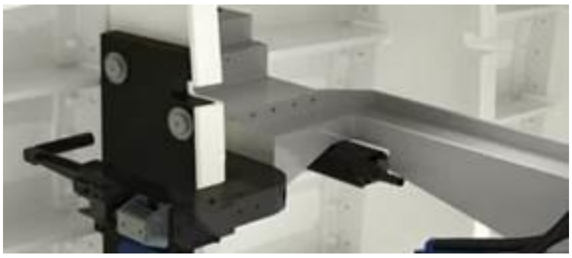


**Figure 35. DEE operation in the Advanced Aerostructure Technology Forum-2016 public video**

During the LOCOMACHS project, the study and test reports of new automated drilling solutions developed in WP32 (Automated structural assembly sub-operations) deal with three different concepts in the frame of aeronautics. These concepts were explored in three targets: **Tg32-2**. Drilling End-Effector (DEE)→ Focus in drilling operation at reduced workspaces; **Tg32-3**. Robotized Drilling → Focus in force control and cooperative robots for drilling tasks and **Tg32-5**. One Way Assembly of Covers to Structure → Focus in accurate drilling in very large surfaces.

The drilling end-effector –DEE- (Tg32-2) was successfully presented in the Advanced Aerostructure Technology Forum (at TRL5 level). This prototype includes a C-clamping that improves the drilling operation and a vision system for robot trajectory correction between the ribs location in the CAD model and the real position in LAWIB. The selection of the best tools to be used in DEE was studied in (**Tg32.1**. Drilling optimization). Innovation in the concept of this end-effector and the good results obtained during testing have ensured to continue its development for further industrialization.

### *Fastening End-Effector*

*Partners involved: Bombardier*

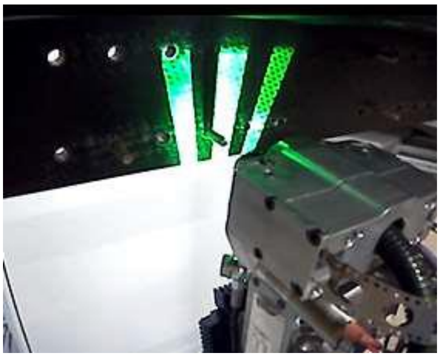


**Figure 36: Rear View of end effector vision activated to derive pin position**

This target contributes to the LOCOMACHS High Level objective to increase the level of automation related to part joining operations. A system was developed to automate aspects of fastener installation for lock bolt type fasteners that use a swage method for collar installation. Typically air craft wing fasteners comprising pin, sleeve and collar are manually installed in each hole by an assembly operator. The automated solution is designed to automate subsequent process steps including fastener pull through (to seat fastener in hole), swaging collar in position, pin tail removal and final inspection to verify that a collar has been placed correctly on the pin.

Controlled via a user friendly HMI interface, the end effector developed utilises a structured light projection system and camera combination to capture images of pin tail location. The control system derives actual pin location and adjusts robot pose prior to commencing fastener pull operation. Once the fastener is seated the collar insertion and swage sequence follow. A fastener delivery system in the form of a flexible tape is utilised to present the collar to the fastener. Subsequently, the vision system is deployed again to verify the swage quality. The fastener pin tail is designed to shear during swage sequence, which is removed to avoid FOD residing in the wing box and verified using a laser counter in the extraction unit. The technology has been demonstrated to TRL 5 on a portion of spar to skin interface on the LAWiB. The system has good potential, and opportunities for improvement have been identified. Wing box geometry particularly spar cross-sectional height provided a significant challenge to package the system hardware into those space constraints. A compact solution was achieved suitable for rib bays from wing root to 50% outboard wing span, further miniaturisation would be required for rib bays progressing outboard to wing tip.

### *Methodology for tooling design & Tolerancing*

*Partners involved: SAAB, PRODTEX, CHALMERS, MTC*

Airframe development today is done in a concurrent environment. The geometrical requirements and tolerances (GD&T) on the product are evaluated and a datum structure is developed. The manufacturing solution to meet the requirements include the tooling solution. Tooling concepts are iterated and then a final solution is developed, very much with repeatable processes.

The aim of this work was to perform development, test and evaluation of intelligent tool design tools (software) and methodology. The methodology starts with the datum definition and tolerance analyses using software tools used and further developed in WP 12. This can be done in each company’s Geometry Assurance process. This is linked to the parallel tool design process so that the best tooling solution can be evaluated in an early stage with respect to geometrical and tolerance requirements. It also means that relevant datum and tolerances can be used on both tooling and airframe structure early in the development process.

The objective of the design tool is to speed up the tool design work. It range from a simplified definition in the concept phase, to the detail design phase when the tool design and manufacturing documentation are to be produced. All software development is to be based on add-on software to make the new functionality and user-interface integrated in CATIA. This cover the usage of the boxjoint reconfigurable tooling and the new hexapod 6DoF pickup development, but can in principle be extended to other customer defined std solutions like welded structures and std pickups etc.

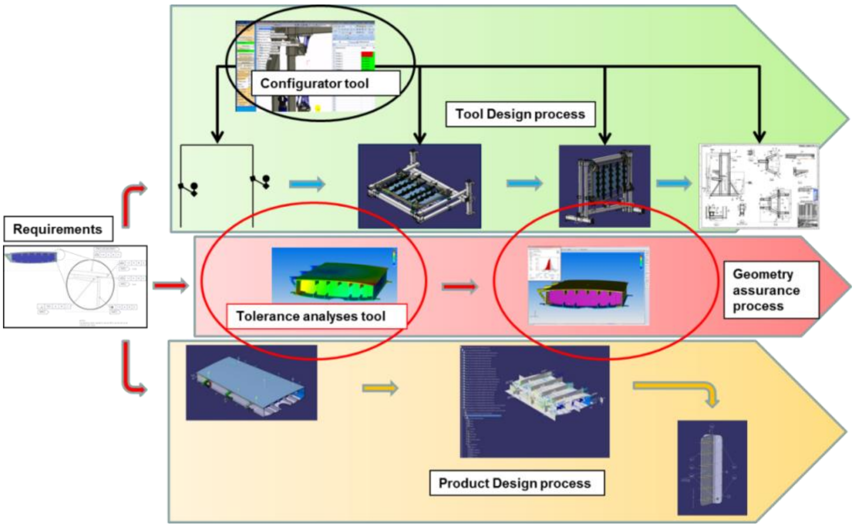


**Figure 37. Integrated tool and product development process**

Figure 37 shows the integrated tool and product development process. In the Tool design process, a software called “configurator” is to be used. Via a computer interface the designer make choices between different tasks like “add a component”, “locate the component”, “check line of sight” etc. The configurator makes use of a database containing a CAD-library and design rules. The Geometry assurance process uses a tolerance analyses tool. In the LOCOMACHS project two different tolerance analysis software tools (RD&T and ANATOLE) have been further developed and both can today handle rigid and non-rigid analysis on a number of materials.

For future work there are four main targets. One is to find a simplified tool definition with properties to run in the GD&T software. The aim is to ease quick tool design iterations and ad the dynamic (e.g. Bending) investigation. The second is to extend the range of std design solutions outside the Boxjoint and Flexapod/Hexapod scoop. Third is to future develop the automatic solution creating documents needed for tool manufacturing. This needs to be in line with one’s MBD roadmap ambition. The fourth target is very much a company internal target. It is to establish and mature the working process within the organization to make full use of the development tools. All this will result in a linked development process with less repeatable work and a cost efficient and robust solution.

### *Electric tooling for best-fit positioning of ribs and front spar*

*Partners involved: PRODTEX, PRODTEX, MTC, Chalmers, UNISA*

Two different Hexapod robot were developed, designed and built within this project. Both with each own separate designed control systems and software. Target TG34-1a, two Hexapods to position the Front spar following a specific trajectory in 6DoF. The innovation here was the synchronization of the devices and the first time a leading edge (front spar) have been positioned inside a wing box automatically. The Rib Hexapod developed in TG34-1 had a similar mechanical design except the force feedback device attached. The Rib Hexapod developed in TG34-1b, showed the capability to support the build philosophy acting as a fixture and best fit positioner using force feedback sensing. The flexible nature of the device was also a great help during the design and build of the LAWiB. Further development is needed to replace mechanical parts that can lead to a stiffer and more rigid device. As the software electrical controller was designed from scratch in this project more testing and debugging will be needed in the future.

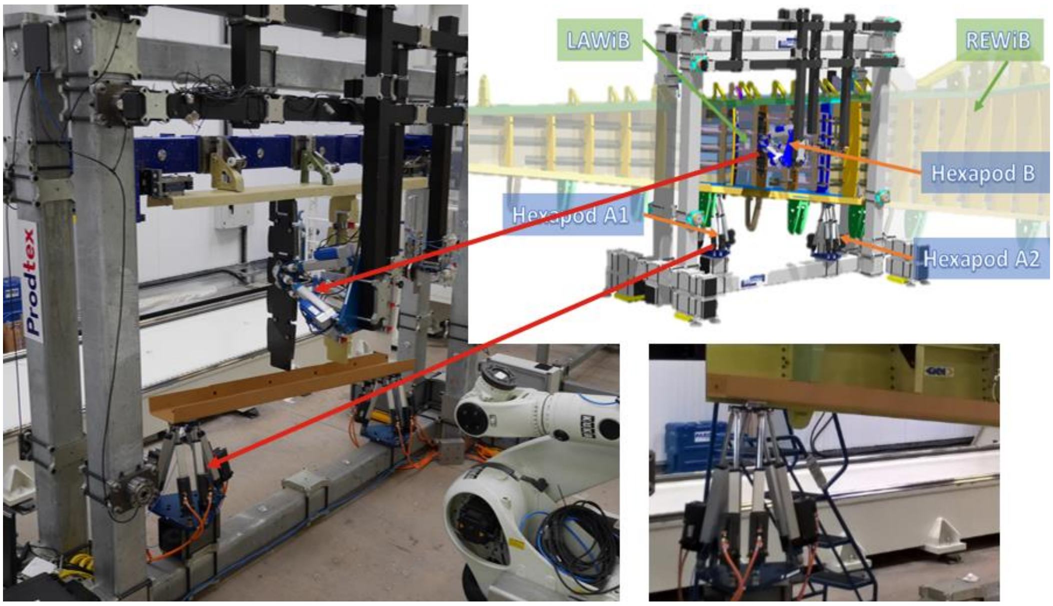


**Figure 38. Rib Hexapod installing the Rib 3 and the two lower Hexapods positioning the Front spar**

Following summary can be made from the both Hexapods:

- Automatic solution the “only way” (Build Philosophy)
- Front spar automatically and accurate installed to the wingbox. 200microns
- Rib was automatically installed by using force feedback sensor to enable a best fit positon and cope with manufacture variation of mating parts.
- Reduced set-up time for both assemblies

- Reduced the amount of shimming for the build
- Cost effective solution due to standard parts used and control architecture
- Can cope with design changes and different variations of the aircraft

### *Forced curing of liquid shim*

*Partners involved: SAAB*

Curing of liquid shimming material is a time consuming process and takes at least 9 hrs at room temperature before the parts can be handled. By curing at higher temperatures the curing time can be reduced, typical to 1-2 hrs at 60°C. A local increase of the temperature by using a resistive release tape in the shimming assembly shortens the curing time and also limits the temperature increase of the surrounding jigs and part. By connecting electrical power to the resistive tape the tape and the shimming material is heated. The thickness of the tested tape is 0,035 or 0,125mm and contains an acrylic adhesive with randomly distributed carbon or metallic short fibres. The resistive tape can either be placed inside the shimming assembly as was demonstrated at the LaWib interface between Ribpost 2 and the Front Spar or, it can be placed on the outside of the assembly, at the part, as was demonstrated at Front Spar/Lower Cover interface, see Figure 39.

Forced curing was demonstrated at 55±5 °C, 1,5hrs and the electrical power required was 41V/6A. The technology started at TRL1 and has reached TRL5 in maturity.

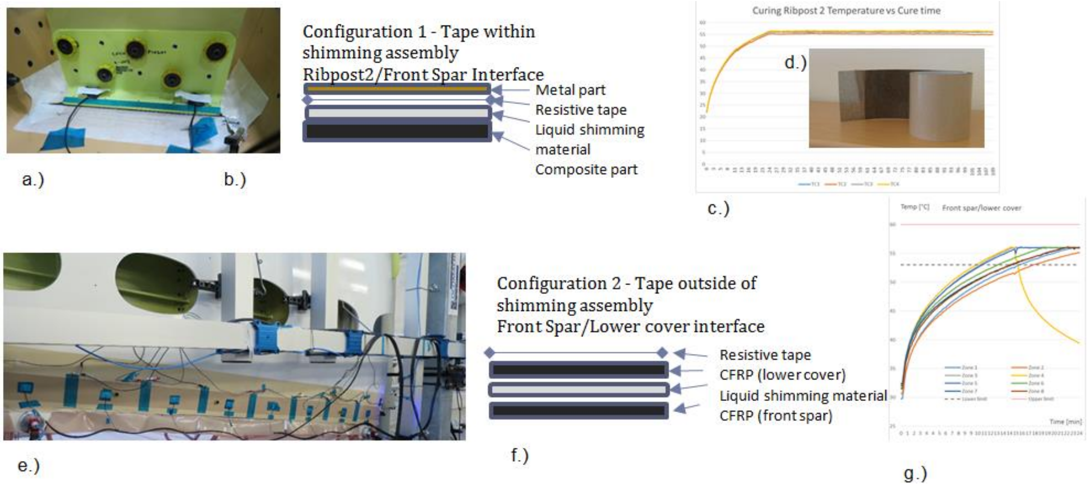


**Figure 39. Forced curing at LaWib**

a.) Shimming of Ribpost2/Front Spar using tape within shimming assembly
b.) Schematic, tape within shimming assembly
c.) Result from curing of Ribpost2/Front Spar
d.) Shimming of Font Spar to Lower Cover, tape on the outside
e.) The resistive tape
f.)Schematic, tape on the outside of the shimming assembly
g.) Result from curing of Font Spar to Lower Cover

### *Predictive gaps simulation for robotic additive manufacturing shimming using low cost precision metrology*

*Partners involved: AGI, Bombardier, ENS Cachan, KTH, MTC, TECNALIA*

The low cost precision metrology KTH Image Metrology System (KIMS), shown in the figure below, was developed on the basis of standard DSLR cameras and a Gobo projector providing a pattern of structured light on the measured object. At a hardware cost of ~2% of commercial large area measurement systems, it must be considered as a great success, as we achieved an accuracy of ~10 um within a measurement volume of 500 x 600 x 100 $mm^3$ . This is achieved by advanced image analysis, new calibration principles eliminating many error sources and a new 3D reconstruction algorithm. In contrast to commercial scanners delivering gigabit files, it delivers just as many measured points as required for the shimming process, and the 3D reconstructed coordinates are obtained in approximately 1 minute. For larger objects than the 500 x 600 $mm^2$ we also developed a stitching technique based on simple circular stickers. The final comparison with GOM measurements confirmed the overall shape of a 2.6 m long spar to a high degree of conformance. The estimated TRL is 4, but several requests of demonstrations from industry and academia will hopefully lead to a development of the system to higher levels.

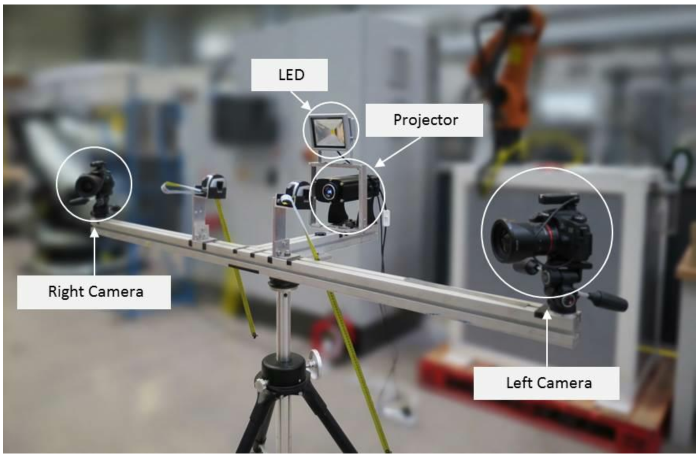


**Figure 40. KIMS low cost image metrology setup based on standard cameras and a Gobo projector. It provides 10 um repeatability within a volume of 500 x 600 x 100 mm3**

### *Assembly lessons learnt*

At the end of the LOCOMACHS project a lessons learnt review was held at MTC and the results were captured in LOCOMACHS D45.5 Final evaluation on physical demonstrators – Lessons Learnt [3]. Lessons learnt can come in many forms but ultimately they are an essential way for capturing and communicating issues encountered during a project and in an ideal world one would hope that they are not repeated. The subjects that are brought up are normally focusing on occurred problems, which might cause a negative impression of the result. It should therefore be said that functionality in technologies demonstrated in the LOCOMACHS assembly demonstrations was proven fulfilled although improvements could in many cases be identified. All lessons learnt captured during the review pertain to the LOCOMACHS physical assembly demonstrators LAWiB & MiWIB. This is a summary of the result.

| TG No. | TECHNICAL TARGET | LESSON LEARNT |
|---|---|---|
| 31-9 | KTH - Image metrology (KIMS). | The system fulfilled the accuracy requirements in measurement of a picture frame. The limited work envelope caused a need to stitch multiple measurements which needs further development in software support and methodology. |
| 31-3 | Predictive gaps simulation for robotic additive manufacturing shimming | Gaps during assembly were partly much bigger than predicted/measured due to that measurements was taken with the parts in a different orientation than in the assembly jig which caused geometrical deviations between the two occasions. |
| 32-2 | Drilling End-Effector (DEE) | Clashes were experienced during assembly (between robot/drill/hexapod/fixtures etc.) due to difficulties in managing design concurrently between involved partners. OWA worked on coupons and had the potential to work on interface upper cover to rib. On the interface rear spar to rib unexpected gaps/angular gaps, occurred which could not be closed by the end-effector. Accessibility for drilling in these confined spaces is very challenging. |
| 32-4 | Fastening End-Effector | Confined space behind spars, especially in square corners of two parts was one of the key challenges for the design of an effective end effector. Hole pitch is limited due to fastener feeding system |
| 32-10 | End Effector for quality control of swaging (see also Tg32-4) | Cycle time too long |

| TG No. | TECHNICAL TARGET | LESSON LEARNT |
|---|---|---|
| 32-5 | One Way Assembly of Covers to Structure | Orbital drilling using the PKM internal axis and the proposed cutters did not work as effectively as was intended. Some doubt as to whether DA really offers advantages when compared with drilling the two parts during final assy. Accuracy is critical and depending on fastener fit to parts and on tooling deviations during drilling. |
| 32-9 | Countersink scan to manufacturing riveting | System was sensitive to vibrations and speed of the PKM machine |
| 34-1 | Electric driven Pick-up for best fit positioning | Used only 4 DOF which was enough for the application – 6DOF system allows for more functionality. Better hardware needed in joints and actuators to avoid play. Could not measure the load on the part during movement |
| 34-2 | Manual driven pick-up for best fit positioning (Shim Box) | Long time to set shimbox (1/2 hour). Should not be used for frequently changing the position. Sliding surfaces needs to be machined. Backlash impacted setting |
| 34-2 | Manual driven pick-up for best fit positioning (rib manipulator) | Balanced version of manipulator was difficult to handle manually. Version with adjusting screws was easier to manage and repeated well in positioning. The long chain of tooling parts caused a spring effect in the manipulation. |
| 34-6 | Thermally stable fixtures | Tooling was not stiff, part was stiffer. Center of gravity was offset to the lifting point which gave an angle to the tooling during loading which gave issues. Vacuum cups did not help the function |
| 34-7 | Self & rapid locating tooling | Male and female part had to be aligned before merged, did not pull in, were not suitable in this vertical orientation as they did not lock the parts enough, some of the parts jumped out of the zero points. |

**Table 3. Lessons learnt from assembly demonstrations LAWiB/MIWiB**

Apart from the assembly technologies demonstrated and commented above there was another comment regarding the CAD-data and 3D element of the project which had an impact on the assembly. Issues occurred in the management of CAD-reference system when designing the tooling and exchanging models between partners which caused a lot of time consuming trouble shooting and finally an error in the physical tooling configuration in the assembly jig. The error could still be managed thanks to the flexibility in the tooling setting. The large number of partners using different CAD methodologies and the absence of working against a common data base in real time caused these issues.

To summarise the lessons learnt the positive part was that 12 of the 14 technologies demonstrated did show functionality which secured the build. The target Tg31-3 Predictive gap simulation could not be carried through since the manufactured shim did not fit. Liquid shim had to replace the intended solid shim. Neither did Tg32-5 One Way Assembly of covers to structure succeed. The method was replaced with conventional drilling and separation of parts for deburring and cleaning before assembly. Otherwise the demonstrated solutions where successful to prove the HLO, although potentials for improvements could be identified.

## 3.6 Design recommendations for cost reduction & Cost models

*Partners involved: KTH*

Predictive production costs are useful towards improving current production and introducing new production techniques and design solutions. A method of establishing predictive production costs and cost potential of lightweight composite structures has been developed in the form of a cost model, see Figure 41, and has been used in cost-efficiency studies. The cost model is generic and uses minimal input data consisting of CAD-extracted geometry data and basic production data and returns material, production and NDT costs.

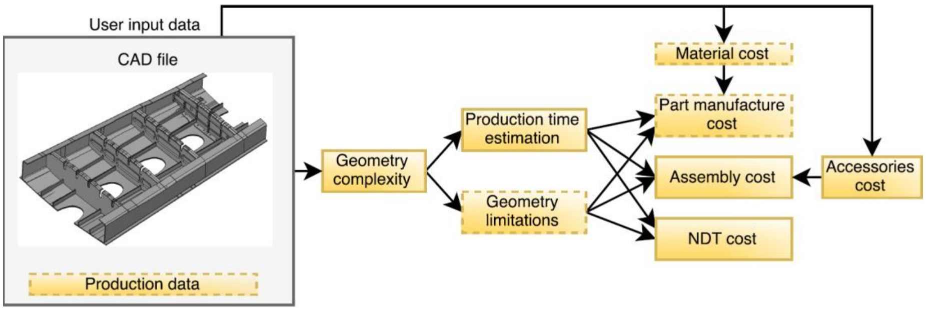


**Figure 41. Composite cost model flow and hierarchy.**

Performed research has resulted in several publications [refs], where developed cost model has been used in order to measure cost-efficiency of different production methods and design solutions. Interesting findings include cost efficiency and attached design recommendations on composite manufacture, assembly and NDT, both on traditional and state-of-the art LOCOMACHS innovation production strategies. Calculated production costs are a function of annual production volume, as well as structure size and complexity. Notable established design recommendations on composite manufacture vary on size, part complexity and annual production volume through for instance confirming that manual production is of higher cost-efficiency when draping complex and narrow component, even for higher production volumes.

Calculated production costs of different assembly strategies has shown that the current trend towards integration of composite parts may need to be revised when production cost is important and lower technology maturity is the facility status, see the low cost decrease potential of different integration strategies in . In addition, cost potential of a selection of LOCOMACHS innovations has been derived as given in , demonstrating both cost benefits of developed techniques and the efficiency of current presented cost estimation tool. The Hexapods developed by Prodtex and the Acousto-Ultrasonic testing (AUT) technique developed by CREO represent cost decreases of approximately 30 % individually. Presented LOCOMACHS innovations represent a cumulative cost decrease of up to 60 %.

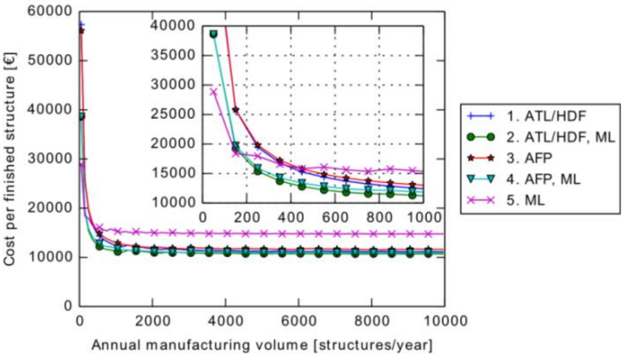


Figure 42. Different production method costs with increasing annual production volume.

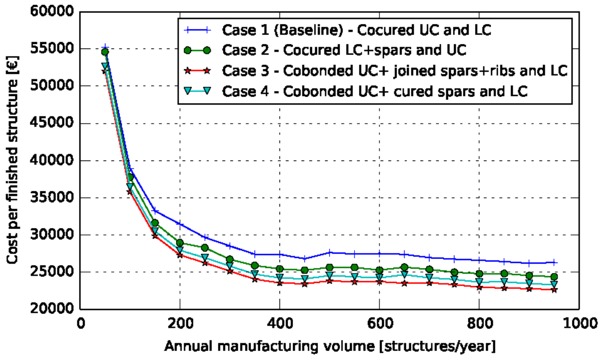


**Figure 43. Assembly cost of different LAWiB assembly scenarios**

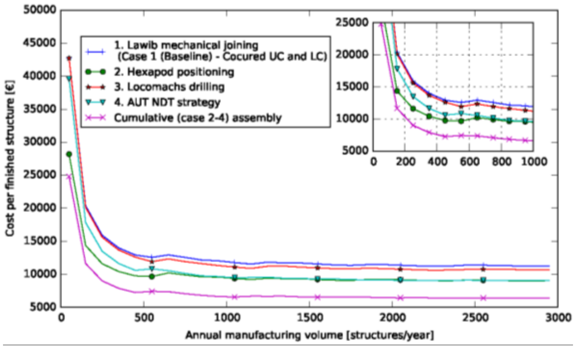


**Figure 44: Assembly costs of LOCOMACHS innovations.**

The developed cost model has proven to be useful when answering overarching design questions, both geometrical and from a production view. Performed studies have shown that it is important to study a full production chain in relation to current facility in order to achieve a cost-efficient production. A cost-efficient production strategy depends on application and facility maturity.

## 3.7 Virtual demonstration

*Partners involved: PRODTEX*

Figure 45. View of the wing factory in the software 3DEXPERIENCE

The report "LOCOMACHS_D43 2_Virtual Demonstration and evaluation report" and evaluation of production flow simulation of the ReWiB wing, LOCO WP43 Virtual Factory Prodtex 17 Small file size Full Version 10 min.wmv forms the deliverable of the virtual demonstration task.

Scale up technologies from LAWiB demo size to full scale, such as Fixtures, Equipment, Robot/Human collaboration and automation processes. Use the new digital manufacturing platform 3DEXPERIENCE to showcase new software capabilities. Below picture shows the designed future wing factory. A selection has been made of assembly technical targets (16 out of 33) developed in the LOCOMACHS project as appropriate for the ReWiB full-scale wing assembly line demonstration. This selection is based on:

- D41.2 High-level production requirements such as a synchronized pulsed production flow with takt time 2 days.
- LOCOMACHS High level objectives (HLO),
- High use of technologies developed in LOCOMACHS
- Potential for reaching **TRL4** or higher through the LOCOMACHS project.

Many of the assembly technical targets have been demonstrated in the physical demonstration of LAWiB. Some tooling solutions has been scaled up and some tooling have been conceptually re-designed to better suit a full-scaled wing. There also exists assembly equipment which has not been worked on in LOCOMACHS, both of high and low maturity.

The conclusion of the evaluation of the virtual demonstration is that the total solution shows a relatively high level of maturity through high level of details in the technical concepts and the use of technologies of mostly medium or high TRL. A remaining question although is if the performance in the solutions can justify the expected high level of investments costs. Focus of the simulation have targeted three areas: Handling of the parts, Robot access studies and human ergonomics. These three are illustrated below.

Figure 46. The Handling of the wing is simulated throw the production line

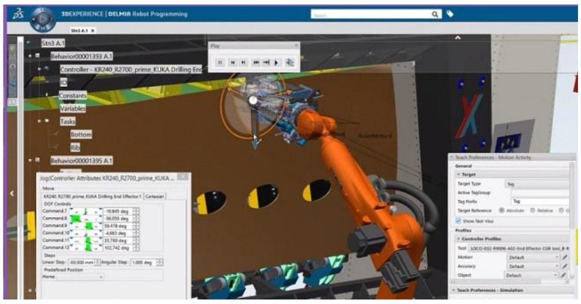


Figure 47. Robot access and reach abilities are studied

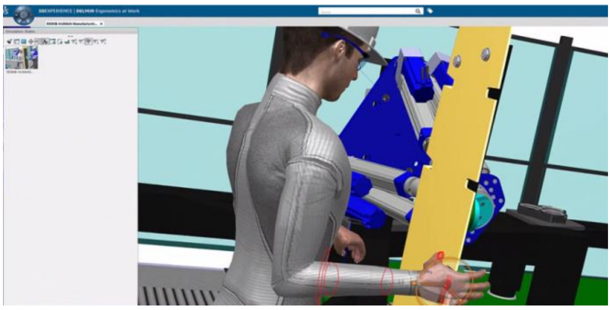


**Figure 48. Operator ergonomics are also considered within the simulation**

**Benefits of using simulation:**

- Ability to work concurrently on demo fixture and full wing concept utilising cloud features to share assets and communicate design evolutions.
- Manage multiple complex manufacturing operations and design modifications concurrently throughout the wing design process.

The conclusion of the evaluation of the virtual demonstration is that the total solution shows a relatively high level of maturity through high level of details in the technical concepts and the use of technologies of mostly medium or high TRL. A remaining question although is if the performance in the solutions can justify the expected high level of investments costs.

# 4 Potential impact

## 4.1 Rated global LOCOMACHS achievements

*Partners involved: DLR*

Within this chapter the objectives and scope, methodology, results and recommendations, as well as conclusions of rating global LOCOMACHS achievements are illustrated. In the first part of the chapter the main objectives and scope are described briefly. The second part includes the methodology and approach that have been followed to perform the rating of global LOCOMACHS achievements. This part illustrates the main assessed LOCOMACHS production processes for the three different LOCOMACHS wing box demonstrators including the Lean Assembled Wing Box (physical demonstrator object) (LAWiB), the More Integrated Wing Box (MIWiB), and the Reference Wing Box (ReWiB). After illustrating the objectives and scope, methodology, the third part shows the results of global LOCOMACHS achievements rating by means of a set of LOCOMACHS use cases of achievements. The last part contains conclusions for the rating of global LOCOMACHS achievements that are based on the rating results.

### 4.1.1 Objectives and scope

As a project that is supported by the European Commission under the 7th Framework Programme, LOCOMACHS aims to enhance the partners and stakeholders from the various sectors in addressing the vision of tomorrow's aviation of Flightpath 2050 and the ACARE SRA2. In order to accomplish that, the goals of both Flightpath 2050 and the ACARE SRA2 have been analysed in order to define a set of LOCOMACHS High Level Objectives (HLOs) that fulfil the associated goals from both Flightpath 2050 and the ACARE SRA2.

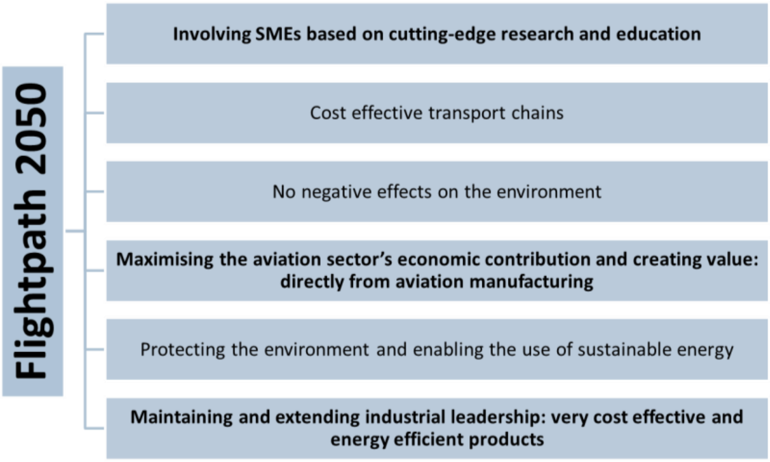


**Figure 49: Goals of Flightpath 2050 (Kallas & Geoghegan-Quinn, 2011)**

Based on the goals of Flightpath 2050 which are shown in Figure 49, the LOCOMACHS HLOs have been driven from the following major targets:

- Involving SEMs based on cutting-edge research and education
- Maximising the aviation sector's economic contribution and creating value directly from aviation manufacturing
- Maintaining and extending industrial leadership: very cost effective and energy efficient products

Considering that LOCOMACHS project covers the four main development processes including design, manufacturing, assembly and NDT, the LOCOMACHS HLOs have been selected to solve the most common challenges that occur in these processes. Therefore LOCOMACHS HLOs were defined to include practical process oriented goals that are shown in Figure 50.

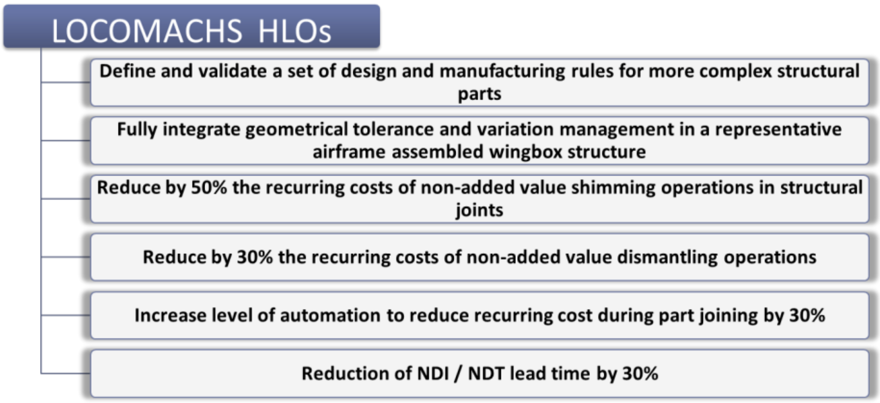


**Figure 50: LOCOMACHS HLOs**

Rating the global LOCOMACHS achievements represent the assessment of how far these HLOs have been achieved. In order to have a clear description within this assessment sensitivity analyses have been performed for a set of the achievements in the form of delivered technologies. Rating the global LOCOMACHS achievements is performed by a set of systematic methodologies and frameworks. In order to have a comprehensive efficient rating of global LOCOMACHS achievements the participating organisations have contributed in rating the achievements of the related deliverables in LOCOMACHS.

### 4.1.2 Methodology

In order to have robust recommendations towards future exploit, gap analysis or additional research of LOCOMACHS achievements, systematic methodologies and suitable assessment applications were developed. Within LOCOMACHS, 31 partners/ organisations participated in delivering 72 innovation targets together with 2 physical and 2 virtual demonstrators. This huge number of partners and targets necessitated the development of a flexible comprehensive rating plan in order to be able to derive global LOCOMACHS achievements and recommendations. In LOCOMACHS cost sensitivity analyses are performed. Based on the framework of ISO 14040, the sensitivity cost analyses is constructed as a simplified gate-to-gate life cycle cost analysis (LCCA). Due to the complexity of activities that's been applied in LAWiB, MIWiB and ReWiB, a sensitivity analyses diagram has been generated to represent these levels of processes and activities to illustrate the process modelling methodology, as seen in (Figure 51) .

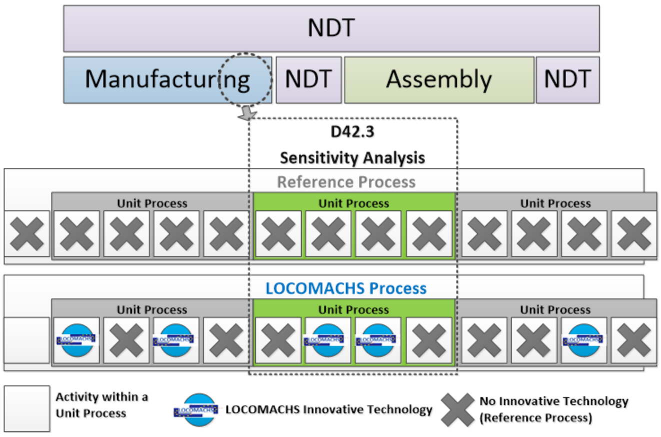


**Figure 51: Sensitivity analyses in LOCOMACHS**

As it is shown in Figure 52, the rating of global LOCOMACHS achievements includes a questionnaire as well as interviews with the partners which have also been designed within systematic approach that serves the targets of both Flightpath 2050 and the ACARE SRA2 by means of LOCOMACHS HLOs.

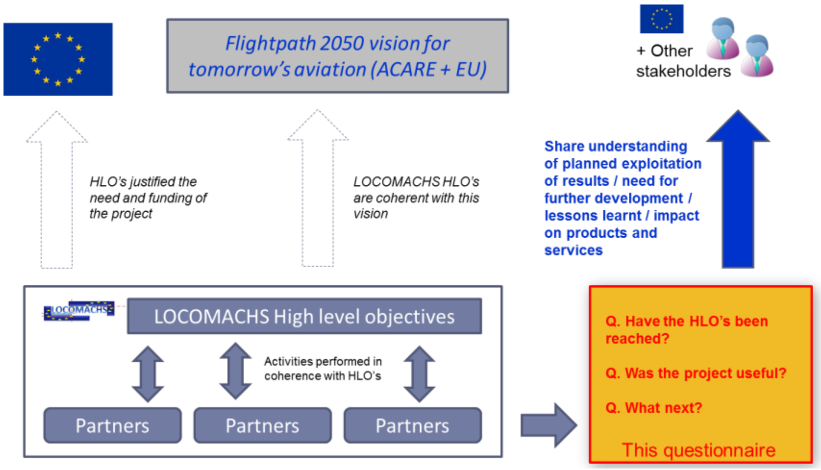


**Figure 52: Flightpath 2050 and the ACARE SRA2 and LOCOMACHS HLOs**

These interviews and questionnaires cover OEMs, R&Ds as well as SMEs listed in Figure 53.

**Figure 53: Partners which have been interviewed**

### 4.1.3 Results and recommendations

The results and recommendations cover both cost sensitivity analyses of LOCOMACHS innovations and rated global LOCOMACHS achievements and recommendations for further activities. Starting with the results of cost sensitivity analyses of LOCOMACHS innovations, these results show a selection of sensitivity analyses case studies as they are listed in Table 4.

**Table 4: Case studies of cost sensitivity analyses of LOCOMACHS innovations**

| Nr | Use Case | Partner | Process |
|---|---|---|---|
| 1 | Rear Spar | Bombardier | Manufacturing &Assembly |
| 2 | Upper Cover Production | GKN | Manufacturing &Assembly |
| 3 | ReWiB vs. conventional build | FNM (former ALA) | Manufacturing &Assembly |
| 4 | Rapid and forced curing of liquid shimming material | SAAB | Assembly |
| 5 | Co-bonded Upper Cover | IAI | Manufacturing &Assembly |
| 6 | Laser Surface Treatment for Increased Bond Strength | TAI | Assembly |
| 7 | RTM Composite Spar | DASSAV | Manufacturing &Assembly |
| 8 | Wing box demonstration with infusion process | DASSAV | Manufacturing &Assembly |
| 9 | US Laminate Thickness Control | DLR | Manufacturing |
| 10 | Countersink scan | SONACA | Assembly |

The detailed results of each case study are illustrated in the deliverable D42.3. In this work, the achievements of LOCOMACHS HLOs are evaluated through these interviews with the partners within discipline related questionnaire for design, manufacturing, assembly and NDT. This questionnaire addresses the dedicated HLOs by a set of structured questions concerning the achievements, usefulness of TRL reviews, and future plans for implementation and development. These results are discussed in details within the deliverable D45.2; however two significant results are shown in this chapter. The first selected result covers the partners' responses on the questions about the Technology Readiness Level (TRL). The answers to both questions about "whether the TRL reviews have been helpful to identify progress and achievements" and "if the partner will continue to use them as a tool" are shown in Figure 54. The second selected result is about the assessment of new gained professional connection in LOCOMACHS which is covers in the question about "finding new Friends in LOCOMACHS", whereas the result is shown in Figure 55.

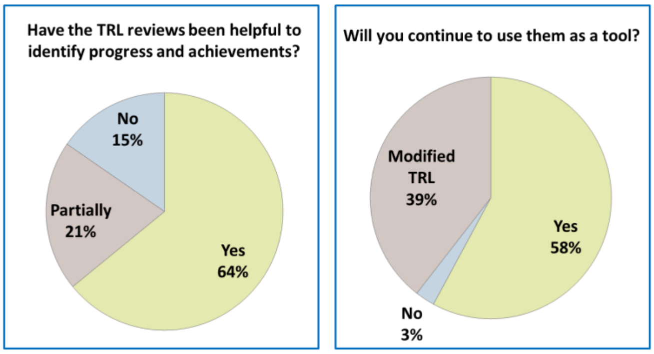


Figure 54: Results of the TRL assessment

Figure 55: Finding new Friends in LOCOMACHS

### 4.1.4 Conclusions

The results of the rated global LOCOMACHS achievements lead to several conclusions in the different discussed disciplines. On one side, the conclusions about the achievements in the HLOs and the cost sensitivity analyses of LOCOMACHS innovations include the following points:

- Defining and validate a set of design and manufacturing rules for more complex structural parts was achieved in LOCOMACHS. Smart shifting of functionalities between parts of the LAWiB proves to save time in assembly. Design and manufacturing rules are addressed in various deliverables.
- Fully integrated geometrical tolerance and variation management in a representative airframe assembled wingbox structure is a significant result of LOCOMACHS. Linked the tool design with geometrical assurances process has been also achieved.
- Reducing the recurring costs of non-added value shimming operations by 50% in structural joints is addressed, which means no shimming on interface rib to UC, no shimming between LC and ribs due to new build philosophy. However shimming should be further reduced.
- Reducing the recurring costs of non-added value dismantling operations by 30% is estimated to be achieved, whereas this is not fully verified.
- Increasing the level of automation related to part joining operations has been enhanced in LOCOMACHS.
- Reducing the NDI/NDT lead time by 30% is also estimated to be addressed; nonetheless this is not fully verified.

Generally, it is concluded that defining sufficient HLOs before the project was a difficult task, while measuring and assessing them during the project was sometimes difficult. Moreover, generating comparable results in a project with many partners and a big variety of disciplines is challenging. Considering the rated global LOCOMACHS achievements, new strategies have been established during LOCOMACHS to assess new developments even if sensitive data are concerned.

## 4.2 Dissemination

*Partners involved: ARTTIC, SAAB, DLR, EADS-IW, MTC*

### 4.2.1 LOCOMACHS Dissemination Events

***Innovative and Lean NDT technologies for Composite materials and Structures in Aeronautics, Nantes - 29th September 2015***

The NDI/NDT Workshop was a one-day event organised as a succession of plenary presentations of the work performed on NDI/NDT in LOCOMACHS in the morning followed by live demonstrations of selected technologies in the afternoon. In total, 66 people from both LOCOMACHS partners and 7 outside organisations attended this specialised event.

**Figure 56: Plenary sessions during the LOCOMACHS NDI/NDT Workshop**

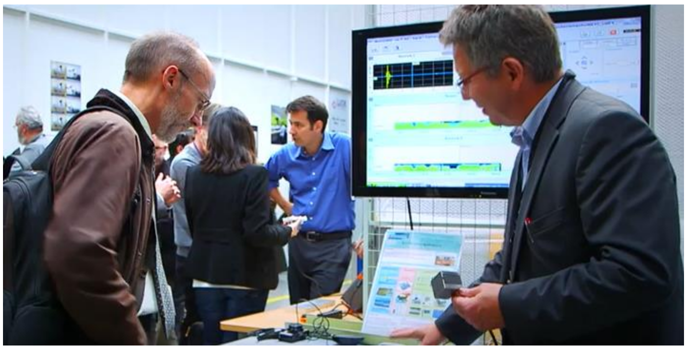


**Figure 57: Guillaume Pierre (SONAXIS) presenting his Air Coupled Ultrasound Inspection technology**

A series of videos was produced on four of the NDI / NDT technologies developed in LOCOMACHS; These videos can be seen in the dedicated LOCOMACHS playlist on the ARTTIC Youtube page.

***LOCOMACHS @ Aerodays 2015, London - 20-23 October 2015***

The LOCOMACHS project shared a booth at Aerodays 2015. In the booth, Prodtex showcased their hexapod and some posters were prepared to present the project's work and demonstrators. Magnus Engström (SAAB, LOCOMACHS Technical Director) also delivered a presentation on LOCOMACHS during the technical session entitled "Competitiveness of Aviation Industry".

**Figure 58: Maria Weiland (SAAB) and Peter Helgosson (PRODTEX) at the LOCOMACHS booth at Aerodays**

**Figure 59: Magnus Engström (SAAB) presenting LOCOMACHS during the "Competitiveness of Aviation Industry" session**

### *Advanced Aerostructure Technology Forum 2016, Coventry - 16th June 2016*

The LOCOMACHS project successfully held its final demonstration event entitled "Advanced Aerostructure Technology Forum 2016" on the 16th June 2016 at the Lloyds Bank Advanced Manufacturing Training Centre on the MTC's campus in Coventry (UK). The forum was organised in two buildings. It consisted of presentations, static demonstrations and poster displays in one building, and of live demonstrations and physical demonstrators in another.

The day was organised in a succession of plenary presentations and demonstration slots. After opening talks on the project, its high level objectives and its virtual demonstration work, the day was organised in sessions dedicated to the three main topics of LOCOMACHS, i.e. Design, Assembly and Manufacturing. For each axis, the participants were given introductory talks as well as presentations on selected success stories, followed by some time dedicated to static or live demonstrations as well as tours of the facilities, the LOCOMACHS demonstrators or virtual facilities using the MTC's Virtual Reality cave.

**Figure 60. Guided tour of the LAWiB cell during the LOCOMACHS Final Forum**

An area was allocated for posters and stands where LOCOMACHS partners could demonstrate some of their technologies (software or hardware). **In total, over 80 technology targets of LOCOMACHS were demonstrated.**

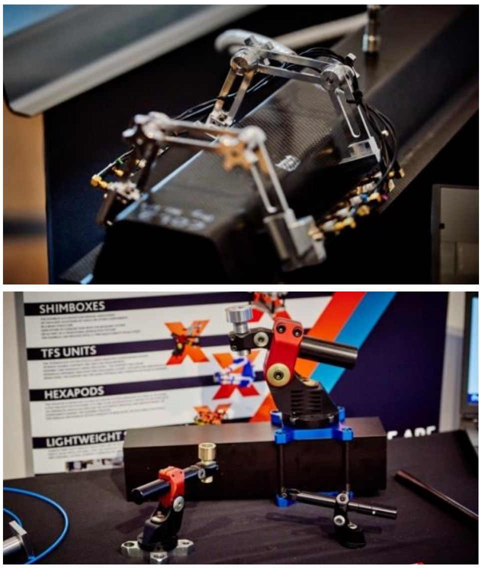


**Figure 61. Some of the booth displays of the LOCOMACHS Final Forum: Metrology solutions (top left), Physical robot-human collaboration tasks (top right), Reconfigurable tooling (bottom left)**

**Figure 62. LOCOMACHS Final Forum poster displays**

During the allocated Demonstration sessions, three 20-minute Technical Sessions were organised:

- Automating aeronautical assemblies : Mildred Puerto (TECNALIA)
- Realistic Assembly Simulation: Hugo Falgarone (AGI)
- Human-Robot Collaboration –Dr Kerstin Johansen (LiU)

In total, 153 people attended the Advanced Aerostructure Technology Forum. The breakdown was as follows:

- LOCOMACHS consortium members: 103
- External attendees: 48
- European Commission: 2 (project reviewers)

The LOCOMACHS project chose to encourage academics to attend the meeting, in particular by offering a student discount. In total, this resulted in 14 attendees from universities from across the United Kingdom.

Finally, 4 VIPs attended. The VIPs were:

- Mr Mark Summers (the Aerospace Technology Institute) – session chair
- Mr John Cornforth (GKN Aerospace)
- Dr Turlough McMahon (Airbus Operations Ltd)
- Mr Anders Rydbom (Saab AB)

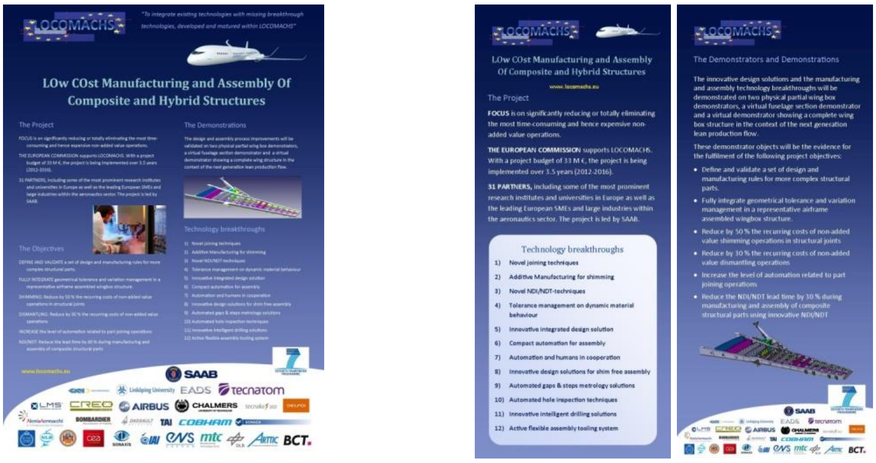
**Figure 63. VIPs talking during the "Industrial take-up beyond LOCOMACHS" session**

### 4.2.2 LOCOMACHS Communication Kit and Presentation Material

As part of its initial tasks, a LOCOMACHS communication kit was created containing material to be used to present the LOCOMACHS project: its objectives, scope, organisation, consortium and expected results. A special focus has been made on the 12 LOCOMACHS Breakthrough Technologies for which one or two technology targets were highlighted to illustrate the work performed and the progress made towards these high level objectives. To produce this update communication kit, target leaders provided slides on their targets their describing their approach and reflecting their current, and the LOCOMACHS Project Office and Coordinator provided more general information about the project progress. The content of this communication material has been agreed for dissemination by the LOCOMACHS Steering Committee and was made available, without modifications, to all LOCOMACHS partners. It is available for download from the publications section of the LOCOMACHS public webpage. This communication kit was updated four times throughout the course of the project.

The initial communication kit contained:

- A project presentation (PowerPoint format)
- Printable material: a bookmark, a folder and a poster



"To integrate existing technologies with missing breakthrough technologies, developed and matured within LOCOMACHS"

LOw COst Manufacturing and Assembly Of Composite and Hybrid Structures

The Project

The Demonstrations

Technology breakthroughs

The Objectives

www.locomachs.eu

LOw COst Manufacturing and Assembly Of Composite and Hybrid Structures

www.locomachs.eu

The Project

**FOCUS** is on significantly reducing or totally eliminating the most time-consuming and hence expensive non-added value operations.

**THE EUROPEAN COMMISSION** supports LOCOMACHS. With a project budget of 33 M €, the project is being implemented over 3.5 years (2012-2016).

**31 PARTNERS,** including some of the most prominent research institutes and universities in Europe as well as the leading European SMEs and large industries within the aeronautics sector. The project is led by SAAB.

Technology breakthroughs

1) Novel joining techniques
2) Additive Manufacturing for shimming
3) Novel NDI/NDT-techniques
4) Tolerance management on dynamic material behaviour
5) Innovative integrated design solution
6) Compact automation for assembly
7) Automation and humans in cooperation
8) Innovative design solutions for shim free assembly
9) Automated gaps & steps metrology solutions
10) Automated hole inspection techniques
11) Innovative intelligent drilling solutions
12) Active flexible assembly tooling system

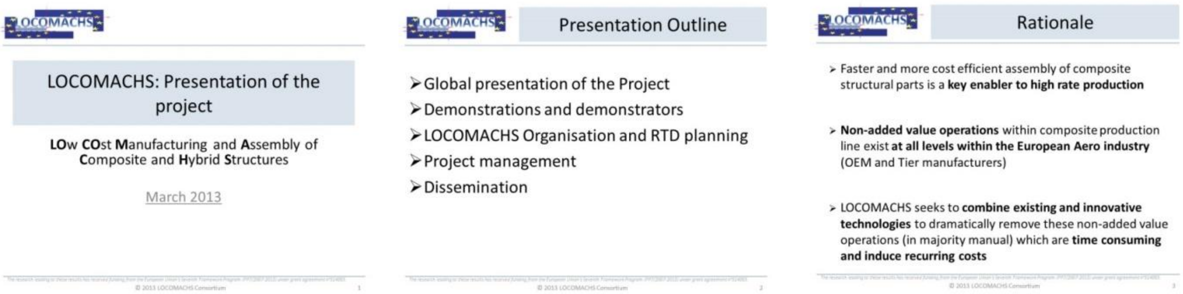
The Demonstrators and Demonstrations

The innovative design solutions and the manufacturing and assembly technology breakthroughs will be demonstrated on two physical partial wing box demonstrators, a virtual fuselage section demonstrator and a virtual demonstrator showing a complete wing box structure in the context of the next generation lean production flow.

These demonstrator objects will be the evidence for the fulfilment of the following project objectives:

- Define and validate a set of design and manufacturing rules for more complex structural parts.
- Fully integrate geometrical tolerance and variation management in a representative airframe assembled wingbox structure.
- Reduce by 50 % the recurring costs of non-added value shimming operations in structural joints
- Reduce by 30 % the recurring costs of non-added value dismantling operations
- Increase the level of automation related to part joining operations
- Reduce the NDI/NDT lead time by 30 % during manufacturing and assembly of composite structural parts using innovative NDI/NDT

**Figure 64. Initial LOCOMACHS poster (left) and double-sided bookmark (right)**



LOCOMACHS: Presentation of the project

LOw COst Manufacturing and Assembly of Composite and Hybrid Structures

March 2013

Presentation Outline

- Global presentation of the Project
- Demonstrations and demonstrators
- LOCOMACHS Organisation and RTD planning
- Project management
- Dissemination

Rationale

- Faster and more cost efficient assembly of composite structural parts is a **key enabler to high rate production**
- **Non-added value operations** within composite production line exist **at all levels within the European Aero industry** (OEM and Tier manufacturers)
- LOCOMACHS seeks to **combine existing and innovative technologies** to dramatically remove these non-added value operations (in majority manual) which are **time consuming and induce recurring costs**

**Figure 65. Extracts from the initial LOCOMACHS presentation**

The communication kit was later incremented with:

- An updated project presentation (PowerPoint format)
- 6 project posters
- A booklet of 20 pages

Low Cost Manufacturing and Assembly Of Composite and Hybrid Structures

www.locomachs.eu

*LOCOMACHS focus on significantly reducing or totally eliminating the most time-consuming and hence expensive non-added value operations in composite aircraft production.*

About the Project

Copyright

Foreword from the Coordinator

Through Thickness Reinforcement (TTR)

**Figure 66. Extracts from the LOCOMACHS booklet**

### 4.2.3 Scientific publications and presentations in key journals and aeronautic conferences.

Both academic and industrial LOCOMACHS partners have actively participated in conferences and workshops, presenting the project in general or focusing on particular LOCOMACHS project results. During the course of the project, over 70 intended dissemination activities were identified and submitted to the LOCOMACHS Steering Committee for approval.

Please refer to section 0 for detailed list of scientific & technical publications and presentations.

# 5 Public website and contact details

The LOCOMACHS public website is accessible at [http://www.locomachs.eu](http://www.locomachs.eu).

This project is co-funded by the European Union

**News & Events**

13/09/2016

The LOCOMACHS Results Catalogue is now online

The LOCOMACHS project has released its online Results Catalogue here.

...More ▸

See All News and Events ▸

The LOCOMACHS project

LOCOMACHS (LOw COst Manufacturing and Assembly of Composite and Hybrid Structures) is a collaborative research and development project coordinated by SAAB AB, gathering 31 partners including the European key players in the aircraft industry.

Faster and more cost efficient assembly of composite structural parts is a **key enabler to high rate production**. The LOCOMACHS objectives are to combine existing and innovative technologies to remove non-added value operations, which are time consuming and induce recurring costs, within composite production lines.

LOCOMACHS is supported by the European Commission under the 7th Framework Programme, grant number 314003. With a project budget of 33M €, the project is implemented during 3.5 years (2012-2016).

THE LOCOMACHS RESULTS CATALOGUE IS NOW ONLINE

The LOCOMACHS project has released its online Results Catalogue. This interactive catalogue provides an extensive overview of the LOCOMACHS exploitable results for the benefit of the LOCOMACHS Consortium industry partners, their supply chain companies and the Aerospace Industry generally.

The LOCOMACHS Results Catalogue can be viewed here.

**Figure 67. LOCOMACHS Public Website homepage**

The main objective of the LOCOMACHS website was to enable access and promote world-wide awareness of the LOCOMACHS project's work, objectives and results. This objective was achieved, with a global coverage as presented in Figure 68 and Figure 69.

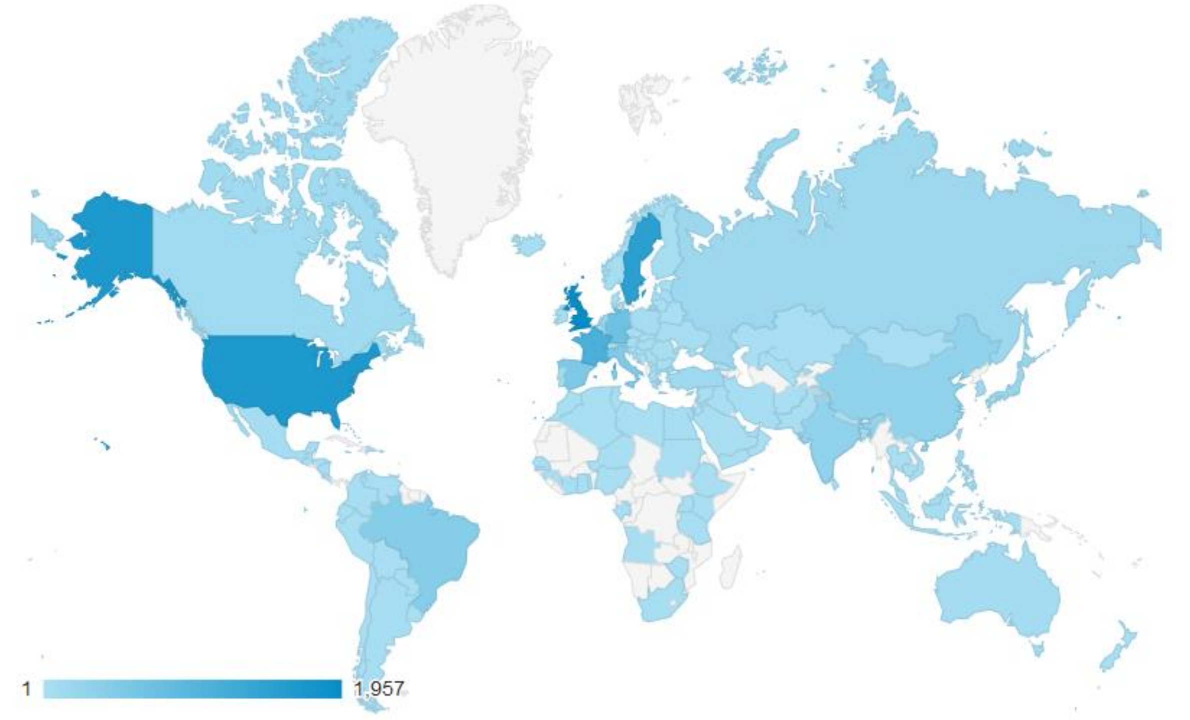
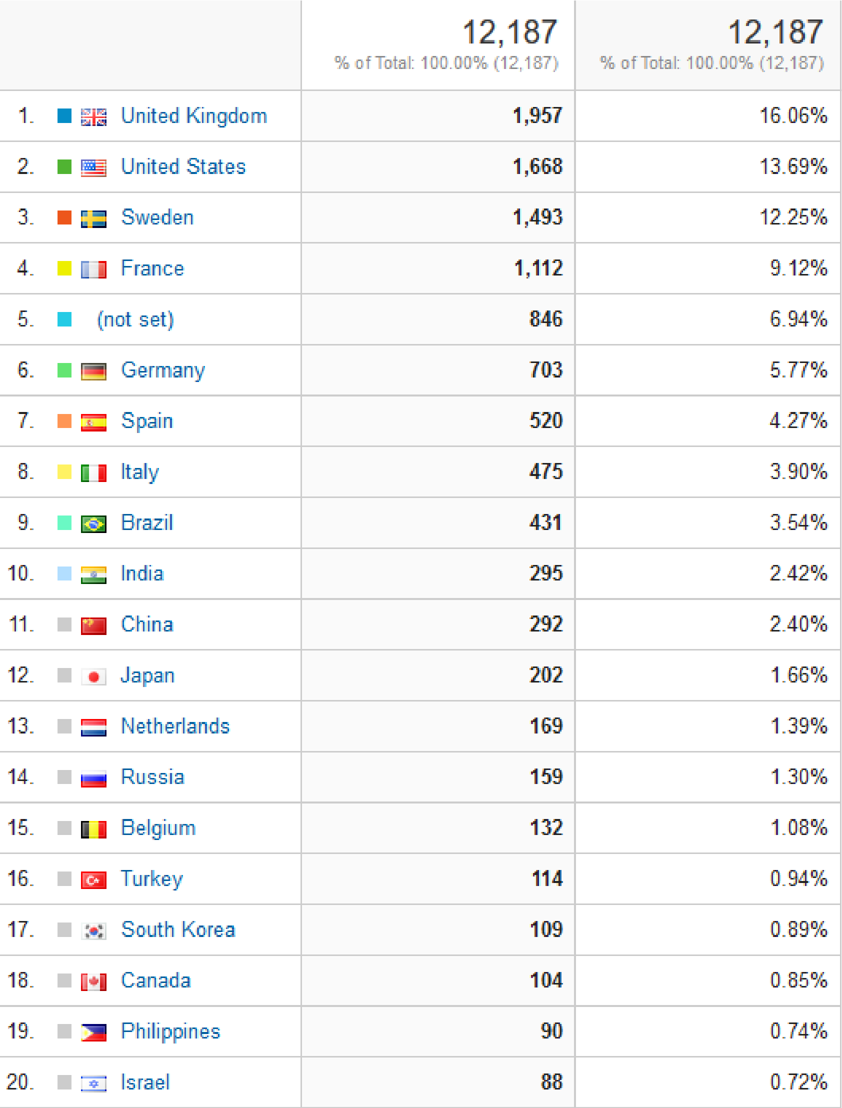


**Figure 68. Geographical spread of connection sessions (map)**



| | 12,187<br>% of Total: 100.00% (12,187) | 12,187<br>% of Total: 100.00% (12,187) |
|---|---|---|
| 1. United Kingdom | 1,957 | 16.06% |
| 2. United States | 1,668 | 13.69% |
| 3. Sweden | 1,493 | 12.25% |
| 4. France | 1,112 | 9.12% |
| 5. (not set) | 846 | 6.94% |
| 6. Germany | 703 | 5.77% |
| 7. Spain | 520 | 4.27% |
| 8. Italy | 475 | 3.90% |
| 9. Brazil | 431 | 3.54% |
| 10. India | 295 | 2.42% |
| 11. China | 292 | 2.40% |
| 12. Japan | 202 | 1.66% |
| 13. Netherlands | 169 | 1.39% |
| 14. Russia | 159 | 1.30% |
| 15. Belgium | 132 | 1.08% |
| 16. Turkey | 114 | 0.94% |
| 17. South Korea | 109 | 0.89% |
| 18. Canada | 104 | 0.85% |
| 19. Philippines | 90 | 0.74% |
| 20. Israel | 88 | 0.72% |

**Figure 69. Geographical spread of connection sessions (top 20 countries)**

**Figure** 70 below highlights the evolution of sessions and page views between September 2012 and August 2016. Connection peaks coincide with the major dissemination events that LOCOMACHS held that generated traffic both before and after the events, thus raising awareness about the LOCOMACHS project and its results. The main events, marked in red in **Figure** 70 were:

- March 2015: Participation of LOCOMACHS to the JEC Conference in Paris (France), co-hosting the Aeronautics session of the JEC conference series and holding a booth at the JEC composite show.
- September 2015: LOCOMACHS NDT workshop in Nantes, France.
- June 2016: Advanced Aerostructures Technology Forum in Coventry, UK.

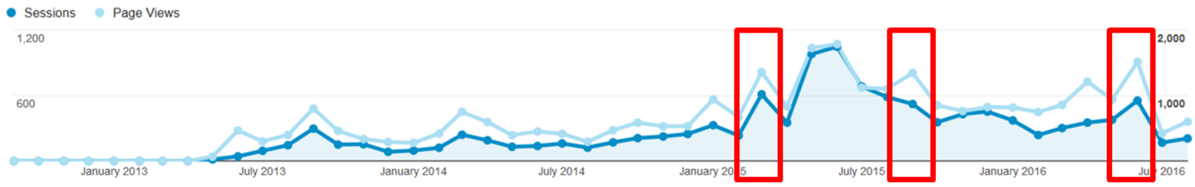


**Figure 70. Evolution of sessions (dark blue) and page views (light blue) over the project's duration, highlighting the project's three main dissemination events**