# 1 Publishable summary

## 1.1 Context and Objectives

Air transport is increasingly becoming more accessible to a greater number of people who can afford travelling by air, both inside and outside Europe, for leisure and business purposes. This is evidenced by the fact that last year the European air transport system moved more than 1 billion passengers and 14 million metric tonnes of freight through its airports, whilst handling more than 12 million movements over the same period. Despite the effects of 9/11, SARS and the IRAQ war, the sector forecasts that over the next decade, both passenger and freight traffic is expected to increase at an average of 4 to 5% p.a., with freight being expected to increase slightly more - both significantly above global GDP growth. In air transport terms, this implies a doubling of traffic about every 16 years. It is evident that environmental requirements, such as noise impact and emissions, will play a dominant role in future transport aircraft development, becoming a driving force for aircraft design. This is the main reason for which ACARE, in the Strategic Research Agenda, established the so-called *greening aircraft* as the first objective of future research activities related to Aeronautics. The adoption of this kind of global requirement has two main consequences: firstly, the greening level becomes one of the criteria for which a new aircraft has to be judged or selected; and secondly, the ***aircraft configuration*** itself must be defined to fulfil the greening requirements. Since other design targets, such as economic and technical factors, must be satisfied, new design criteria arising from the greening requirements must be taken into account right from the beginning of the design cycle.

Looking at actual transport aircraft it is very easy to identify many similarities in shape and configurations of different airplanes, even if during the last decades great technological improvements have been reached, for example concerning engine emissions and noise reduction, high-lift device configurations and advanced materials. One of the reasons is related to the fact that configuration and performance of commercial aircraft, especially fixed-wing aircraft, have been optimized within a limited range of conditions, especially cruise conditions, in terms of speed and altitude. Outside this range, aircraft behaviour is less than optimal.

Concurrently, technological developments in materials and computer sciences have evolved to the point where their synergistic combination has culminated in a new field of multi-disciplinary research in adaptation. Advances in material sciences provide a comprehensive and theoretical framework for implementing multi-functionality into materials, and the development of high-speed digital computers has permitted the transformation of that framework into methodologies for practical design and production. Adaptive structures represent a new approach or design philosophy that integrates the actions of sensors, actuators and control circuit elements into a single system that can respond adaptively to environmental changes in a useful manner. These integrated systems possess a functionality that adds significant value to materials, technologies or end-products, which in turn enables system performance enhancements that are not possible with traditional conventional approaches.

The aim of the NOVEMOR (**NO**vel Air **VE**hicle Configurations: From Fluttering Wings to **MOR**phing Flight) research project is to **investigate novel air vehicle configurations** with new lifting concepts and **morphing wing** solutions to enable cost-effective air transportation. A multidisciplinary analysis and design optimization environment developed in an earlier EU Project (SIMSAC) will be used and improved to include analysis of novel configurations, such as the joined-wing concept for improved lift, and morphing wing solutions to tailor the wing for optimum lift and maneuvering capabilities. The design and development of the proposed solutions will be performed an integral part of the aircraft conceptual design, rather than just as an add-on later in the design cycle, thus enabling innovative aircraft designs to be made through the use of morphing structures technologies. Such concepts will enable improved aircraft efficiencies, aerodynamic performance, reduced structural loads and lighter weight structures, leading to overall lower fuel consumption and therefore improvement on the greening level of the aircraft.

The NOVEMOR project will be focused on the following primary objectives:

1. Design and evaluation of a new aircraft concept, the joined-wing configuration, including structural, aerodynamic and aeroelastic scaling simulations and analysis, and multidisciplinary design optimization techniques. This configuration will be evaluated against a reference aircraft.
2. Morphing wing solutions (span and camber strategies and wing-tip devices) will be proposed to enhance lift capabilities and manoeuvring. These will be considered early in the design process, right from the beginning of aircraft design cycle, included in the conceptual design.
3. Design, test and evaluate the joined wing configuration and some of the more promising adaptive/morphing concepts and mechanisms as part of a conceptual design environment, capable of augmenting performance characteristics in terms of drag reduction, loads reduction, weight and noise impact reduction;
4. To evaluate the overall benefits of these new proposed concepts in terms of reducing operational cost.

## 1.2 Partners

| | Organization Name | Acronym | Scientific Team Leader | Country |
|---|---|---|---|---|
| 1 | Instituto Superior Técnico | IST | Suleman, Prof. Afzal | PT |
| 2 | Politecnico di Milano | POLIMI | Ricci, Prof. Sergio, | IT |
| 3 | University of Liverpool | ULIV | Cooper, Prof. Jonathan | UK |
| 4 | Kungliga Tekniska Högskolan | KTH | Rizzi, Prof. Arthur | SWE |
| 5 | Deutsches Zentrum für Luft- und Raumfahrt | DLR | Monner, Dr-Ing Hans Peter | DE |
| 6 | Centre for Scientific and Industrial Research | CSIR | Gerryts, Dr. Beeuwen | SA |
| 7 | EMBRAER S.A. | EMB | Negrão, Dr. José Ricardo | BRA |
| 8 | University of Bristol | UBRIS | Cooper, Prof. Jonathan | UK |

## 1.3 Description of Work

The project is split into two parallel lines of work which are complementary (Figures 1.1 and 1.2):

1. The study of morphing concepts and their application to a Reference Aircraft Model of a regional transport aircraft provided by the industrial partner EMBRAER.
2. The study of morphing concepts and their application to novel configurations, particularly the joined wing configuration.

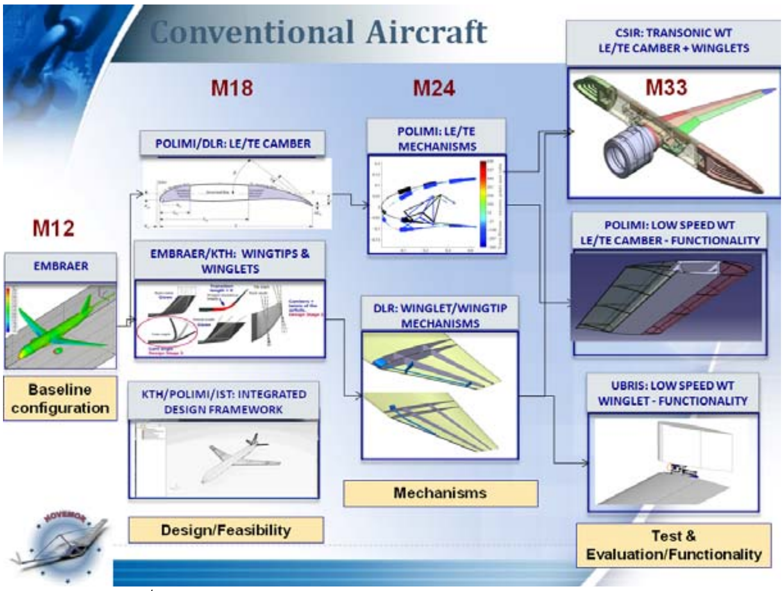


Figure 1.1: 1st line of research – Morphing of Conventional Aircraft

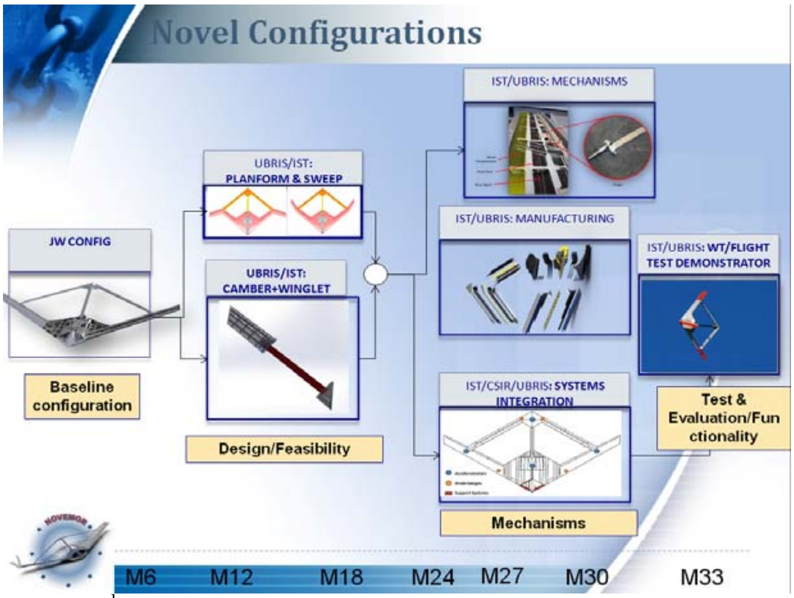


Figure 1.2: 2nd line of research – Morphing of Novel Configurations Aircraft

A short description of each WP objectives follows:

WP1- Project Management, Dissemination and Exploitation

- To secure the prompt initiation and smooth running of the project activities and the timely production of all deliverables, to the EC as well as to the partners, within the budget, and according to the EC rules.

WP2- Design of Morphing Concepts and Mechanisms

- To develop and assess new concepts for adaptive wing camber and twist
- To develop and assess new concepts for adaptive wingtip and winglet
- To develop and assess new concepts for variable planform and sweep wings

WP3- Novel Configuration, Simulation and Analysis

Enhance the CEASIOM software suite with:

- Parameterized geometrical representations for morphing aircraft, suitable for conceptual design and mesh generation for CFD and CSM;
- Techniques for the automatic generation of structural and aerodynamic models;

- Optimization procedures for the design of compliant mechanisms;
- Aeroelastic analysis tools adapted for morphing configurations;
- Flight-dynamic stability analysis of flexible and morphing configurations and apply these enhanced tools to assess the
- Setup of a complete aircraft reference model, e.g. the Clean-Sky-type configuration, to serve as the critical benchmark, against which the proposed configurations will be evaluated in terms of efficiency gained in increased performance, reduced weight, costs etc

WP4- System Analysis and Integration
- Evaluation of aeroservoelastic stability across the entire flight envelope for morphing systems including all failure and payload cases
- Definition of aerodynamic performance gains (drag, flight handling qualities, control effectiveness, etc.)
- Definition of an approach to determine the energy balance of the implementation of a particular morphing concept compared to conventional control surfaces
- Definition of an approach to determine the weight balance of the implementation of a particular morphing concept.
- Definition of an approach to assess the systems integration and avionics issues of implementing morphing concepts
- Definition of an approach to assess the trade-offs between the above issues in order to determine a ranking for various morphing concepts.

WP5- Wind Tunnel and Flight Demonstrators for Validation of Morphing Concepts and Joined Wing Configuration
- Build upon WP2 and WP3, the goal of WP5 is to develop physical models for validation of the proposed solutions and validation of the simulation results.
- To manufacture WT and flight test wings with the proposed morphing solutions. It is noted that only **the most promising morphing solutions** will be tested in the WT and in flight.
- To support WP6 with experimental data for the benefit analysis and also provide validation results to the numerical tools developed in WP3.
- Experimental validation of adaptive/morphing wing-tip and winglet concepts.
- Experimental validation of adaptive/morphing wing planform, camber and sweep change
- Design, manufacture and wind tunnel testing of a half wing equipped with a continuous active camber device based on compliant mechanisms designed in WP2 and WP3
- Flight test on the 5-m span ANTEX-C RPV for aircraft with planform and sweep change.

WP6- Benefit Evaluation in Terms of Impact on Lift, Drag, Weight and Aeroelastic Response
- Benefits assessment for the different adaptive/active concepts studied,
- To evaluate potential weight saving (including aspects related to concept installation and systems) for the different adaptive/active concepts studied
- Analysis for the reference test case of weight saving related to the active camber concept
- To evaluate aeroservoelastic response (flutter margins, loads alleviation, aerodynamic stability derivatives, structural vibrations) for the different adaptive/morphing concepts studied.
- Trade off between drag reduction, aeroelastic stability and loads alleviation.
- Aeroelastic analysis of reference case implementing the morphing concepts
- The trade off between the effect on drag reduction, aeroelastic stability and external noise will be evaluated.

- Benefits assessment for different adaptive/morphing concepts studied when applied to *Reference Aircraft.*

Up to this moment work packages WP1, WP2 and WP3 have been extensively developed and are close to completion. Work package WP4 depends on the results from WP2 and WP3, and is delayed due to delays on the referred work packages, mainly related to the 2nd line of research (Novel Configurations). Developments related to WP5 have been made mainly within the 1st line of research (Morphing of Conventional Aircraft). WP6 is starting in the 3rd year of the project.

## Summary of Activities per WP

WP1 - Project Management, Dissemination and Exploitation:

The deliverables are up to date. All documentation regarding the management (Project Manual (IST), Dissemination Plan (UBRIS), Technology Implementation Plan (EMBRAER), Internet Page (IST), Consortium and Grant Agreements) within the partners is available to them through the website at www.novemor.eu. The periodic meetings the between the partners have also been performed. In the kick-off, 6th month, 12th month, 18th month and 24th moth meetings the partners have presented their work and discussed the action items to the following period of the project. All presentations and meeting minutes are available to the partners in the website.
Regarding the dissemination of the project results so far several proceedings have been and will be presented in conferences.

WP2 - Design of Morphing Concepts and Mechanisms:

Within WP2 work has been done more extensively regarding deliverables D2.1, D2.2 and D2.3. Some work has been done on deliverable D2.4.

- D2.1 Morphing Wingtips and Winglets

DLR has developed a tool for topology optimization of morphing devices with a shell-based composite skin and compliant mechanism as a kinematic system. Numerical validation of the tool was performed. The tool will be used on the design of morphing wingtips and winglets for the Reference Aircraft Model. Preliminary results show the applicability of the tool for mechanism dimensioning of the morphing wingtip, although the expected benefits from this concept are reduced.
EMBRAER and IST worked on the assessment of the morphing benefits of wingtip and winglets morphing. The several studies performed do not show significant improvement for the morphing wingtip relatively to a fixed wingtip, for the conventional configuration aircraft and regarding the typical mission flight phases.
IST researched on the lateral-directional stability and authority increase on the Joined-Wing configuration aircraft using a wingtip bend-twist morphing concept. Preliminary aerodynamic results show potential benefits.

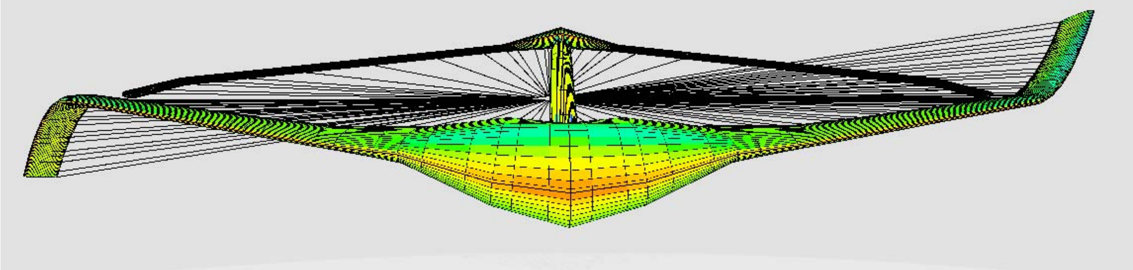

*Figure 1.3 JW bending-twist morphing concept.*

- D2.2 Morphing Camber and Twist:

POLIMI has been using a set of tools developed earlier (PHORMA and MORFEU) for the design of wings which is able to model active camber concepts based on compliant structures.
The camber morphing concepts involve Leading Edge and Trailing Edge deflections from the wingbox front and aft spars respectively.
The optimal 2D airfoil shapes for different flight conditions obtained from this tool are already constrained from a structural feasibility point of view, that is, the airfoil shape is the optimum airfoil shape that the internal structure can produce.
This airfoil shapes have been passed on to EMBRAER for high fidelity aerodynamic calculations. Results show benefits in wing drag of 7.2 drag counts when considering a rigid wing and an improvement of 10.1 drag counts if accounting with wing elasticity for the transonic regime (M=0.78) with Trailing Edge morphing. Leading Edge morphing showed improvements L/D for the CL range between 0.53 up to 1.10. This is reflected in fuel savings in the reserve segment of 62Kg.
Global improvements in the typical mission using the morphing LE and TE are estimated as a total of 98Kg.
UBRIS also performed studies first in individual and afterwards in combined morphing of structures (rotating spars and ribs), outboard front wing twist and LE-TE drop on the main wing airfoils.

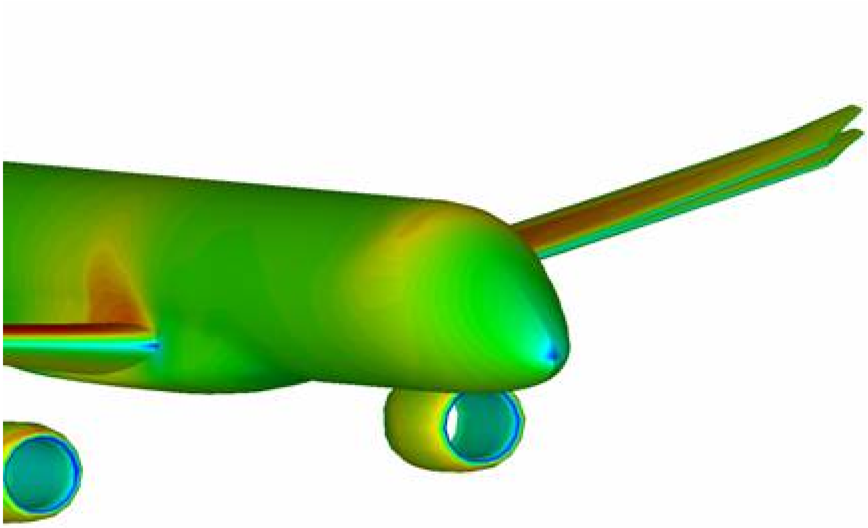

*Figure 1.4 Wing deflection and torsion due to the elastic effect.*

- D2.3 Variable Planform and Sweep

UBRIS investigated the effect of planform changes on a baseline joined wing UAV model. 4 different types of planform change were applied and the effects on L/D, aeroelastic characteristics and Stability & Control behaviour considered.

- D2.4 Study on selected materials and actuators for morphing

DLR has been screening of possible materials and actuator concepts that are able to provide the desired grade of morphing for the morphing wingtip device.

WP3 - Novel Configuration, Simulation and Analysis:

- D3.1 Aerostructural models and analysis for the reference aircraft with morphing and conventional surfaces.

EMBRAER worked on 1) definition and development of the Reference Aircraft Model; 2) preparation of the CATIA model for the wind tunnel evaluation; 3) preliminarily aerodynamic and performance analysis considering the morphing wingtip capabilities; 4) evaluation of the CEASIOM modules; 5) structural analysis computing the V-n diagram; 6) generation of an engine deck to obtain propulsion data; 7) flight qualities analyses were conducted.
POLIMI worked on the generation of the models describing the Reference Aircraft. Starting from the aircraft main properties provided by EMBRAER summarized in the single XML file, a complete structural sizing has been performed using NeoCASS software.

- D3.2 Computational design framework for a fully parametric virtual aircraft with morphing surfaces.

KTH worked on the enhancement of the preliminary aircraft design software CEASIOM with with: 1) parameterized geometric representations for morphing aircraft, suitable for conceptual design and mesh generation for CFD and CSM; 2) techniques for automatic generation of meshes for structural and aerodynamic models; 3) optimization procedures for the design of compliant mechanisms; 4) aeroelastic analysis tools adapted for morphing configurations; 5) flight-dynamics stability analysis of flexible and morphing configurations. This new framework used CPACS language for interaction between several disciplines modules and is designated CPACS Creator.
CPACS Creator was then used to parameterise the reference aircraft and redesign the main wing in order to generate an aerodynamic loading closer the optimum elliptical aerodynamic loading, more susceptible to aerodynamic improvements in the presence of a morphing winglltip/winglet.
Aero-Structural optimization of the Joined-Wing concept applied to a transport aircraft will be performed by KTH and UBRIS.

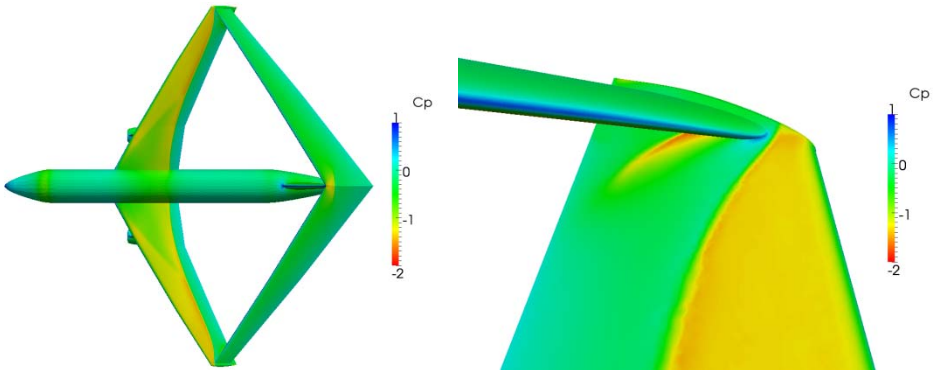


*Figure 1.3. Euler computation from Edge for M=0.8 and AoA=2 deg for the JW configuration.*

- D3.3 Multidisciplinary design, analysis and optimization of joined wing configuration.

IST is developed a performance based MDO framework for preliminary design and analysis of novel configurations, including the capability to analyse morphing solutions. This tool was built to be comprehensive and user friendly. It was also developed to be both modular and versatile, allowing the user to create custom plug-in like modules to tailor the software to each user's

needs. Some test cases were analysed: the reference aircraft with morphing wingtip and the Joined-Wing configuration with bending-twist morphing of the outboard part of the front wing.
Results for the reference aircraft show insignificant or no improvements for the morphing wingtip. These results are in-line with EMBRAER's results.
For the Joined-Wing configuration, analysis of the bending-twist concept show potential benefits on lateral stability and lateral control authority.
Further studies will include aero-structural optimization of the Joined-Wing configuration applied to a transport aircraft, performance and optimization calculations on the bending-twist concept applied to the Joined-Wing aircraft and the performance calculation of the LE-TE morphing applied to the reference aircraft.

- D3.4 Conceptual design framework for aeroelastic modelling and optimization of morphing aircraft.

POLIMI worked on the description of the wing with and without morphing devices. The 3D model of the wing is completely described by a limited number of geometrical parameters, namely the coefficients of Bernstein polynomials as well the LE and TE characteristics.

WP4 - System Analysis and Integration

- D4.1 Aero-Servo-Elastic performance quantification of the morphing concepts

At the moment the work on this deliverable is in stand-by, waiting for definition on the morphing mechanisms. This deliverable is delayed and expected to be uploaded in M30.

- D4.2 Weight and Energy Balance:

Based on the data from High Fidelity CFD calculations, IST will use the MDO framework to determine the best morphing strategy for the RA mission and assess the sensibility of the performance to weight increase and actuation energy estimates.
EMBRAER has been using their own tools for fuel savings calculations with morphing devices that will be complemented with a better assessment on the implications of the morphing devices in weight increase.
IST will use the MDO framework to determine the best morphing strategy within the adopted morphing concepts for the JW configuration and assess the sensibility of the performance to weight increase and actuation energy estimates.
This deliverable is delayed and expected to be uploaded in M30.

WP5 – Wind Tunnel and Flight Demonstrators for Validation of Morphing Concepts and Joined Wing Configuration:

- D5.1 Definition of subsonic and transonic Wind Tunnel tests for wings with morphing surfaces and flight test plans.

At this point work, the transonic WT test matrix is defined. There is still work to be done in the flight tests in coordination with IST and in the subsonic WT tests to be performed at UBRIS definition

- D5.2 Design, manufacturing and WT tests (transonic and subsonic) of wings with morphing concepts.

CSIR has been working on the transonic wind tunnel tests planning as well on the test model specifications. The wingbox structure, stand-off adapter, fuselage, lower fuselage and balance, conception is done. Manufacturing is progressing well and the reference aircraft model parts are already made. Testing is postponed to M30 to be coincident with the 30th month consortium meeting.

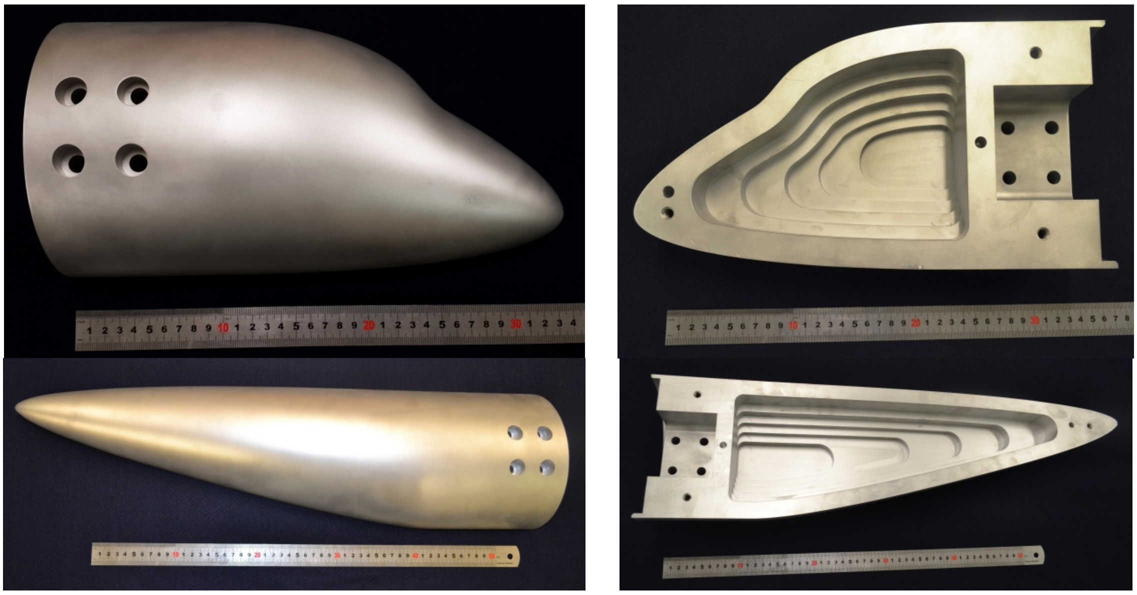

*Figure 1.4 EMB9Mor wind tunnel model, manufactured fuselage components.*

- D5.3 Design, manufacturing and low speed WT tests of wings with morphing concepts.

Waiting for some further info from EMBRAER that will influence the design, and hence testing of the active camber concept.

- D5.4 Design, manufacturing and flight tests results of the Joined-Wing configuration.

This deliverable still needs inputs on the morphing concepts to be applied to the JW prototype.

WP6 – Benefit Evaluation in Terms of Impact on Lift, Drag, Weight and Aeroelastic Response:

- D6.1 Drag, Weight, ASE, Noise and Performance benefits evaluation of adaptive/morphing concepts.

Enough technical material is available for the final report to evaluate drag and fuel consumption reductions over the entire flight envelope. Although in regard to weight savings, aeroelastic response and benefits exploitation for efficient short/mid-range transport aircraft design EMBRAER needs to receive more information from the partners.

## 1.4 Expected Final Results

Research topics and technologies to be developed during the NOVEMOR project will guarantee significant progress beyond the state-of-the-art in the following aspects:

- Modelling capabilities integrated into simulation and MDO numerical tools will allow the use of adaptive and morphing technologies from the beginning of the design process, rather than considering their possible use later in the design cycle. The approach will include optimization, robustness and reliability from the onset instead of the typical approach where these come at the end of the design cycle. Such an approach will enable the entire benefits of using an adaptive/morphing aeroelastic structural approach to be assessed.

- Novel configurations and morphing concepts to be developed in this project have the promise of delivering substantial capabilities in aircraft design.
- The number of unique and available wind tunnel models and facilities [IST, UBRIS, POLIMI] and the transonic wind–tunnel capability at CSIR will allow for the first time a small scale project to test different concepts in parallel and to substantiate the obtained measurements by means of cross testing of reference models.
- Develop a wind tunnel test to measure time-dependent pressure distributions typical of those associated with rapid wing geometry morphing. This effort would define the test article, instrumentation and data to provide a standard for future analytical unsteady aerodynamic predictions. Candidate models are variable camber and twist, variable planform and sweep, and morphing wingtips and winglets.
- Develop an aeroelastically scaled joined-wing remotely piloted vehicle to experimentally evaluate the lifting and aeroelastic response of the new proposed configuration.

In summary, NOVEMOR project contributes to the following objectives addressed by the call:

**Improving cost efficiency**: Advanced design tools for a cost efficient design process, contributing to reduce development costs, time to market ("right-first-time") and travel charges (due to weight and/or drag reduction).

**Enhanced lifting capabilities**: Advanced configurations, concepts and technologies for increased and optimized use of new lifting configurations and control surfaces.

In this view, NOVEMOR addresses the two top level objectives identified in the Strategic Research Agenda for European Aeronautics and in the Vision 2020 Report: to meet society's needs for more efficient and environmentally friendly air transport; and, to win global leadership for European Aeronautics.

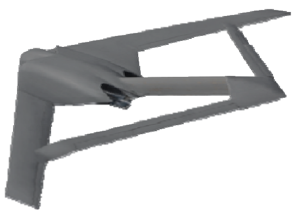

*Figure 1.3 The Boeing Sensorcraft (left) and the Box Wing Concept (right)*

**Website address: [http://www.novemor.eu](http://www.novemor.eu)**