NODESIM CFD

NON-DETERMINISTIC SIMULATION
FOR CFD-BASED DESIGN
METHODOLOGIES

D1.1-06
Publishable summary report

Partner: NUMECA
Author: Charles Hirsch
Date: 26th May 2010
Nature: Report
Dissemination level: PU

ABSTRACT: Deliverable D1.1-06 provides a summary description of the scientific and technological objectives in NODESIM-CFD project, the structure of consortium, the developed methodologies and the outcomes of the exploitation and dissemination activities.

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)
PROJECT N°: AST5-CT-2006-030959

CONTENTS

1 SCIENTIFIC AND TECHNOLOGICAL OBJECTIVES 3
2 NODESIM CONSORTIUM 3
3 DEVELOPMENTS AND ACHIEVEMENTS 5
4 EXPLOITATION AND DISSEMINATION 10

1 Scientific and technological objectives

The NODESIM-CFD project addresses the EU objectives of reduction of aircraft development costs and increase of safety, through the introduction of a new paradigm for CFD based virtual prototyping, aimed at the incorporation of operational and other uncertainties in the simulation process.

New methodologies are therefore required to incorporate the presence of uncertainties at the level of the simulation tools in order to improve the predictive reliability of the simulation process by introducing the existence of these "uncertain" simulation results in the decision process related to industrial design.

This is translated into the following measurable scientific and technological objectives:

- Identification and quantification of the uncertainty parameters associated to a wide variety of aeronautical applications; the domains of application cover: engine aerodynamics, wing aerodynamics, conjugate heat transfer and fluid-structure interactions.
- Development of several non-deterministic methodologies focusing on the most promising methods, such as Perturbation techniques and adjoint based methods, efficient Monte Carlo methods and Polynomial Chaos methods.
- Applications to subsystems and systems: the general methodologies and software tools developed under the previous actions will be applied, tested and validated for the various applications for which the uncertainty variables have been identified and analyzed.
- Introduction of non-deterministic simulations into the design and decision process, focusing on the development of aerodynamic optimization algorithms that provide designs, which are robust with respect to uncertainties in geometry, operating conditions, and code simulation uncertainties and to control and reduce risks by providing designs with aerodynamic performances insensitive to intrinsically uncertain quantities
- Stimulate the scientific co-operation and transfer of knowledge within the NODESIM-CFD consortium, through a specific task of support from the developers to the implementation of the developed new methodologies in the in-house codes of the industrial partners.

2 NODESIM Consortium

The NODESIM consortium comprises 17 teams from 8 European countries:

- 3 aircraft manufacturers
- 2 engine manufacturers
- 4 research establishments
- 4 SMEs active in CFD and design software
- 4 academic institutions

The actual structure is given in the table "Consortium overview". The coordinator of the project is Numerical Mechanics Applications International (NUMECA), an SME established in Brussels-Belgium represented by Professor Charles Hirsch.

A detailed presentation of the NODESIM-CFD project and of the members of the consortium can be found on the public part of its website located at www.nodesim.eu.

Consortium's structure

CONSORTIUM OVERVIEW					
No.	**Participant**	**Participant short name**	**Country**	**Business Activity**	**Role in project**
1	NUMECA Int.	NUMECA	BE	Software developer	Co-ordinator of project, developer and end-user
2	AIRBUS-UK	AUK	UK	Aircraft manufacturer	End-user
3	ALENIA	ALENIA	IT	Aircraft manufacturer	End user
4	QinetiQ	QQ	UK	R&T organization	Developer and End user
5	CIMNE	CIMNE	S	Academic institution	Developer
6	Dassault Aviation	DASSAV	FR	Aircraft manufacturer	End-user
7	DLR	DLR	GE	Research organization	Developer and End-user
8	ESTECO	ESTECO	IT	Software developer	Developer and End-user
9	INRIA-Sophia	INRIA	FR	Research organization	Developer
10	MAN TURBO	MAN	GE	Gas turbine Manufacturer	End-user
11	ONERA	ONERA	FR	Research organization	Developer and End-user
12	NPO-SATURN	SATURN	RU	Engine manufacturer	End-user
13	SIGMA	SIGMA	RU	Software developer	Developer and End-user
14	Univ. TRIESTE	UNITS	IT	Academic institution	Developer
15	TU DELFT	TUD	NL	Academic institution	Developer
16	VU Brussel	VUB	BE	Academic institution	Developer
17	WS Atkins	WSA	UK	Engineering company	End-user

3 Developments and achievements

The first objective listed in section 1 has been accomplished by an intensive and thorough analysis of the potential uncertainties to be accounted for. Three classes of uncertainties were identified: operational, geometrical and numerical uncertainties. The identified uncertainties are statistically described through a probability distribution functions (pdf). In order to prescribe the input parameters of a selected pdf based on expert opinion or to identify the type of pdf from experimental data two software tools have been developed: a beta pdf defining tool and a distribution fitting tool. Snapshots of the outputs of these software tools are shown in figure 1.

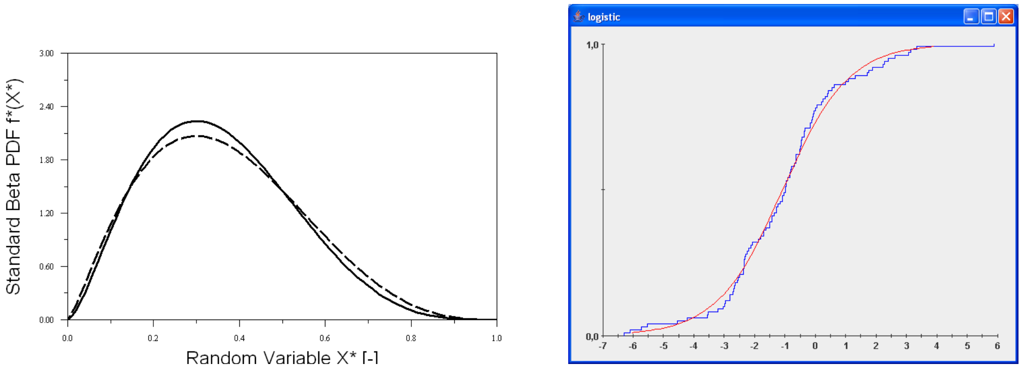


Figure 1 Software tools: left – output of the beta pdf defining tool (courtesy NUMECA), right – output of the distribution fitting tool (courtesy ESTECO)

The second objective, namely the development of the non-deterministic methodologies for uncertainty propagation represented the core of the NODESIM-CFD project. Three categories of non-deterministic methodologies were developed and applied:

- Perturbation techniques with adjoint methods
- Monte Carlo (MC) methods with surrogate methods
- Polynomial Chaos methods (PCMs)

For the first category of techniques, actions were directed towards the automatic differentiation for the management of uncertainties, studies on the influence of the computational mesh on the drag and lift output functionals and an adjoint-based error estimator have been developed. INRIA succeeded in identifying and implementing strategies for computing second derivatives of CFD codes, while DLR developed an error based adaptation technique.

Figure 2 gives an example of usage of the automatic differentiation engine TAPENADE of INRIA for the propagation of uncertainties in a transonic flow around a wing. In figure 3, the results obtained by DLR with its adjoint-based adaptation are shown.

The second category of developed non-deterministic methodologies aimed at circumventing the high computational cost and consequently the MC analysis systems were combined with surrogate models based on various response surface methods or design of experiments. CIMNE has achieved the adaptation and integration in its Monte-Carlo analysis system STAC of new capabilities related to the needs of multidisciplinary codes. Among these capabilities we underline the generation of random variables from given marginal distribution as well as a joint distribution of all the variables and STAC's usage for robust design. ONERA focused on the following surrogate models in combination with their developed MC method: eight order polynomial approximation, radial basis function neuronal network and simple Kriging. SIGMA focused in turn to surrogate model construction tools based on polynomial regression, simplified “weighted” approximation and radial basis function neuronal networks. UNITS developed DACE technologies with the classical and adaptive versions particularly.

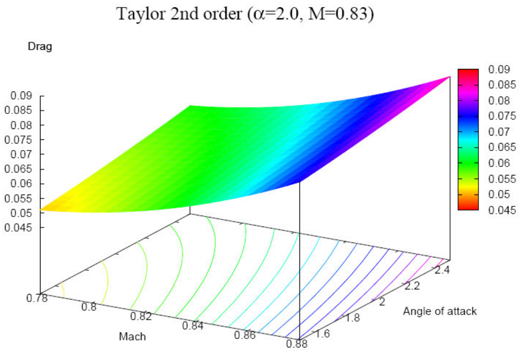


Figure 2 Output of the automatic differentiation tool TAPENADE with the drag sensitivity for a transonic flow around a wing (courtesy INRIA)

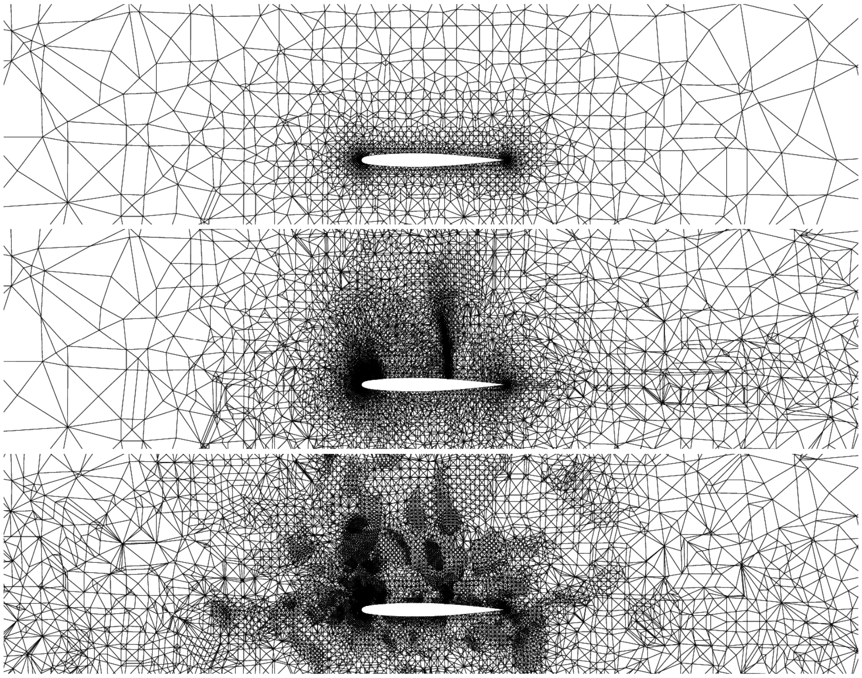
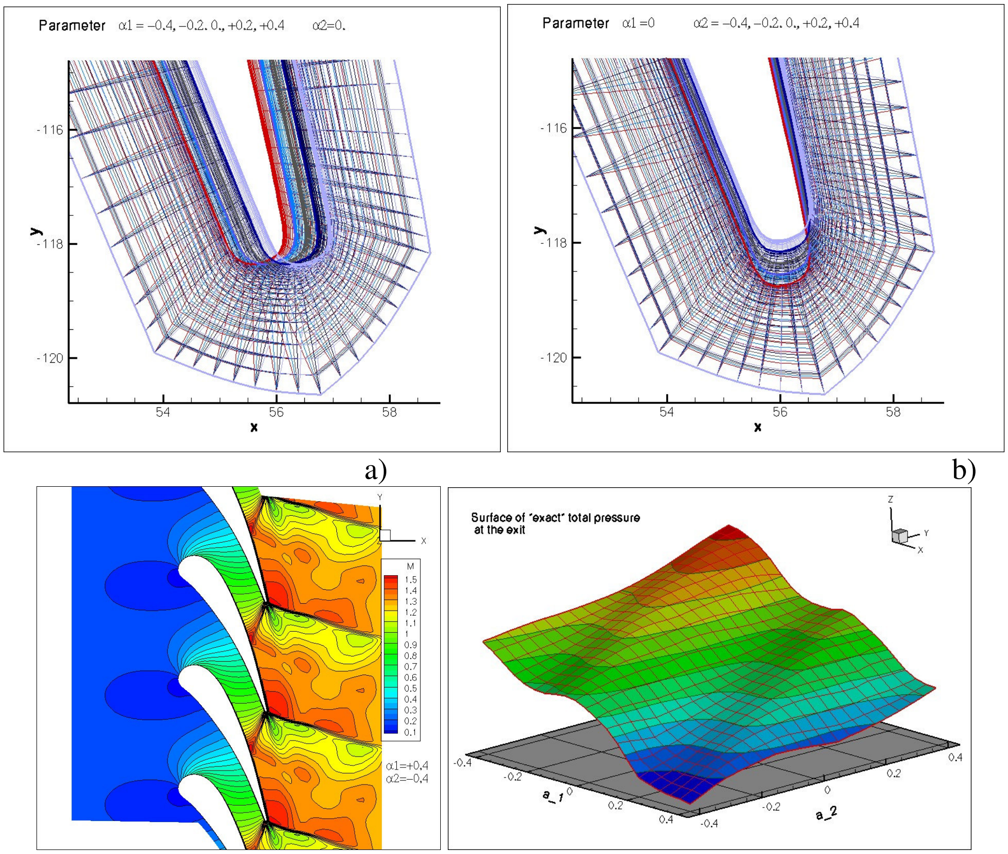


Figure 3 Meshes around the wing section of ONERA M6. Upper figure shows the initial mesh, middle figure the mesh adapted gradient-based and the lower figure the mesh adapted adjoint-based (courtesy of DLR)

Figure 4 shows the results obtained by ONERA using their MC method for the case of the flow in VEGA2 transonic turbine rotor. A geometrical uncertainty has been chosen, x and y deformation of the trailing edge particularly. The outcome of the simulation is the surface of total pressure in the design space.



a) b)

c) d)

Figure 4 Uncertainty estimation using Monte Carlo method in VEGA2 transonic turbine rotor: a) – trailing edge deformation due to x-displacement (α1=a1); b) trailing edge deformation due to y-displacement (α2=a2); c) solution α1=0.4 and α2=-0.4; d) design space – total pressure function of a1 and a2 (courtesy ONERA)

The third category of non-deterministic methodologies accounts for two main types of PCMs: intrusive and non-intrusive. For both types of PCM, the principal interest was concentrated on the assessment of the effects due to the nonlinear character of the flow governing system and to improve the computational efficiency. VUB developed an intrusive PCM, tested by NUMECA, and non-intrusive Probabilistic Collocation Methods were developed by , QQ and WSA. In addition TUD developed also the Probabilistic Radial Basis Function approach.

Figure 5 emphasizes the results obtained with non-intrusive PCM's for flow around NACA0012 airfoil by TUD (left) and the non-deterministic analysis of the flow and thermal phenomena in a large turbofan IPC front bearing housing cavity system performed by WSA (right).

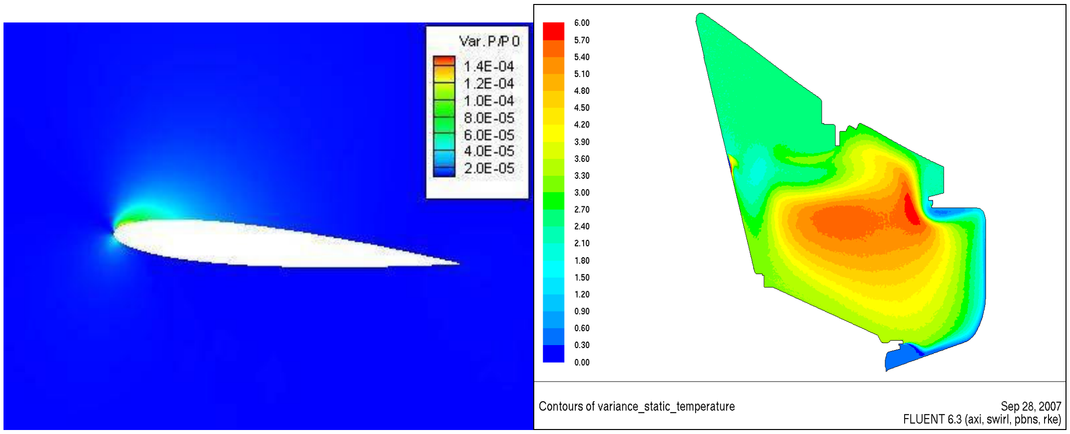


Figure 5 Methods for propagating uncertainties: left – pressure variance for the flow around a NACA0012 airfoil obtained with a non-intrusive Polynomial Chaos Method (courtesy TU Delft), right – temperature variance in the front bearing housing cavity system of a turbofan obtained with a non-intrusive Polynomial Chaos Method (courtesy WS Atkins)

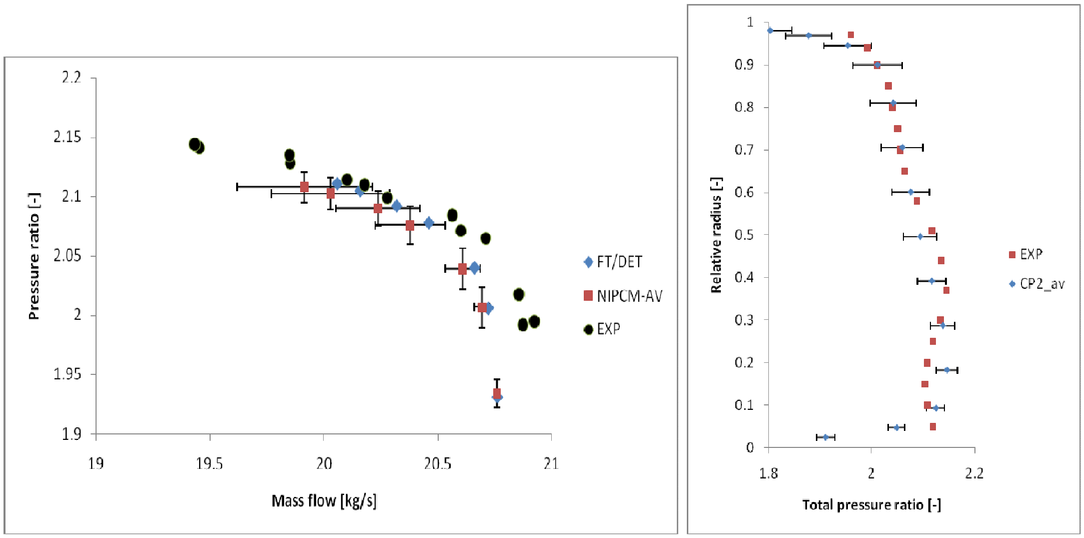


Figure 6 Evaluation of non-intrusive Probabilistic Collocation Method of TU Delft: left – non-deterministic compressor map for the transonic NASA Rotor 37 due to imposed operational uncertainty, right – error bar plot of the radial pitch-wise averaged distribution of the total pressure ratio (courtesy NUMECA)

Figure 6 (left) emphasizes the non-deterministic computational results for an operational uncertainty imposed on the outlet static pressure in the NASA Rotor 37 test case. One can see the computed error bars quantifying the effect of the imposed operational uncertainty on the mass flow rate and pressure ratio.

The third listed objective in section 1 aimed at validating the non-deterministic methodologies on representative test cases and for various uncertainties sources. Therefore, a data base of test cases has been built up with different levels of complexity. Academic test cases and industrial ones coexisted and have been classified following the range of applications: external flows around wings, propulsion flows and multi-physics. As applications to external flows around the wings, the transonic flows around the RAE 2822 airfoil and ONERA M6 wing have been selected as compulsory tests. With respect to applications to propulsion flows the transonic flow in NASA Rotor 37 configuration has been selected as compulsory test case. As applications to multi-physics the flutter of AGARD 445.6 wing, an aero-elastic of wing model and a planar combustor test rig (see figure 7) have been considered.

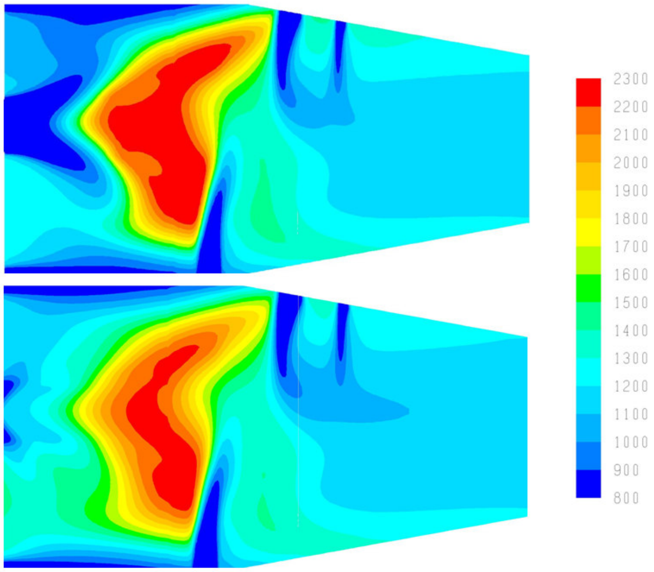


Figure 7 Comparison of probabilistic reacting temperatures calculations (bottom) against deterministic (top)

The last two objectives have foreseen actions for the transfer of knowledge among the developers' teams and the end-user partners. This was a two way process: a direct action was dedicated to the actual transfer of the non-deterministic software modules, coupling with end-users' in-house codes and training. An important feed-back arrived from the end-users towards the developers on the appropriateness of a specific uncertainty propagation method with respect with a range of applications and suggestions of improvement.

Figure 8 provides a collaboration chart where each slice represents the monitored number of reported interactions of each partner necessary to achieve the objectives.

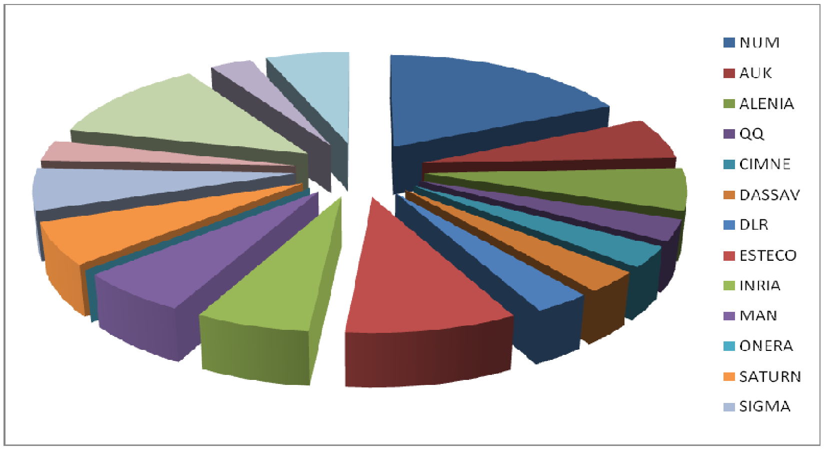


Figure 8 Collaboration chart: interactions in NODESIM-CFD project

It can be seen that the collaboration has been relatively balanced, the higher numbers of interactions being usually focused on the developer's teams and coordinator. As a result of such transfer of knowledge the end-user partners have integrated non-deterministic methodologies in their optimisation technologies for robust design. We are mentioning end-user partners as ALENIA, CIMNE, ESTECO, MAN, NUMECA, QQ, SIGMA, while AUK and SATURN tested non-deterministic methodologies.

4 Exploitation and dissemination

During the NODESIM-CFD project, 9 types of exploitable knowledge have been materialized or are in progress to become exploitable products.

There are already agreements between academia and software developers for industrialization of the developed non-deterministic methodologies, while other industrial partners, who gained awareness on this subject, are developing themselves uncertainty quantification modules tailored for their intended applications.

These products are or will be stand alone software or additional uncertainty quantification features at already existent ones. Moreover, these exploitable products cover applications from the domains as aeronautical and compressor design, propulsion, power and energy production or motorsport.

The most important dissemination action was represented by the *NODESIM-CFD Workshop on Quantification of CFD Uncertainties* organized in Brussels-Belgium at Vrije Universiteit Brussel on 29-30 October 2009 (http://www.nodesim.eu/workshop.html). To our knowledge, this was the first ever organized workshop dedicated exclusively to the management of uncertainties in Computational Fluid Dynamics. Two separate sessions dedicated to external and internal aerodynamics representative test cases, the turbulent flows around the RAE 2822 airfoil and inside NASA Rotor 37 particularly, have been scheduled. Each session has been preceded by lectures delivered by renowned practitioners in this novel domain. The audience was formed by representatives from aerospace industry, academic and research organizations.

Among other collective efforts of the NODESIM consortium we are emphasizing:

- NATO RTO-AVT-147 Symposium on "Computational Uncertainty in Military Vehicle Design"
- two special sessions in Non Deterministic Simulations in Computational Fluid Dynamics as part of the 10th AIAA Non-Deterministic Approaches Conference
- A mini-symposium entitled "Uncertainty Quantification Methods for CFD and FSI" in ECCOMAS CFD 2008 .

During the first 40-months period the consortium has been involved in activities for disseminating knowledge measured by the following items:

- 27 articles in journals
- 28 papers in conferences
- 6 papers in congresses
- 15 contributions in workshops
- 17 contributions in symposiums
- 4 contributions in seminars
- 7 contributions in colloquia

- 2 contributions in user meetings
- 1 contribution in a forum
- 3 invited lectures
- 2 PhD theses and 1 master thesis completed

The NODESIM consortium has been active in events with wide audience as ECCOMAS congresses, AIAA and SAE conferences. Also, parts of the aforementioned results have been published in renowned journals as Journal of Computational Physics, Journal of Fluid and Structures, Computers and Fluids, International Journal for Numerical methods and Fluids or SIAM Journal of Scientific Computation.

Also, few partners have been sustained their dissemination through a website, dedicated mailing list or 3-month presentation sessions for aerospace industry.