

Feasibility study on Multi Disciplinary Optimization for aerospace application

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ThalesAlenia
A Thales / Finmeccanica Company *Space*



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Outline

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- ☐ Company Profile
- ☐ Objectives
- ☐ Test Case Implementation
 - Test case definition
 - Identification of the discipline codes and Interfaces
 - Process integration
 - Design Optimization
- ☐ Conclusions

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☐ Introduction



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- CAE (Computer Aided Engineering) and CAO (Computer Aided Optimization) have been widely used in development and design process of products in aerospace and automotive industry.
An Integrated and Optimized Process is proposed applied to a hypersonic space vehicle.
- Fiper software has been selected for a first demonstration of integration into a unified process of multi-disciplinary design analyses and of its subsequent optimization.
- This is the preliminary output of a feasibility study on MDO (Multi Disciplinary Optimization) process evaluation in the frame of CAST program financed by **ASI (Italian Space Agency)**, and conducted by **CIRA (Italian Aerospace Research Centre)**, aiming at the study and development of innovative methodologies and processes for aerospace vehicle design and analysis.
- Special tanks to **Exemplar Solution** for the support provided during the whole study.

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- ☐
- ☐ **Company Profile**
- ☐
- ☐



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Thales Alenia Space

- European leader for satellite systems and at the forefront of orbital infrastructures, TAS is owned by Thales (67%) and Finmeccanica (33%) and forms with Telespazio the “Space Alliance”.
- TAS represents a worldwide standard for space development: from navigation to telecommunications, from meteorology to environmental monitoring, from defense to science and observation.
- TAS has 11 industrial sites in 4 European countries (France, Italy, Spain and Belgium) with over 7,200 employees worldwide.
- #1 worldwide in terms of satellites ordered in 2006, TAS is at the heart of the most high-performance satellite technologies in both civil and defense sectors.
- The company is deeply involved in:
 - ❑ Environmental projects based on Earth observation such as the Global Monitoring for Environment and Safety (GMES) program; and Meteorology such as MSG (Thales Alenia Space provided all the Meteosat satellites for Eumetsat);
 - ❑ Navigation with Galileo (as prime contractor of EGNOS - the precursor of Galileo, and founding member and shareholder of Galileo Industries and Galileo Concession);
 - ❑ Defense with major programs such as the French Syracuse (I, II and III) and the Italian (Sicral) telecommunication satellites ; and in dual civil-military observation programs such as Helios (France), COSMO-SkyMed (Italy) and SAR-Lupe (Germany).
 - ❑ Space infrastructures: The International Space Station is one of the most advanced technology projects in the world and Thales Alenia Space has designed and built 50% of the Station’s pressurized volume, that is the living space. The company also contributed to the related launch, transportation and re-entry systems.

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- ☐ Italian Reseller of  **Engineous**
software
- ☐ Company in the Aerospace Network of Piedmont (North-ITALY)
- ☐ Projects and collaborations with the most important Aerospace and Automotive Italian Companies
- ☐ Special Knowledge/Development of Stochastic Design Improvement (SDI)

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- ☐
- ☐
- ☐ **Objectives**
- ☐



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- **Demonstrate the feasibility of:**

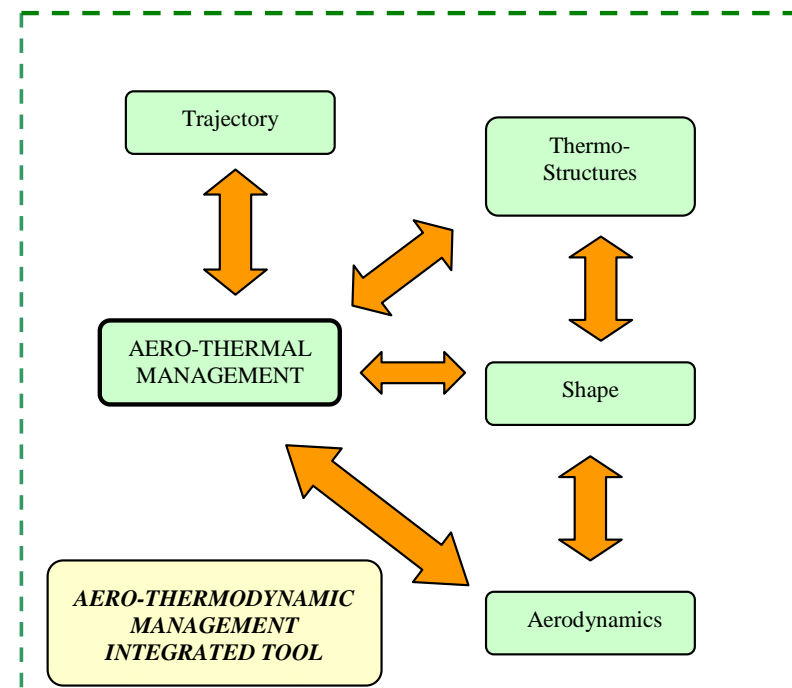
- ❑ A complete integration into an unified process of the disciplines:

- Aero-thermodynamics
 - Structure
 - Thermal Control
 - Trajectory computation
 - Configuration

- ❑ MDO applied to the hypersonic vehicle design

Avionics

Propulsion



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- ☐
- ☐
- ☐
- ☐ **Test Case Implementation**



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In order to validate the proposed MDO approach and to test the Fiper software, a demonstration based on a design problem solving has been organised.

The activity has been split into the following main phases:

- ☐ Test case definition
- ☐ Identification of the discipline codes and Interfaces
- ☐ Process integration
- ☐ Design Optimisation

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■ Test case definition



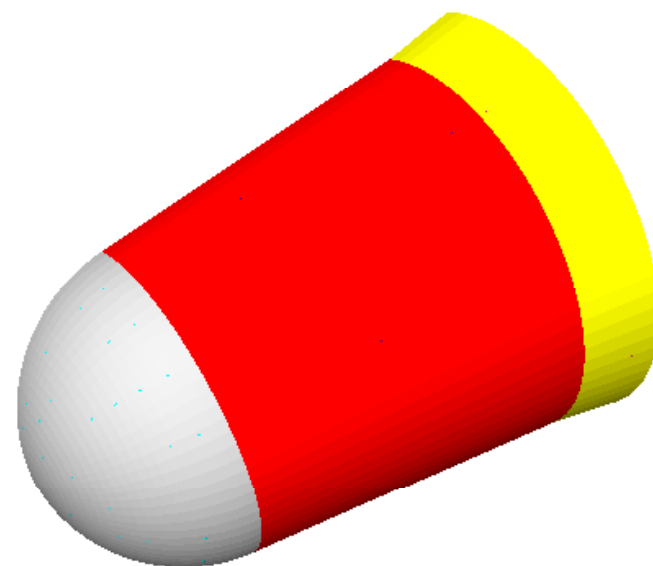
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This first test case is characterised by:

- ☐ Fast, limited-fidelity discipline codes and models, in order to reduce the complexity of the system and the CPU time necessary for each simulation.
- ☐ Small number of variables
- ☐ Simple objective functions

For these reasons, the proposed feasibility test case has the objective to optimise a hypersonic vehicle characterized by:

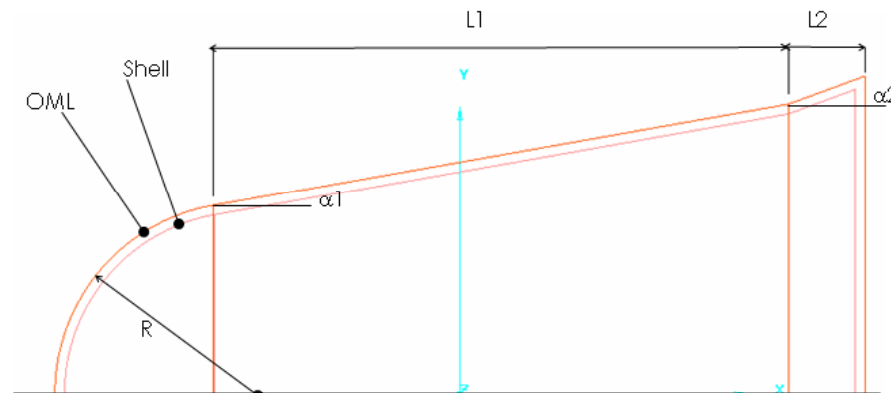
- ☐ Hypothesis of project in phase A/Study
- ☐ Fully ballistic re-entry
- ☐ Bi-conic geometry
- ☐ An internal Al2219 shell characterized by:
 - Constant thickness (to be optimized)
 - No ribs or local reinforcements
- ☐ An external Thermal Protection System (TPS) characterised by:
 - An external layer of CSiC (3 mm over all the vehicle)
 - An internal layer of HTI (thickness to be optimized)
- ☐ An additional constant mass of 300 Kg (payload + hardness)



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Aim of the study is the optimization of the vehicle in terms of:

- ☐ Geometry
 - Vehicle lengths L_1 and L_2
 - Vehicle angle α_1 and α_2
 - Nose radius R
- ☐ Structure dimensions:
 - TPS thickness
 - Shell thickness



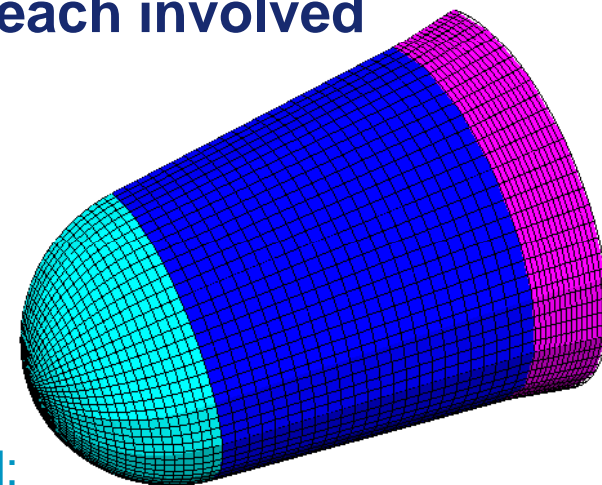
The optimised vehicle has to satisfy the following requirements and constraints:

- ☐ Maximum shell temperature: 150°C
- ☐ Maximum shell displacement: 18 mm
- ☐ Maximum shell Von Mises stress: 324 MPa
- ☐ Maximum external volume: 3 m³
- ☐ Minimise the total vehicle mass
- ☐ Maximise the internal available volume

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Dedicated simplified models have been developed for each involved discipline:

- ❑ Configuration and Grid generation
 - GRIDGEN (Pointwise) software has been used
 - The reference geometry and the meshes have been parametrized and automatized by GLYPH file.
 - 3 different surface mesh in CGNS format are generated:
 - 40x85 for SHABP inviscid computation (pressure distribution and C_D coefficient)
 - 10x25 for SHABP viscous computation (pressure distribution and C_D coefficient)
 - 18x10 for NASA 71-CR111921 (Aerothermal fluxes computation)
 - The reference geometry is saved in IGES format (for structural analysis)
 - The computations of total vehicle mass and volumes is performed by EXCEL worksheet.

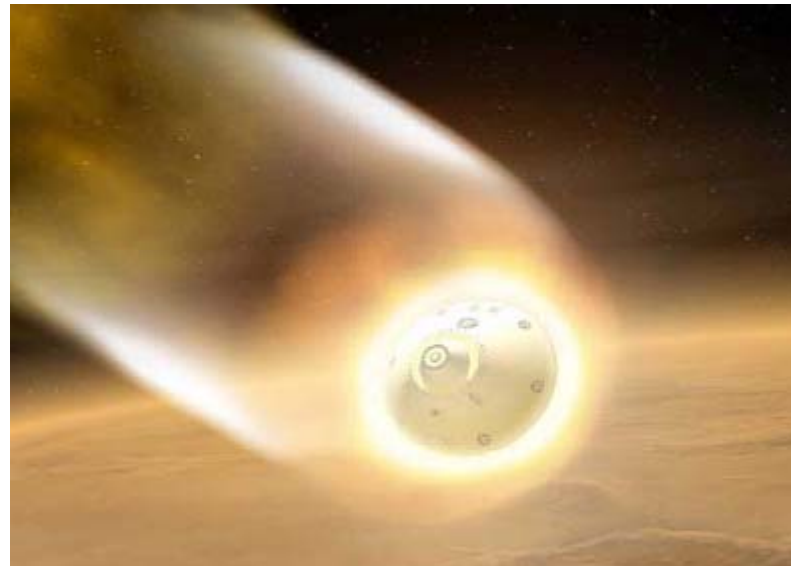


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□ Aerothermodynamics

■ Two different tasks are performed:

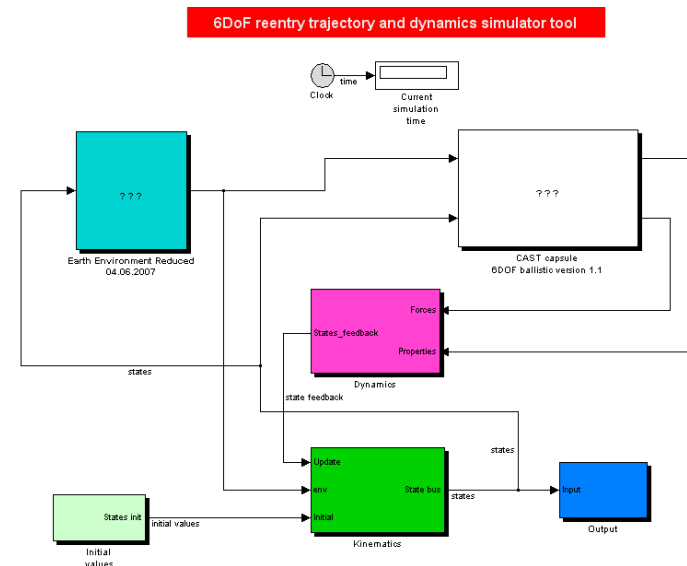
- Generation of a database containing C_D behavior vs. Altitude (10 values: 15÷120 Km) and Mach number (7 values 2 ÷ 20) using SHABP code.
- Computation of pressure distributions (by SHABP) and aerothermal fluxes (by NASA 71-CR111921) for each time-step of the reentry phase (10 values).



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□ Trajectory

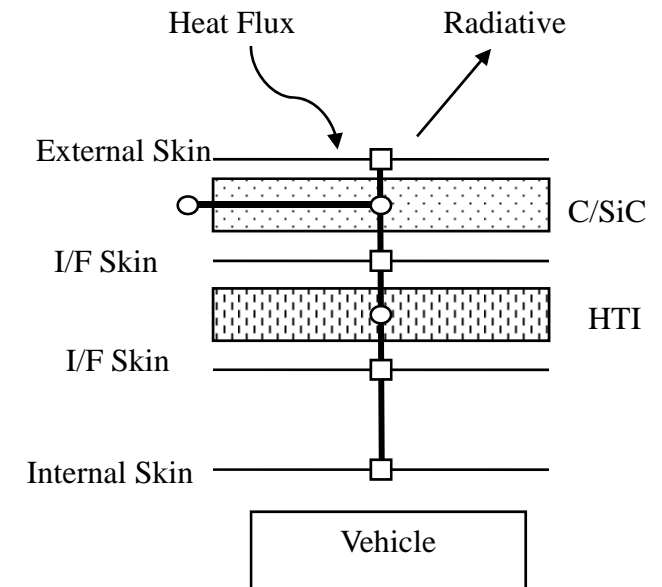
- The trajectory computation is performed by TAS in-house code developed in MATLAB-SIMULINK environment.
- 'Only' 10 significant time-step points are extracted from the global timeline, in order to capture the minimum/maximum values of heat flux and G-loads (by EXCEL worksheet).
- The analysis computes the G-load, Altitude and Mach number vs. time.



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□ Thermal Control

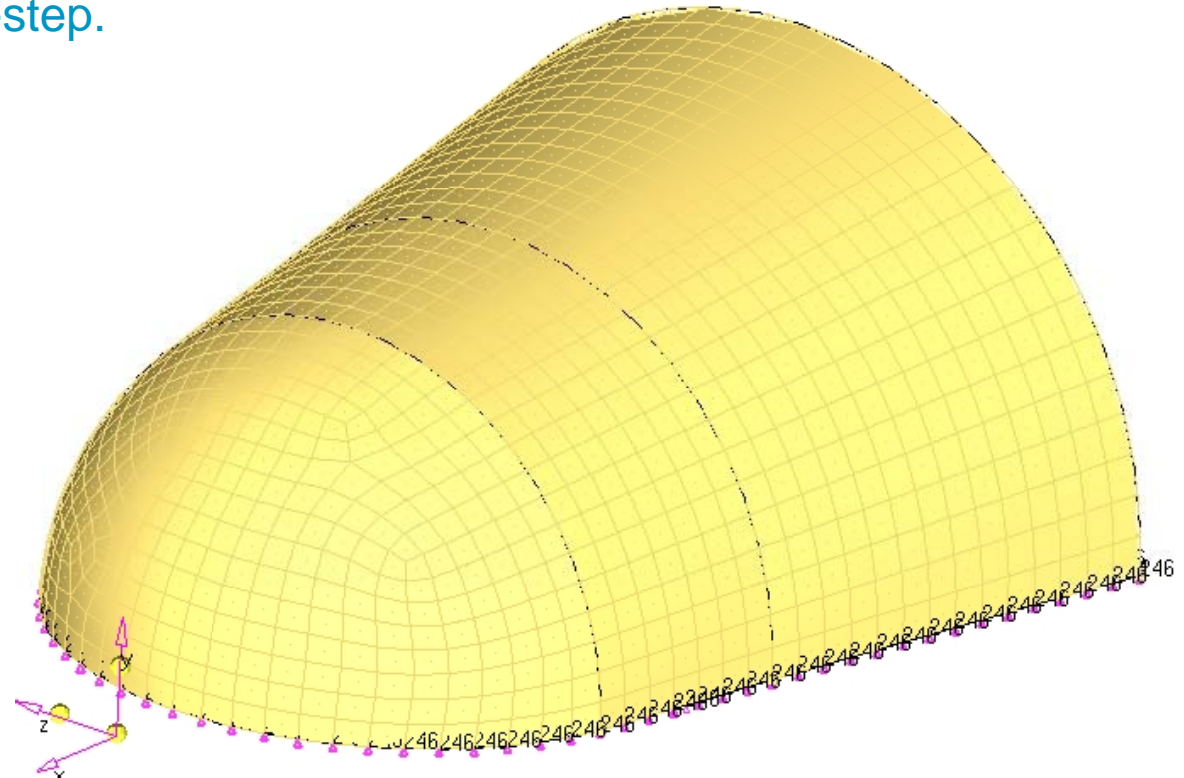
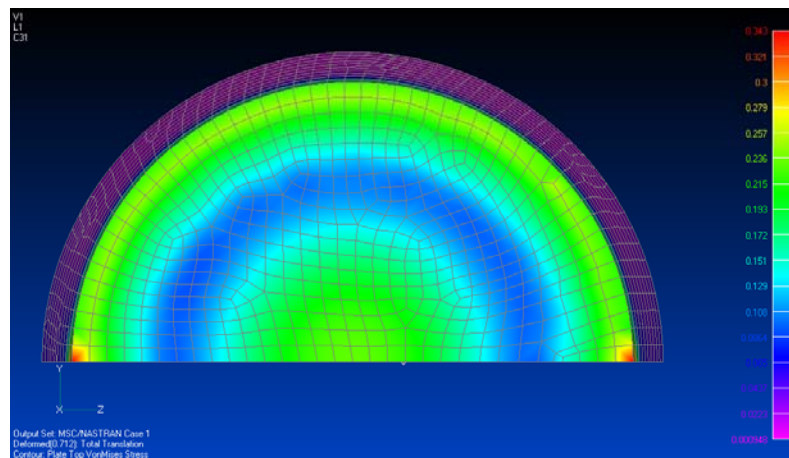
- Simplified local thermal models have been developed for each zone of the vehicle in order to compute TPS and shell temperature distributions during the whole re-entry and post-landing phases (by SINDA/FLUINT software)



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□ Structure

- The generation of the structural mesh and the mapping of temperatures and pressures on it is performed by HYPERMESH software.
- The structure displacements and Von Mises stresses are computed by MSC NASTRAN for each time-step.



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- **Identification of the discipline
codes and Interfaces**



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DISCIPLINE		Vehicle Shape & Configuration	Aerodynamics	Flight mechanics & Trajectory	Aerothermal Management /TPS	Structure
TOOL		Gridgen Mesh Generator	VECC/SHABP Supersonic/Hypersonic Arbitrary Body Program	AAS Reentry Flight Simulator in SIMULINK Environment	SINDA	MSC Nastran Hypermesh
INPUT	Data	Shape parameters	Mesh	vehicle properties vehicle aerodynamic coefficient DB	Heat Flux External Temperature TPS Thickness	Mesh Pressures Temperatures
	Format	ASCII	Type3 card	ASCII	ASCII	ASCII / Iges
	I/F FROM		Gridgen	Gridgen Aerodynamics	Aerodynamics	Gridgen Aerodynamics Thermal
OUTPUT	Data	Mesh Volume/Mass	Flowfield variables	Vehicle states vs time	Max Temperatures	Strains Deformations
	Format	Tecplot Iges	ASCII	ASCII	ASCII	ASCII
	I/F TO	Aerodynamics Structure Optimizer	Structure (pressures) TPS (Heat flux)	Optimizer	Structure Optimizer	Optimizer

I/F to be developed
Design Variable
Objective Variables

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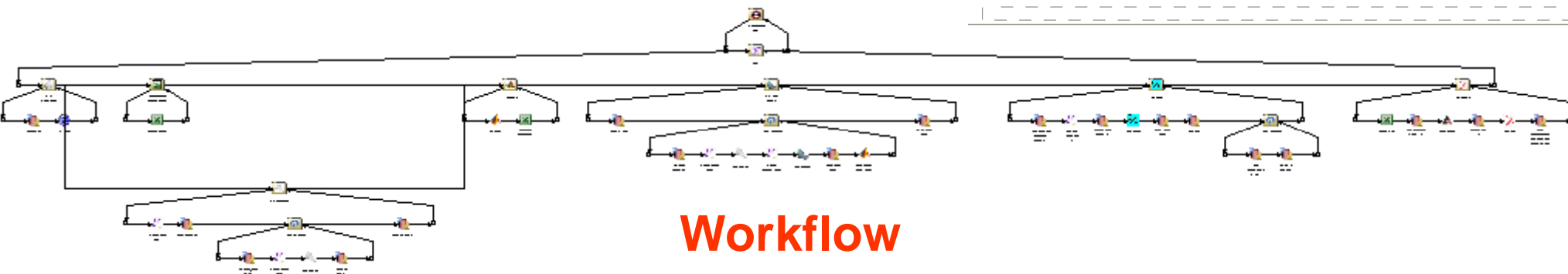
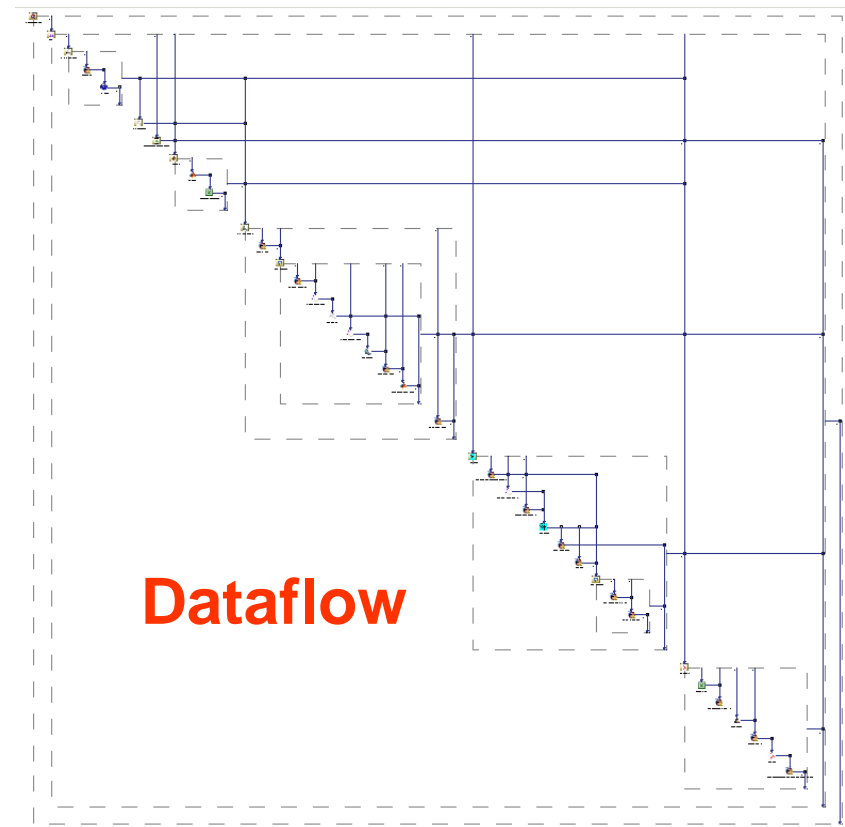
■ Process integration



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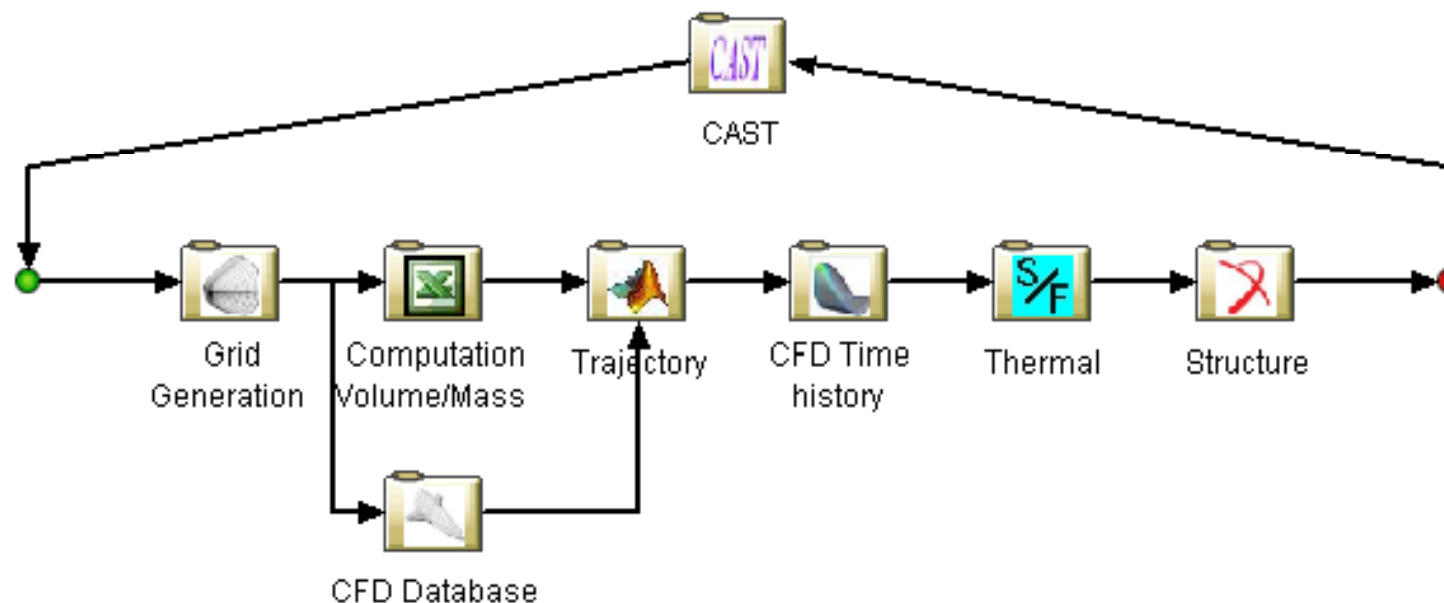
■ Quite complex process:

- 5 disciplines involved
- 7 Tasks
- ~ 40 sub-tasks
- 6 Commercial software
- 5 developed Fortran codes
- 2 free Aerodynamic codes



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Workflow



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Grid Generation

☐ Input files:

- None

☐ Input variables:

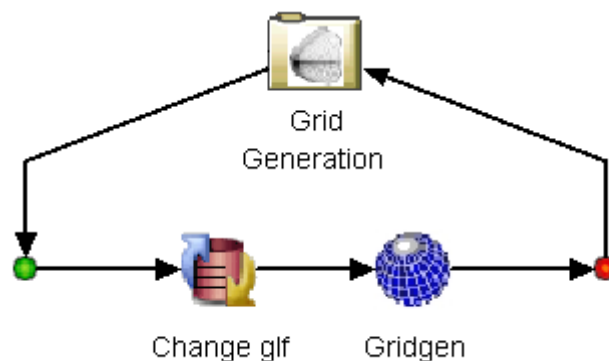
- Geometry variables (L_1 , L_2 , α_1 , α_2 , R)
- TPS and Shell thicknesses

☐ Output files:

- Mesh file for Shabp in CGNS format
- Mesh file for NASA-71 in CGNS format
- Reference geometry in IGES format

☐ Output variables:

- None



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Computation Volume/Mass

☐ **Input files:**

- None

☐ **Input variables:**

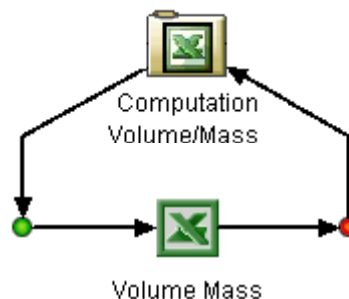
- Geometry variables (L_1 , L_2 , α_1 , α_2 , R)
- TPS and Shell thicknesses

☐ **Output files:**

- None

☐ **Output variables:**

- TPS mass
- Shell mass
- Total vehicle mass
- Internal/External volumes



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CFD Database

Input files:

- Mesh File in CGNS format

Input variables:

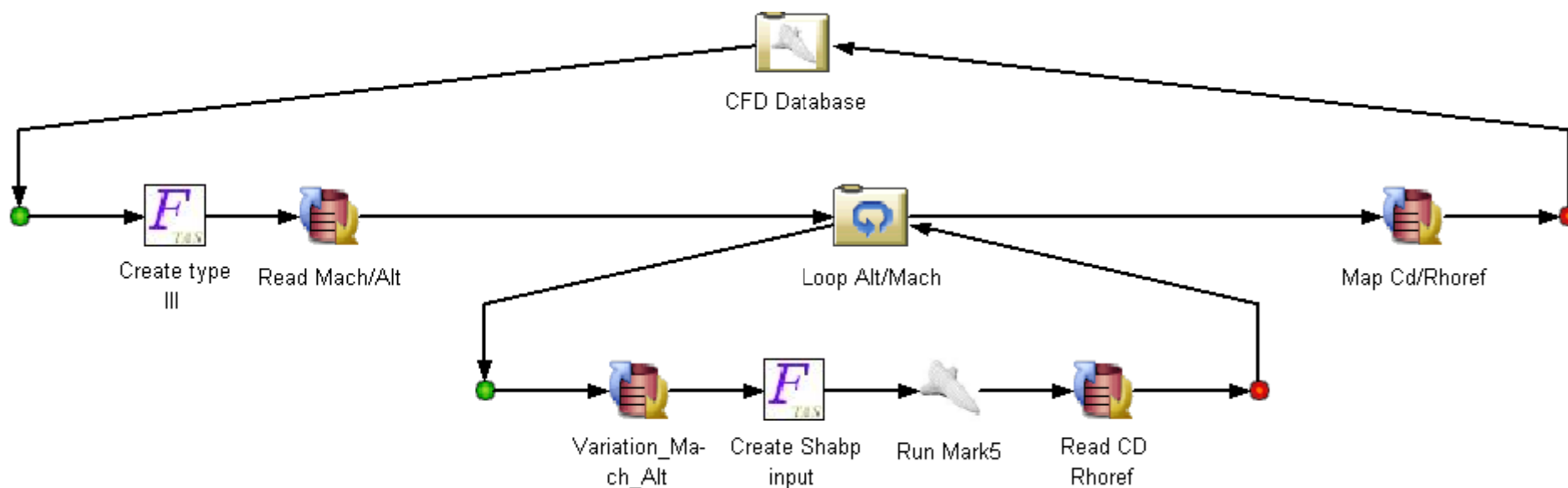
- None

Output files:

- Mesh file for Shabp in type III format

Output variables:

- CD coefficients vs. Altitude/Mach



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Trajectory

☐ **Input files:**

- None

☐ **Input variables:**

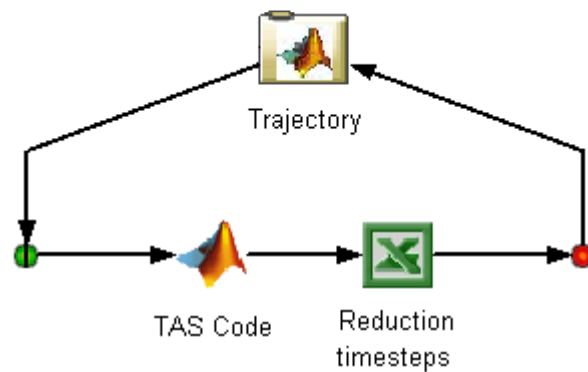
- CD vs. Altitude/Mach
- Total vehicle mass

☐ **Output files:**

- None

☐ **Output variables:**

- Trajectory timeline
- G-loads vs. time
- Mach vs. time
- Altitude vs. time



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CFD Time History

Input files:

- Mesh file for Shabp in type III format
- Mesh file for NASA-71-CR111921 in CGNS format

Input variables:

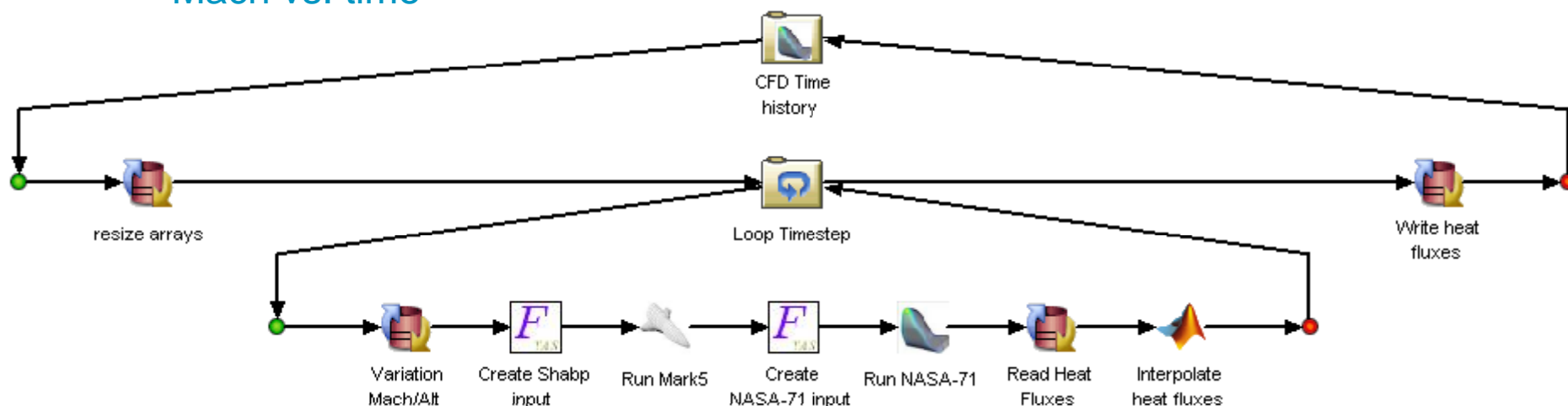
- Altitude vs. time
- Mach vs. time

Output files:

- Pressure distribution
(one file for each time step)
- Aerothermal fluxes

Output variables:

- None



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Thermal

Input files:

- Aerothermal fluxes

Input variables:

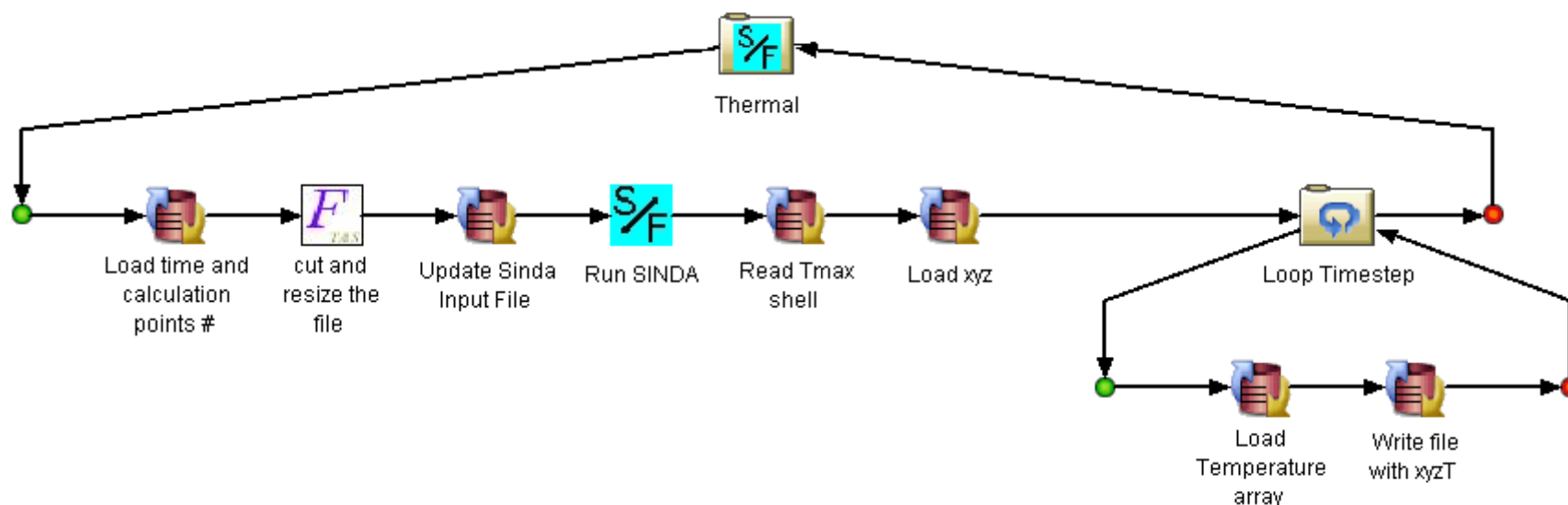
- Geometry

Output files:

- Shell Temperature distribution
(one file for each time step)

Output variables:

- Maximum Shell temperature



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Structure

□ Input files:

- Temperature distribution (one file per each time step)
- Pressure distribution (one file per each time step)
- Reference geometry in IGES format

□ Input variables:

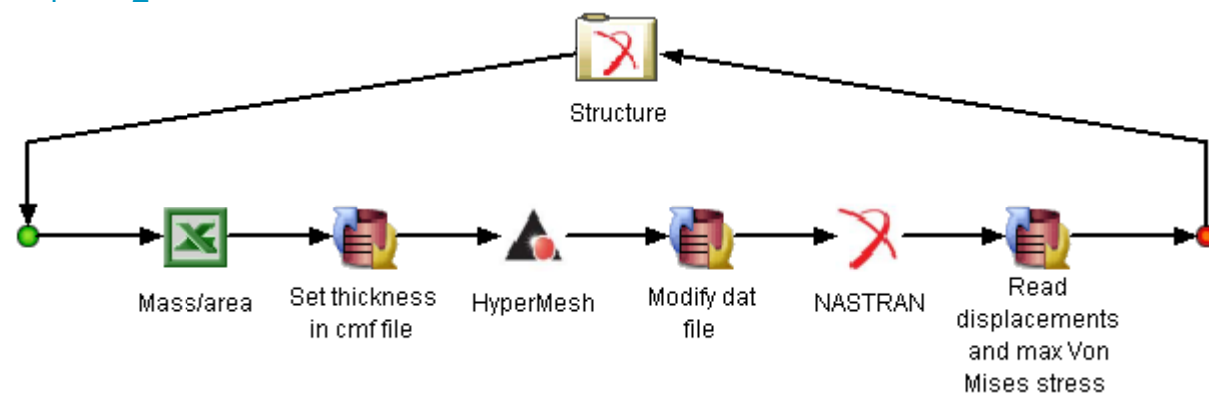
- Geometry variables (L_1 , L_2 , α_1 , α_2 , R)
- TPS and Shell thicknesses
- G-loads vs. time

□ Output files:

- None

□ Output variables:

- Maximum Shell displacement
- Maximum Von Mises stress



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■ Design Optimization



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Design Variables:

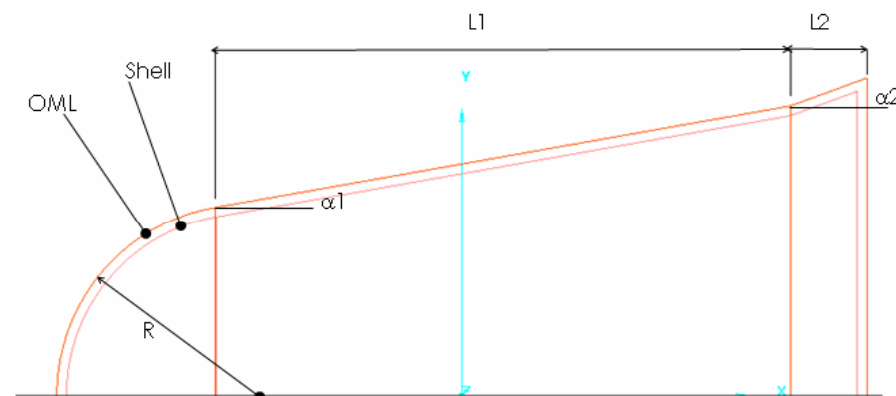
- ☐ Vehicle length L_1 [500÷1500 mm]
- ☐ Vehicle length L_2 [100÷500 mm]
- ☐ Vehicle angle α_1 and α_2 [0÷30°]
- ☐ Nose radius R [300÷1000 mm]
- ☐ TPS thickness [2÷100 mm]
- ☐ Shell thickness [2÷8 mm]

Constraints Variables:

- ☐ Maximum shell temperature: 10°C
- ☐ Maximum shell displacement: 18 mm
- ☐ Maximum shell Von Mises stress: 324 MPa
- ☐ Maximum external volume: 3 m³

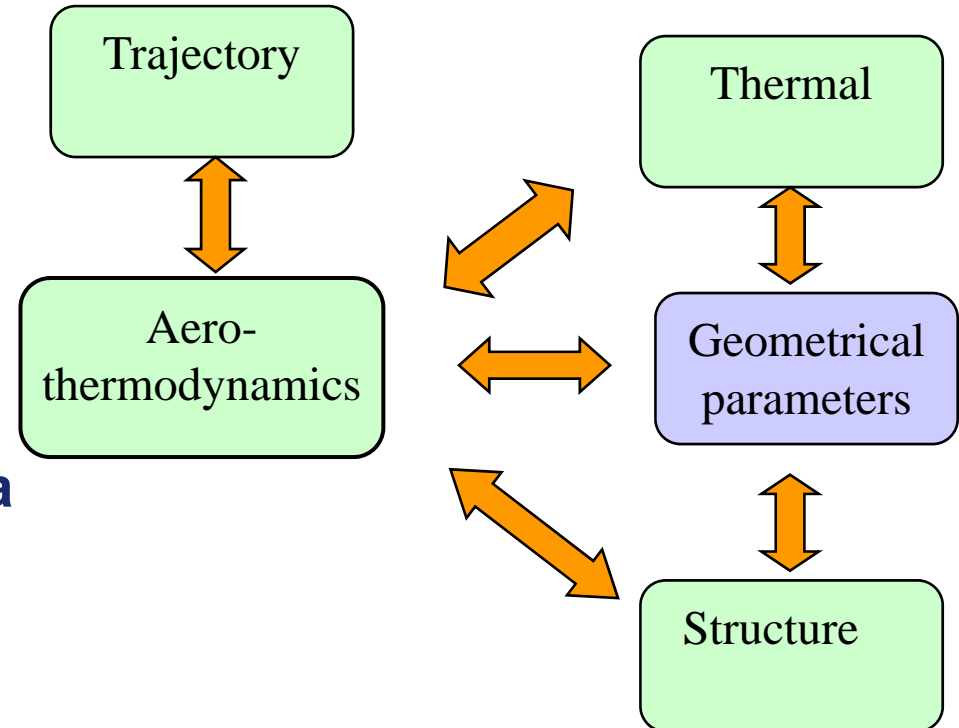
Objective Variables:

- ☐ Minimise the total vehicle mass
- ☐ Maximise the internal available volume



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- The Design process is characterized by a strong correlation between the trajectory computation and the other disciplines.
- For that reason we have opted for a global optimization instead of several local optimizations



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Optimization Algorithm

- ❑ A first optimization process has been performed using the Adaptive Simulated Annealing algorithm:
 - Exploratory Technique
 - Obtains a solution with a minimal cost, from a problem which potentially has a great number of solutions. Distinguishes between different local optima.
- ❑ ~ 200 iterations have been performed:
- ❑ ~ 1 day of computational time necessary to find the global optimum.

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Optimization Results

- ❑ Several design solutions satisfying the requirements have been found.
- ❑ Of course a strong linear correlation exists between the Total Mass and the internal Volume; therefore the best design has to be a compromise between the max volume and minimum mass (see Fig.2).
- ❑ Due to the absence of ribs and local reinforcements in the structure, the dimensions of the vehicle have necessarily be reduced, in order to avoid extreme displacements or stresses, particularly in the rear closure disc (see Fig.1).

Fig. 1

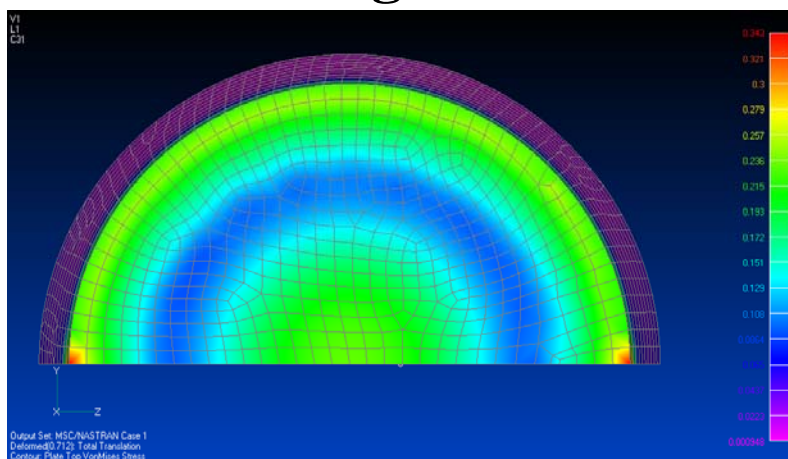
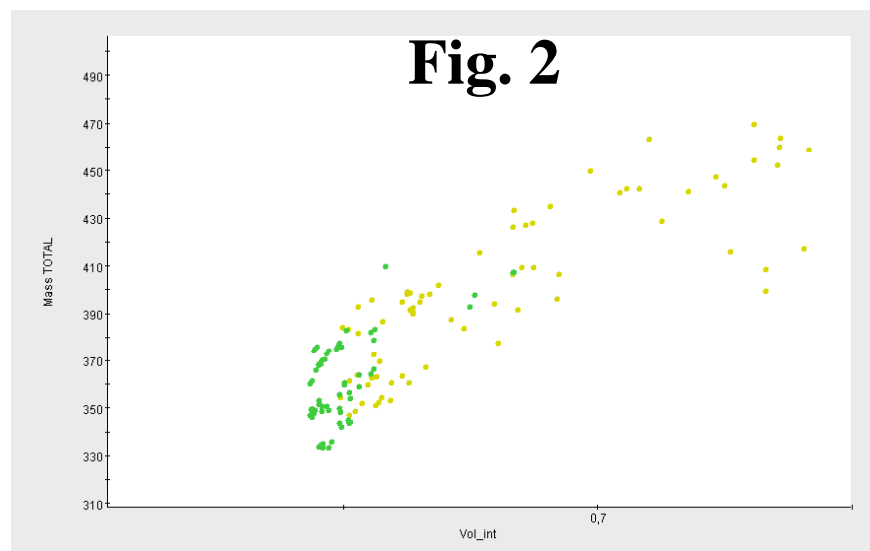
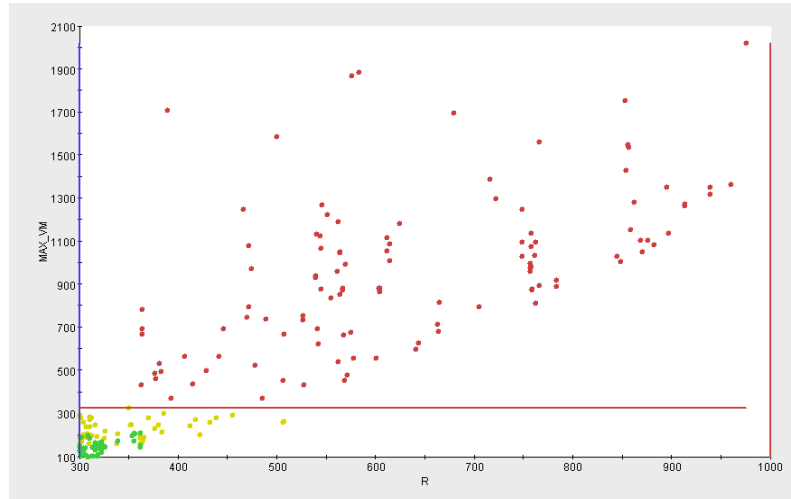


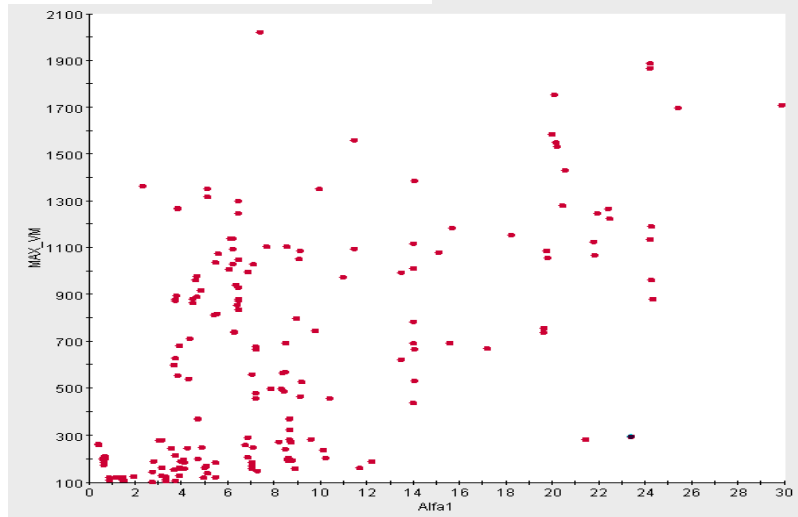
Fig. 2



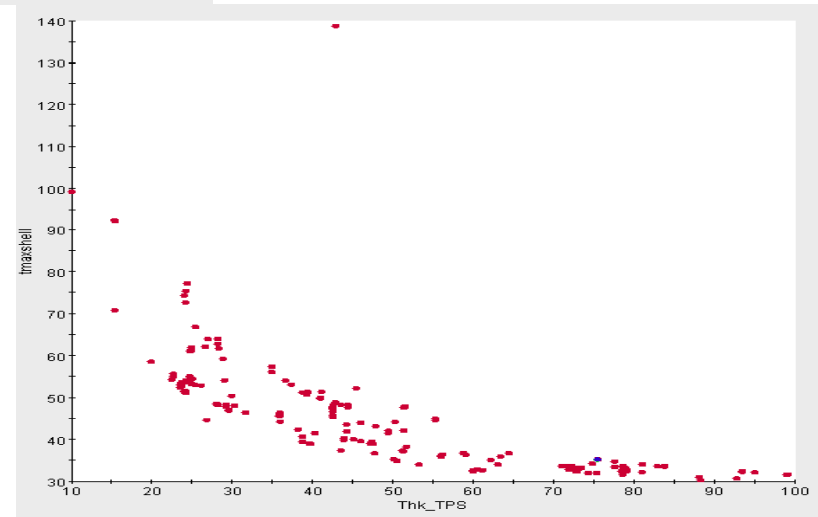
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**Strong correlation exists
between Stress and Nose
Radius**



**Light correlation exists between Stress
and Alfa angles**



**Strong correlation exists between
Max Temp. and TPS thickness**

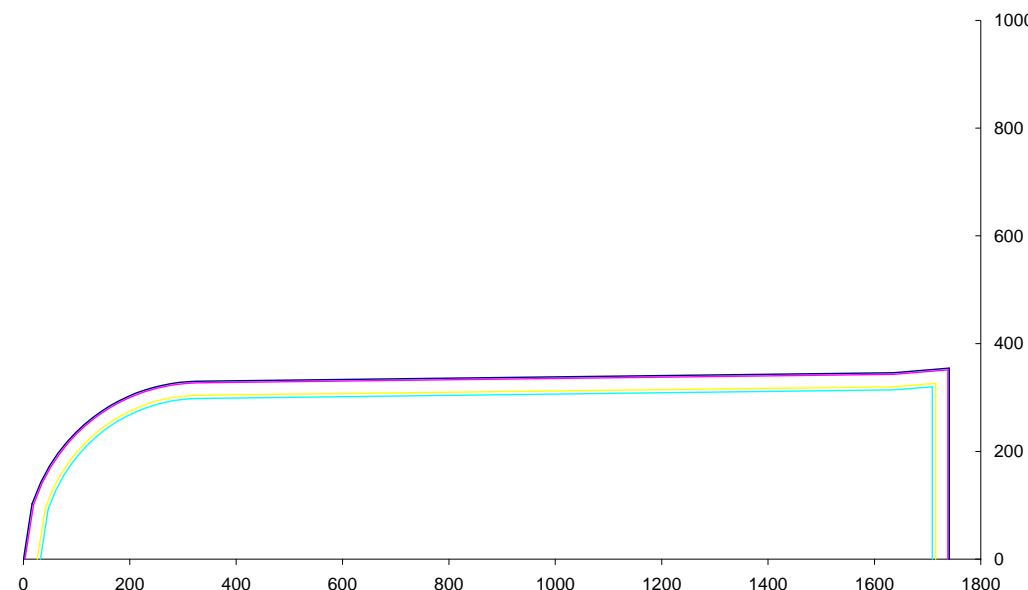
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Optimization Results

□ One of the possible best designs is:

- Vehicle length L_1 = 1310 mm
- Vehicle length L_2 = 105 mm
- Vehicle angle α_1 = 0.7°
- Vehicle angle α_2 = 4.8°
- Nose radius R = 355 mm
- TPS thickness = 23 mm
- Shell thickness = 6.5 mm

- Maximum shell temperature = 52°C
- Maximum shell displacement = 18. mm
- Maximum shell Von Mises stress = 211 MPa
- External volume = 0.7 m^3
- Internal volume = 0.55 m^3
- Total vehicle mass = 409 Kg



This result has to be considered preliminary. It will be the basis for subsequent improved optimization.

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☐ Conclusions

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- **The presented study, although preliminary, has demonstrated that:**
 - ☑ The integration into an unified process of the main disciplines involved in the hypersonic vehicle design is possible.
 - ☑ The design optimization applied to that integrated process is possible.
- **The presented results have to be considered as the first step of a more complex activity. Additional tasks are foreseen:**
 - ☐ A local additional optimization starting from the best obtained design will be performed in order to reduce the mass: the reached T_{MAX} is quite lower than the requirement (150°C) -> probably the TPS thickness can be reduced.
 - ☐ Other optimization algorithms (Genetic, Gradient, etc.) will be tested
 - ☐ The vehicle design has to be reviewed: local reinforcements in the structure are necessary, particularly in the rear closure disc, in order to increase the available volume.

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- **Each discipline activity has to be reviewed introducing more complex analysis models and/or high fidelity analysis codes:**
 - ❑ Configuration and grid generation:
 - More complex geometries have to be investigated
 - A CAD based management of the configuration has to be introduced; it has to be linked to the grid generation code.
 - ❑ Aerothermodynamics:
 - Full Navier Stokes codes have to be introduced.
 - The computational time will be hugely higher; approximation techniques have to be introduced in order to speed up the computation.
 - ❑ Thermal Control
 - Coupled radiative and thermal models have to be introduced.
 - ❑ Structure
 - High fidelity structural models have to be introduced
 - ❑ Trajectory
 - The extraction of significant points from the computed timeline has to be improved.

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