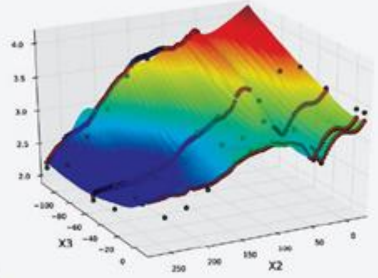
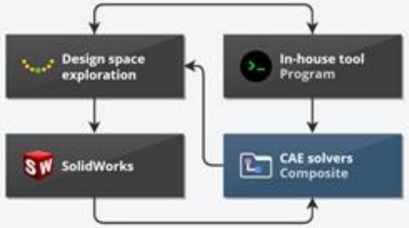
EXPLORE AND OPTIMIZE YOUR DESIGNS





Multidisciplinary design space exploration of a turbine rotor blade using Cradle scTetra, Patran/Nastran, and pSeven

DATADVANCE

April, 2019

Content

About DATADVANCE

- We provide Design Exploration and Predictive Modeling software tools and services to customers in aerospace, automotive, energy, marine and related industries.
- Our roots go to French aviation and Russian mathematics. We evolved out of a joint research program between:
  - Airbus Group – a global leader in aerospace and defense industry
  - Institute for Information Transmission Problems – one of the leading mathematical centers in Russia with three Fields prize winners on the staff
- 9 years history
- Our offices:
  - Toulouse, France (HQ & Operations)
  - Moscow, Russia (R&D Team)
- World-wide sales through a network of distributors

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Goals of turbine rotor blade multidisciplinary design space exploration

Object:

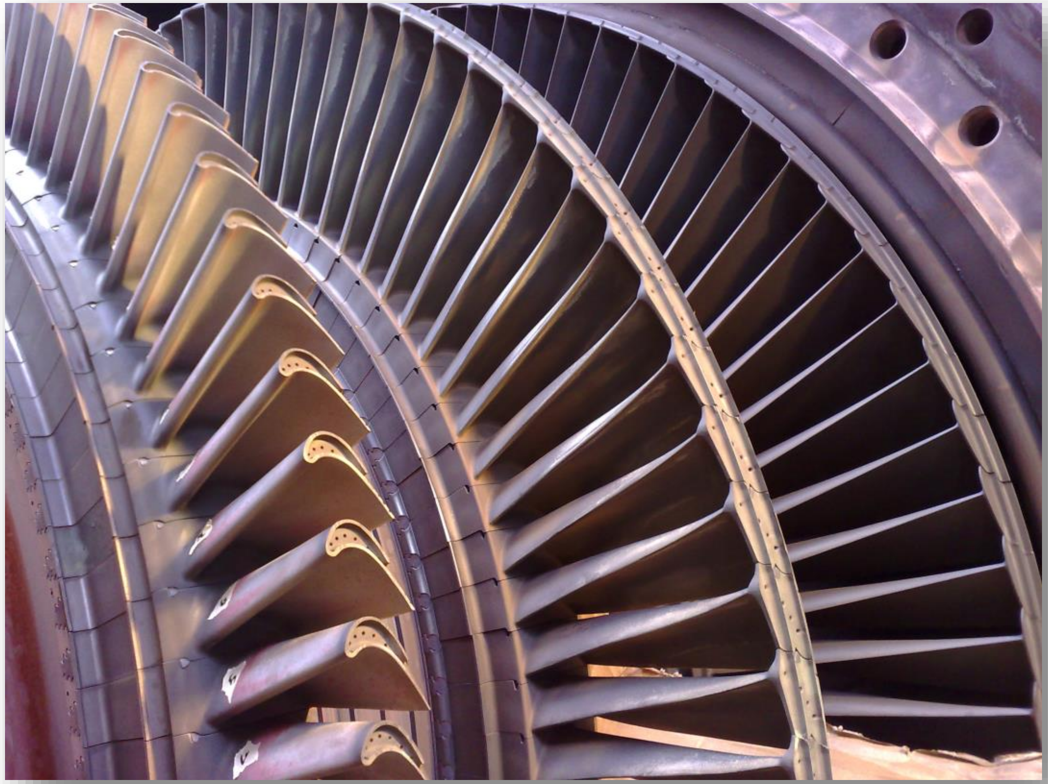
- The object of the study is a rotor blade of a steam turbine

Optimization goal:

- The classical approach to design a rotor blade consists of two steps:
  - Blade profiling to maximize efficiency, calculated using gas-dynamic calculation
  - Detuning the eigenfrequencies of turbine rotor blades away from critical areas, using preloaded modal analysis
- In some cases, detuning is impossible without reprofiling the flow part. This is a critical situation in which the design of the machine actually needs to be restarted.
- **The actual task is to perform blade profiling and check the possibility of detuning simultaneously**

Predictive modelling goal:

- Blade profiling for efficiency maximization is performed in the nominal operational regime
- Safety to be ensured for the whole variety of operational regimes
- It is possible to build an predictive model to predict gas-dynamic and structural characteristics on such regimes



The same process for different turbines
Thus it’s worth to automate

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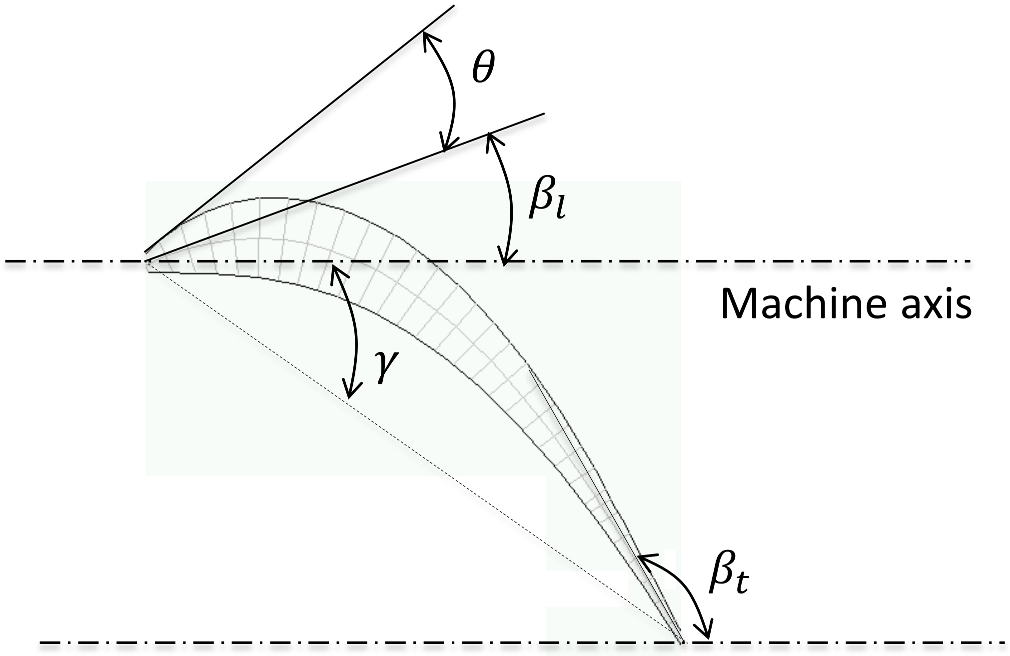
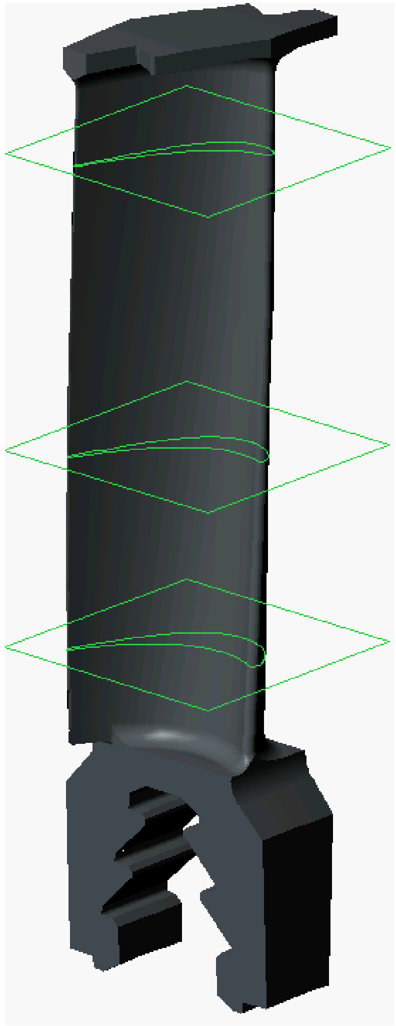
Multidisciplinary rotor blade optimization: Blade efficiency optimization

- Blade profile geometry optimization:
  - **Objective** – maximum blade efficiency : $\max \eta$
  - **Constraint** - pressure drop on the blade: $2000\ [Pa] < dP < 2700\ [Pa]$
  - **Variable parameters** – 4 profile parameters of blade types in 3 sections (**12** parameters in total):
    - Stager angle: $30^o < \gamma^i < 40^o$
    - Mean line leading angle: $-30^o < \beta_l^i < -40^o$
    - Mean line trailing angle: $60^o < \beta_t^i < 70^o$
    - Leading wedge angle: $10^o < \theta^i < 20^o$





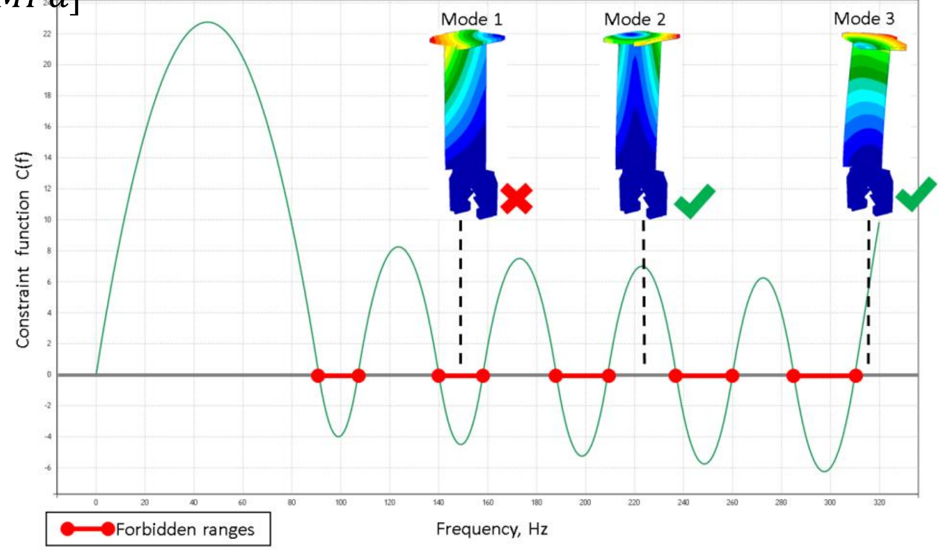
Multidisciplinary rotor blade optimization: Blade eigenfrequencies detuning problem

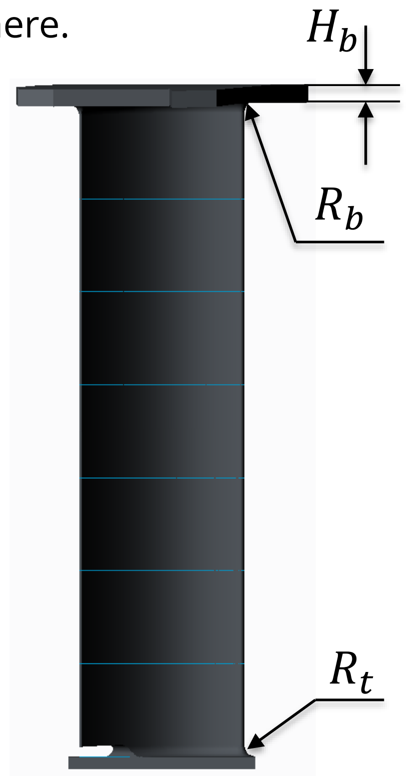
- One of the most important issues in ensuring operational safety is to tune the blade eigenfrequencies under operating conditions away from possible resonances with the rotation frequencies and pulsations of the flow.
- Detuning is considered as a parametric optimization problem based on automated modal analysis of a preloaded blade.
- The constraint for blade eigenfrequency values $\boldsymbol{f_j}$ is constructed as a function of allowed and forbidden frequency ranges. These ranges come from design methodology and in fact are located near the multiples of the basic rotation rate.
- The constraint function $\boldsymbol{C(f_j)}$ separates feasible and unfeasible blade geometries and should automatically fit the given resonance regions. We used a piecewise-quadratic function, which is negative for the forbidden frequencies and positive elsewhere.
- As a result, we face a **Constraint Satisfaction Problem** with the following properties:
  - Set of **constraints on eigenfriequencies:** $C(f_j) > 0, where\ f_j = (\gamma^i, \beta_l^i, \beta_t^i, \theta^i, R_t, R_b, H_b)$
  - **Constraint** on equivalent **stress** from preload: $S_{eqv} < 500\ [MPa]$
  - Variable parameters:
    - Blade profile parameters: $\gamma^i, \beta_l^i, \beta_t^i, \theta^i$
    - Hub and shroud fillet radii:

      $3\ [mm] < R_t < 8\ [mm]$

      $3\ [mm] < R_b < 8\ [mm]$
    - Shroud ring height:

      $5\ [mm] < H_b < 10\ [mm]$





Multidisciplinary rotor blade optimization: Problem factorization – Nested optimization

- The full multidisciplinary optimization problem definition:

$$\begin{cases} \max \eta(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) \\ 2000\ [Pa] < \ dP(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) < \ 2700\ [Pa] \\ C(f_j) > 0, where\ f_j = (\gamma^i, \beta_l^i, \beta_t^i, \theta^i, R_t, R_b, H_b) \\ S_{eqv}(\gamma^i, \beta_l^i, \beta_t^i, \theta^i, R_t, R_b, H_b) < 500\ [MPa] \end{cases}$$

CFD analysis responses (first two lines)

Structural analysis responses (last two lines)

- Note there are three parameters R_t, R_b, H_b in structural responses, which do not affect CFD responses. This allows us to move structural constrains satisfaction to an internal optimization (CSP) loop over these 3 parameters. So, we can change the problem definition to:

$$\begin{cases} \max \eta(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) \\ 2000\ [Pa] < \ dP(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) < \ 2700\ [Pa] \\ \Psi_{struct}(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) > 0 \end{cases}$$

External optimization loop

where Ψ_{struct} is the feasibility measure of structural characteristics found from the constraint satisfaction problem:

$$\begin{cases} C(f_j(R_t, R_b, H_b)) > 0 \\ S_{eqv}(R_t, R_b, H_b) < 500\ [MPa] \end{cases} for\ each\ considering\ (\gamma^i, \beta_l^i, \beta_t^i, \theta^i)$$

Internal optimization loop

$$\Psi_{struct} = -\max[C(f_j(R_t, R_b, H_b)), \frac{(S_{eqv}(R_t, R_b, H_b) - 500.)}{500.}]$$

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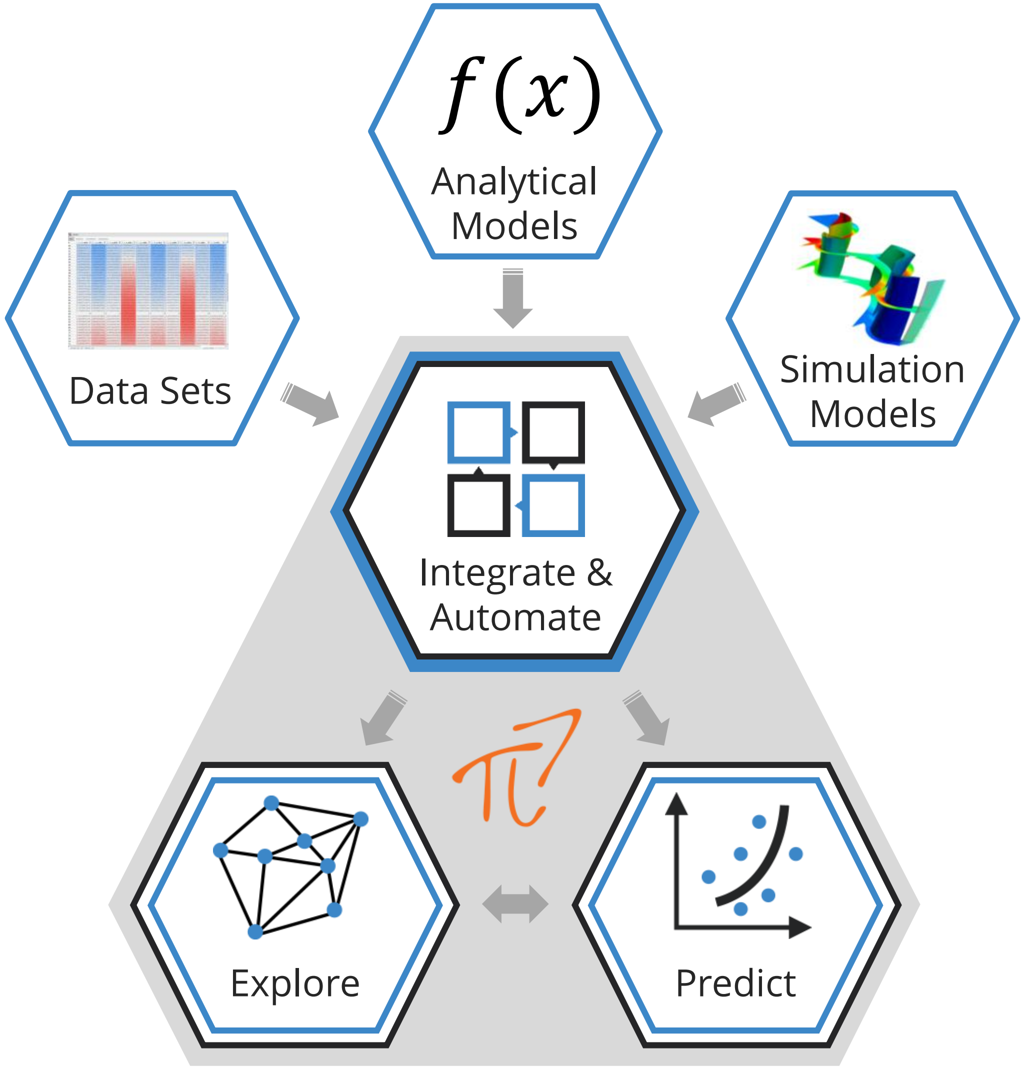
pSeven is developed to:

- Automate complex product design processes and integrate all external software and data into a single workflow
- Solve engineering problems with a complete toolset for Design Exploration and Predictive Modeling

pSeven allows to:

- Build composite model of the product from different data sets, analytical and simulation models
- Explore your model with tools for Design Exploration
- Predict responses for new designs or operational regimes of the product with Predictive Modeling



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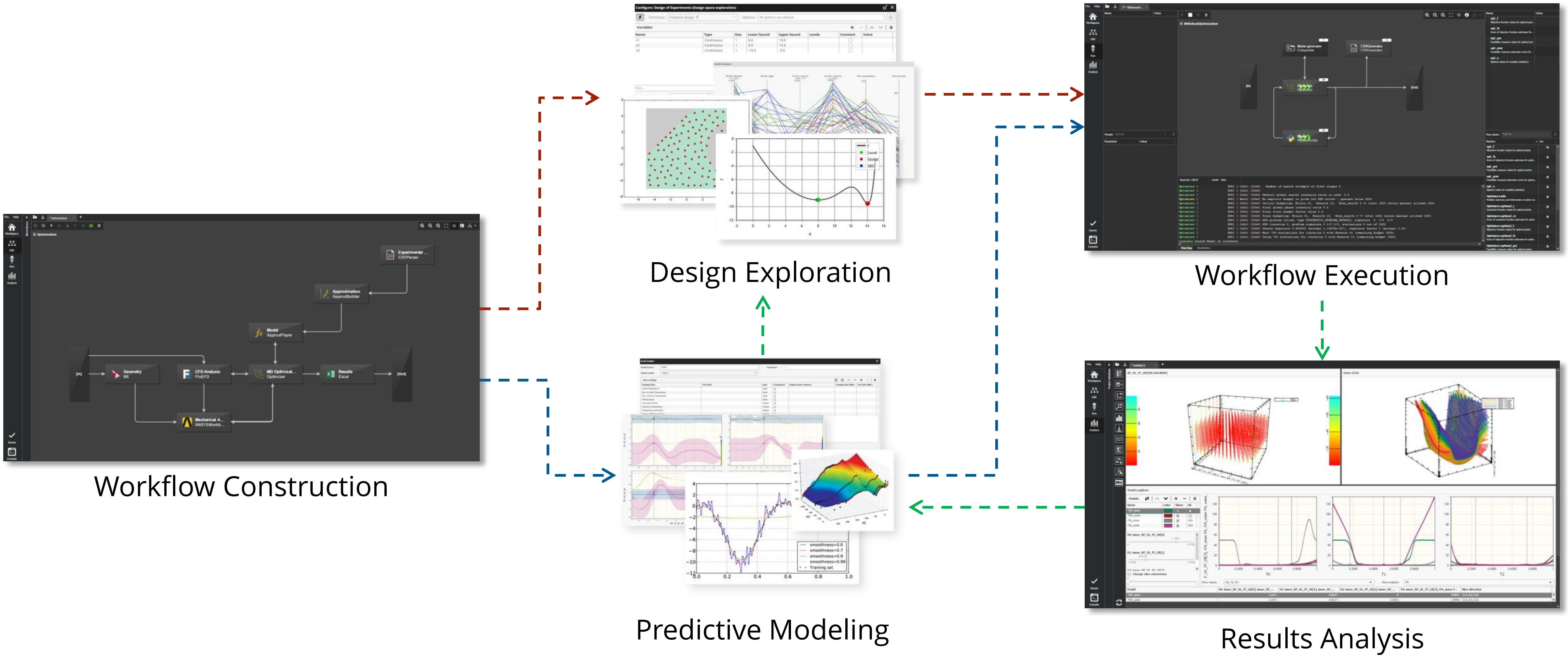
Interface & Components

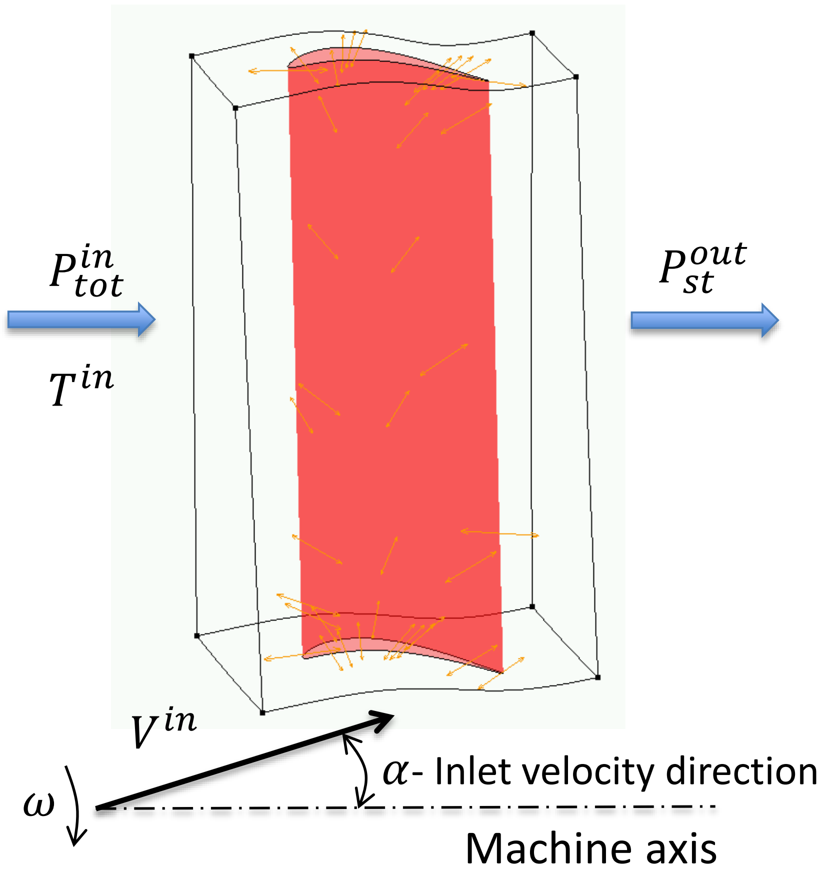


CFD computation scheme

- All CFD computations were performed using *Cradle scTetra*

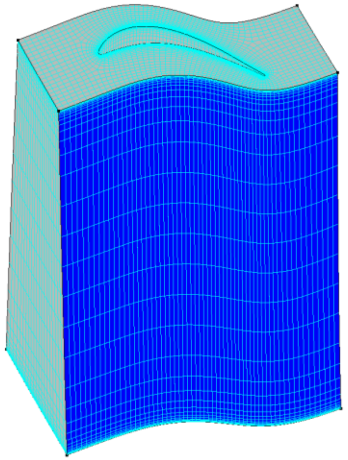
- Rotating domain with the following analysis conditions:
  - Inlet: $P_{tot}^{in} = 10000\ [Pa], T^{in} = 300C,\ \alpha = 25^o$
  - Outlet: $P_{st}^{out} = 0\ [Pa]$
  - Periodic boundary conditions on sides
  - $P_{ref} = 101325\ [Pa]$

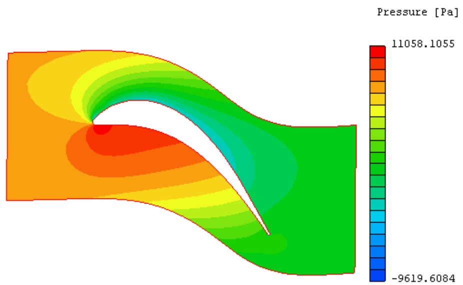
- *scTetra Turbomachinery output* was used to evaluate blade efficiency and pressure drop

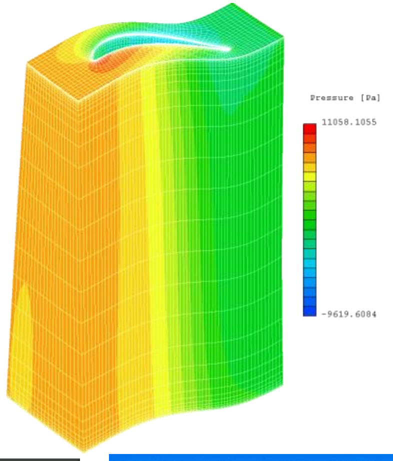


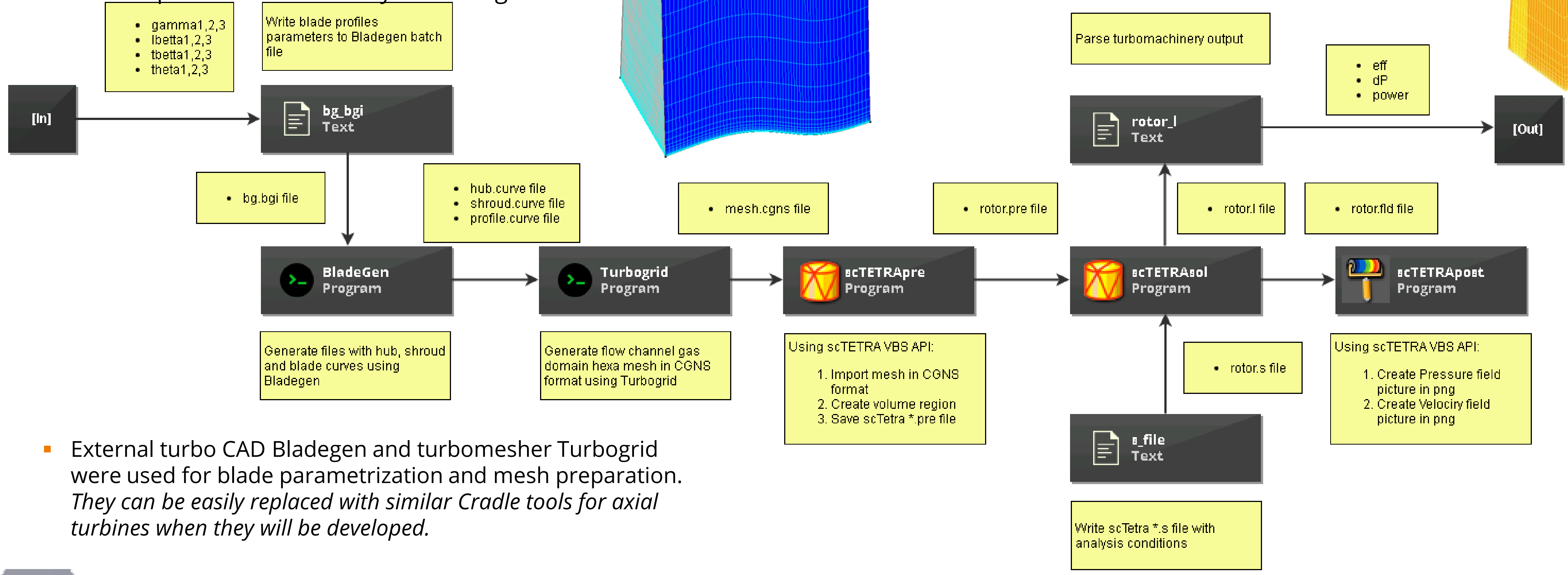
CFD rotor blade analysis
CFD blade analysis automation using scTetra

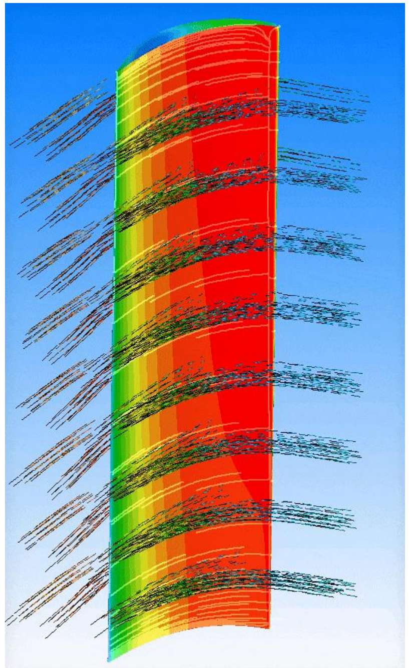
- Full automation of rotor blade efficiency calculation was performed using scTetra VBS API and a scTetra *.s file with analysis conditions. Specifically:
  - Import mesh in CGNS format
  - Create volume region
  - Set analysis conditions
  - Save pressure and velocity field images











- External turbo CAD Bladegen and turbomesher Turbogrid were used for blade parametrization and mesh preparation. *They can be easily replaced with similar Cradle tools for axial turbines when they will be developed.*

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Structure rotor blade analysis
Preloaded modal analysis computation scheme

- Patran is used to perform preprocessing for the preloaded modal analysis.
- Solution scheme contains two subcases: SOL101 (static preload) and SOL103 (modal).

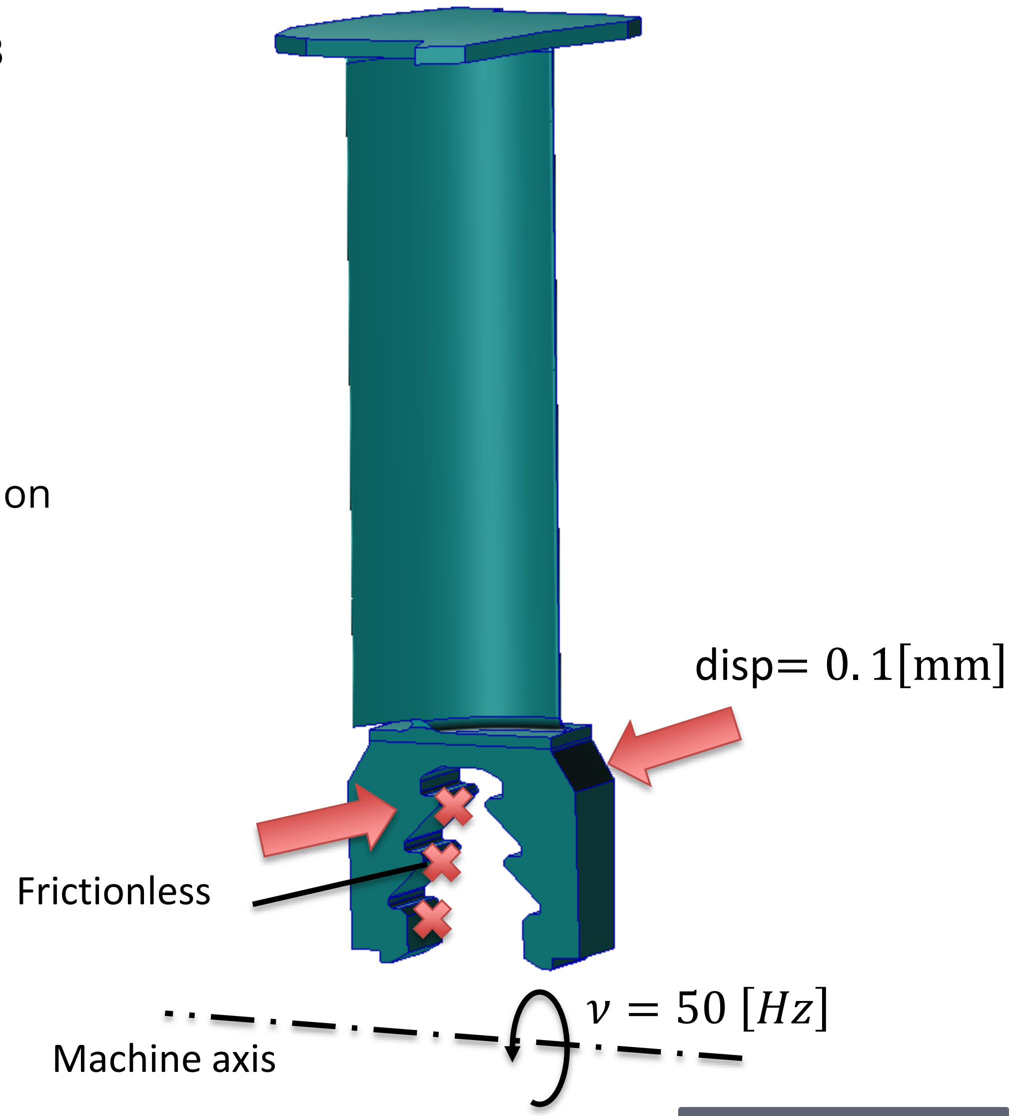
The full blade CAD model was separated into two parts: *blade* and *tail*. It is necessary for the automation of the boundary condition appliance: during the modification of a blade part geometry, renumbering of surfaces is possible.

Boundary conditions are the following:

- Frictionless condition on inner surfaces of the *tail* part;
- The tail circuit tension on the *tail* by appliance the fixed displacement condition $disp = 0.1$ [mm]
- Inertial load on the full body with $\nu = 50$ [Hz] rotation velocity around the machine axis

Output parameters:

- Eigenvector $\boldsymbol{f}$
- Maximal equivalent stress S_{eqv}



Structure rotor blade analysis
Structure analysis automation using Patran/Nastran

The **SES** text block enables to vary parameters of the FE mesh size, rotation velocity, modal analysis roots count.

Patran runs the prepared session file (PCL script) over the *blade* and *tail* Parasolid models:

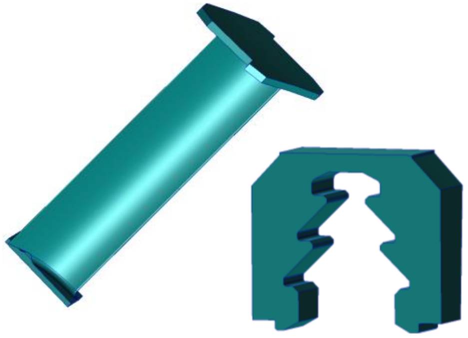
- Builds a finite element grid,
- Defines material properties,
- Applies boundary conditions,
- Prepares solution sequence,
- Defines required format of the output result file.

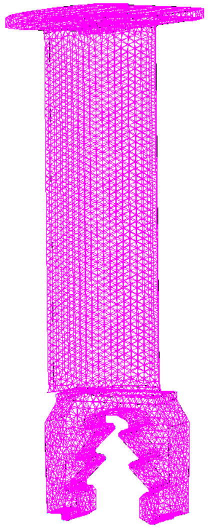
scConverter performs conversion of the CFD result fields distribution (temperature and pressure) to structure BCs.

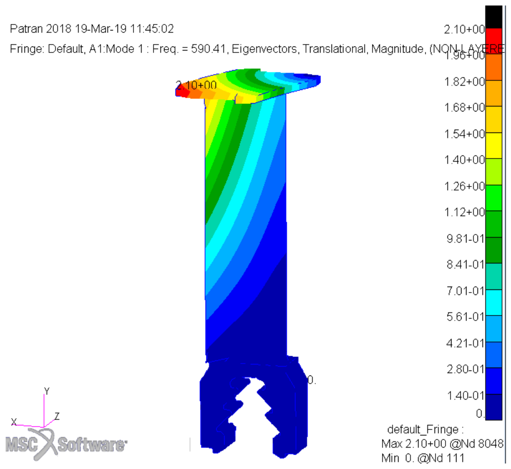
Note: a more detailed description is available on the next slide

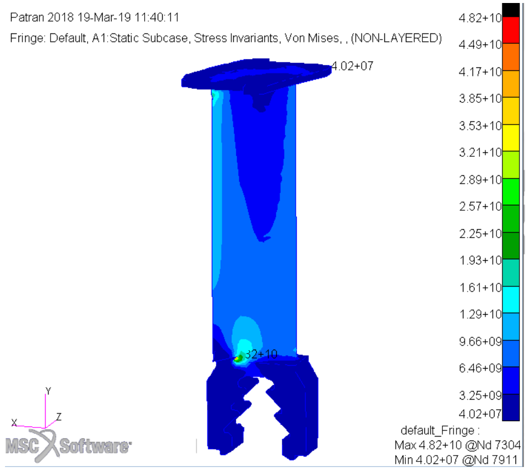
Nastran solves the task described in a *.bdf file.

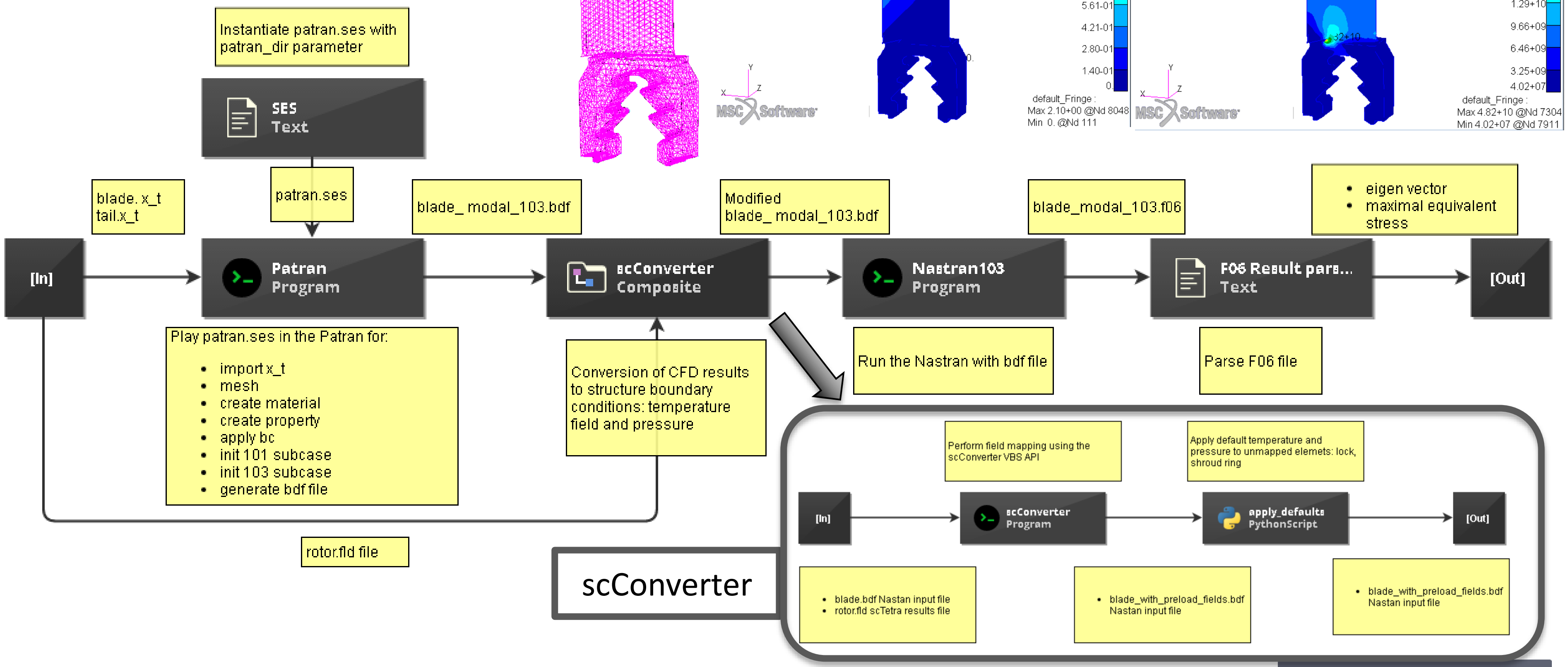
F06 Parser derives resulting maximum equivalent stress and eigenvector from the *.fo6 file











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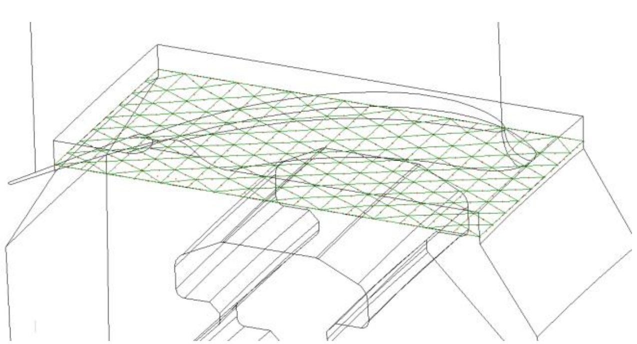
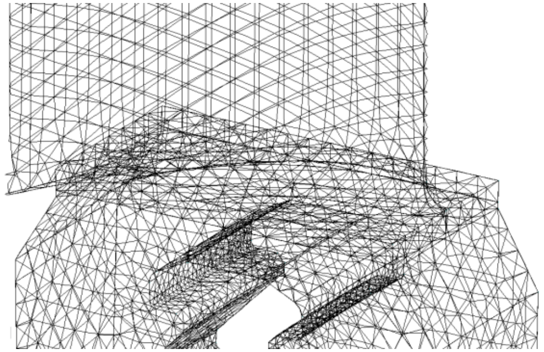
Structure rotor blade analysis
Structure integration features



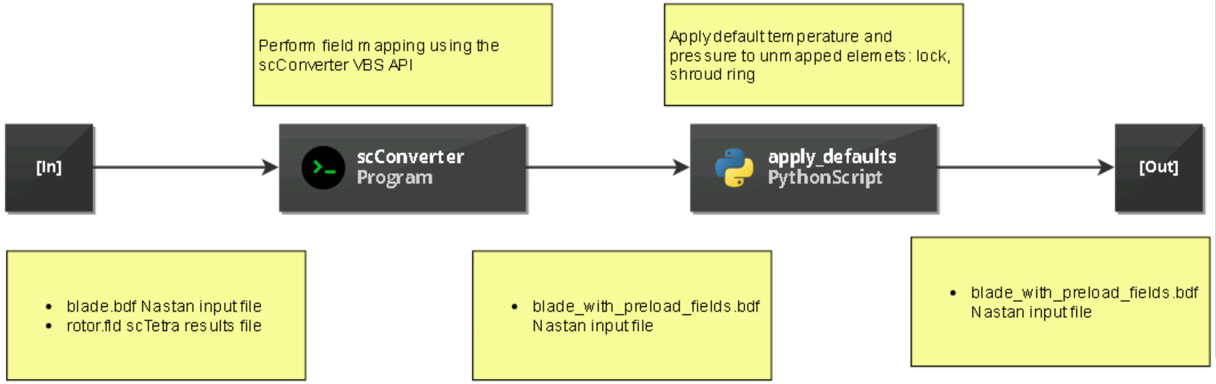


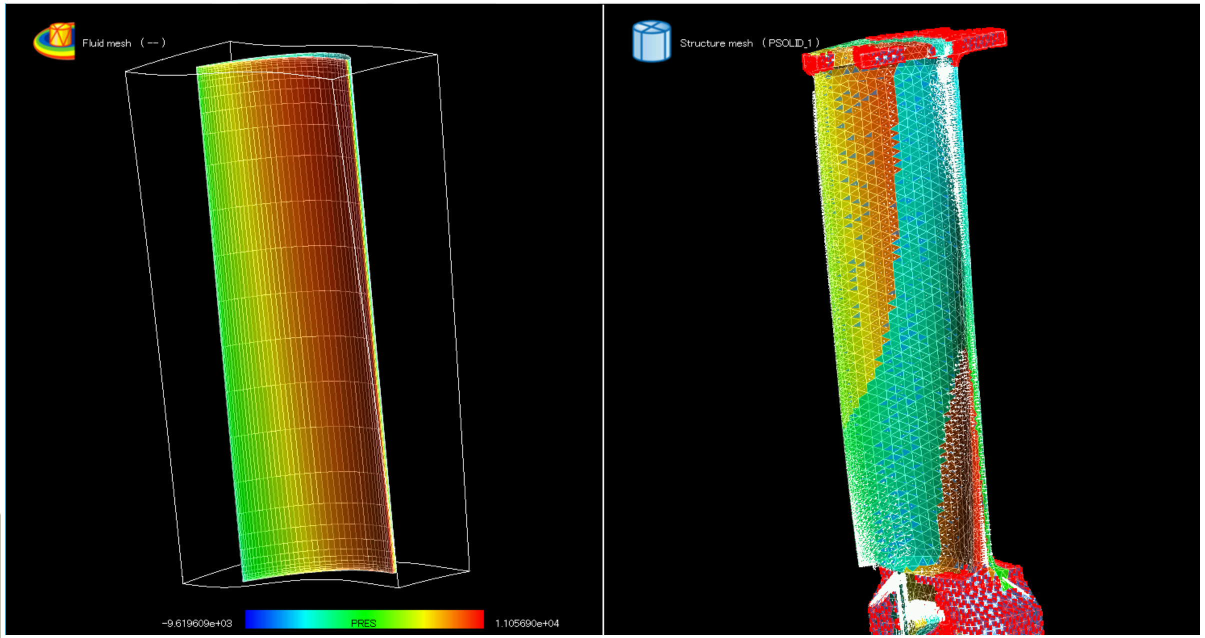
The trick with the separation of the full blade model into two parts for independent application of the BCs demands to unite the meshes of Parasolid parts.

It is possible thanks to these Patran's features:

- Direct Access to CAD Geometry and import from the Parasolid format. Parts are loaded from different files.
- Assembly solids feature is used for meshing, including the "Create Duplicate Nodes" and "Match Parasolid faces" adjustments.

- Mapping the pressure and temperature fields of CFD results to the structure model was fully automated using the scConverter VBS API:
  - The input of the pSeven workflow are the scTetra results file (*.fld) and the Nastran input file (*.bdf) prepared using Patran
  - The output of the pSeven workflow is a Nastran *.bdf file with initial temperature and pressure field





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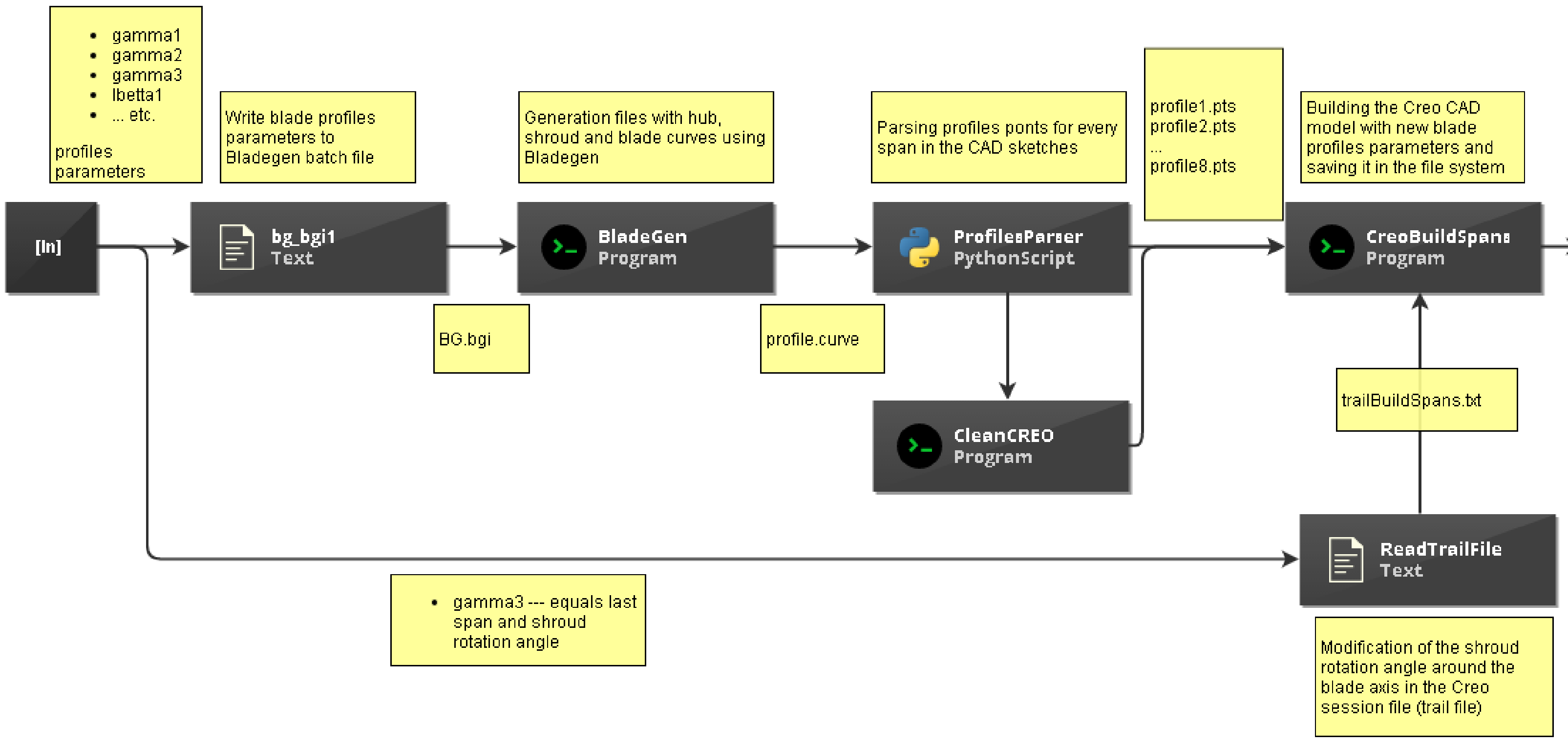
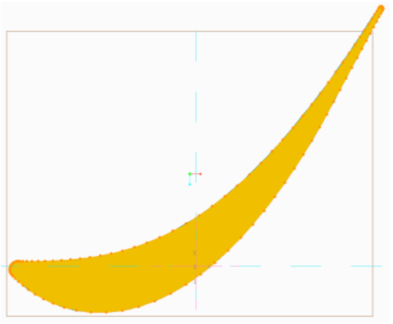
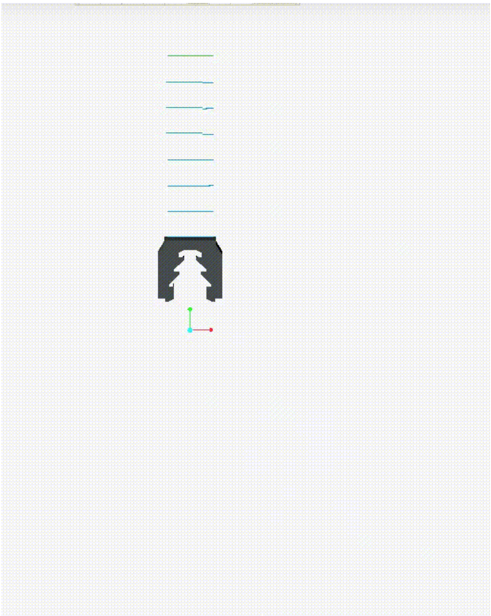
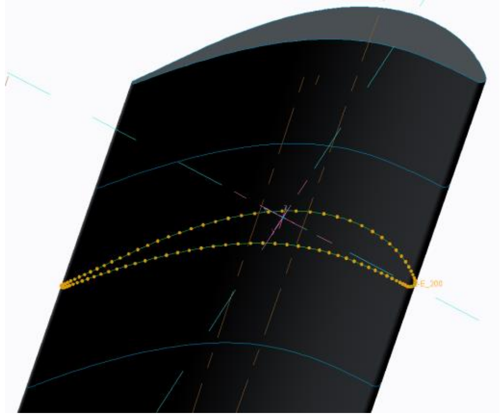
Structure rotor blade analysis
Automatic blade generation in PTC Creo

- Since we have blade profile points along the spans, we can easily add them to the proper sketches in the CREO *.prt model.
- For this purpose, a special session file with CREO instructions was recorded (a trail-file, in CREO terminology)









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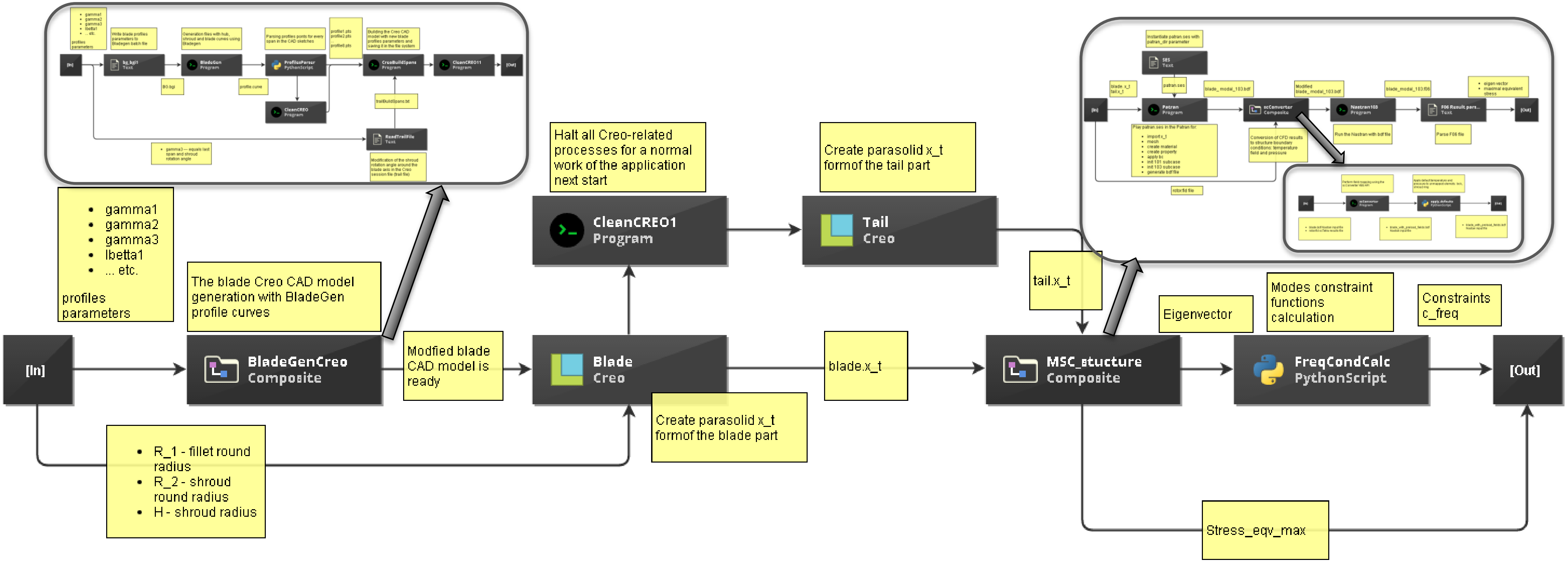
Structure rotor blade analysis
Top-level workflow

- All processes related to structural analysis are combined in the top-level workflow
- The Creo CAD *blade* (modified by the **BladeGenCreo** block) and *tail* models are saved to the Parasolid format by the **Blade** and **Tail** Creo blocks respectively
- Eigenmodes calculated by the **MCS_structure** block are processed by the **FreqCondCalc** script block to calculate constraints for the resonance detuning



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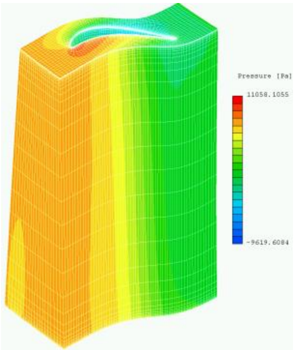
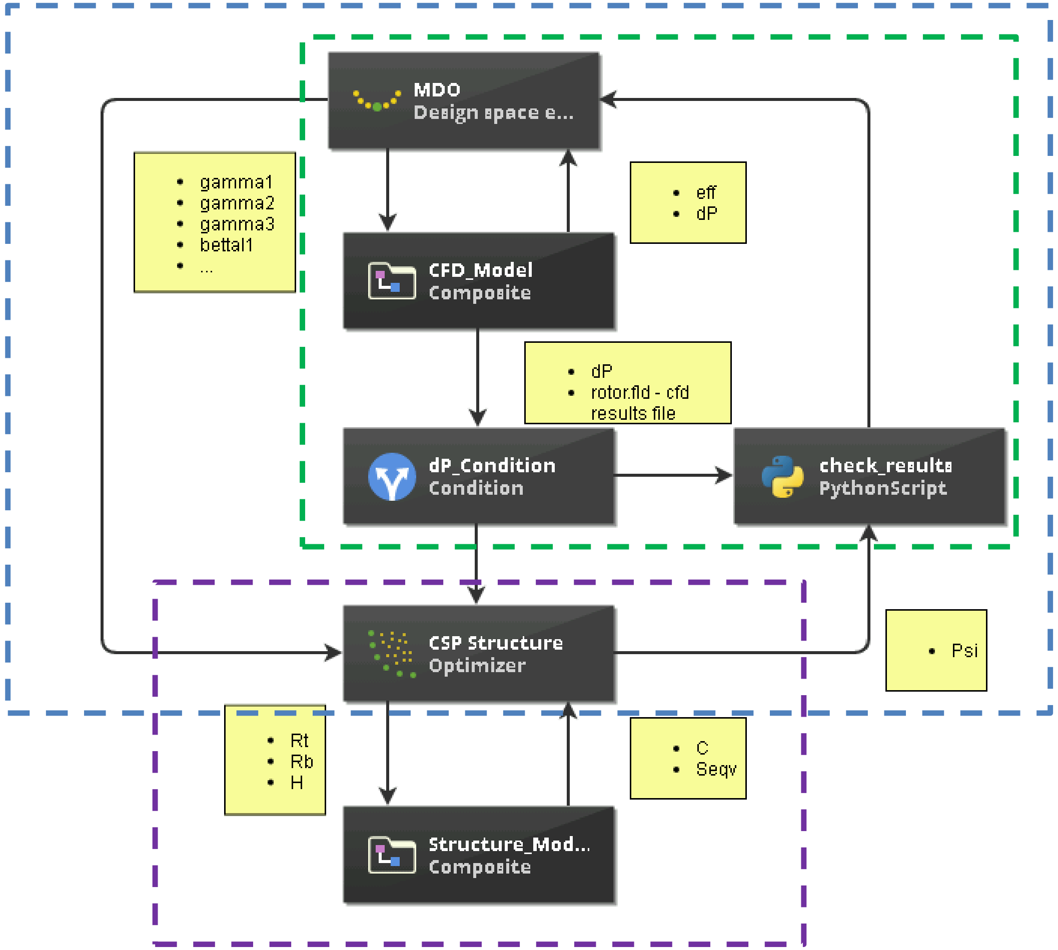
Full optimization workflow

External optimization loop

$$\begin{cases} \max \eta(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) \\ 2000\ [Pa] < dP(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) < 2700\ [Pa] \\ \Psi_{struct}(\gamma^i, \beta_l^i, \beta_t^i, \theta^i) > 0 \end{cases}$$

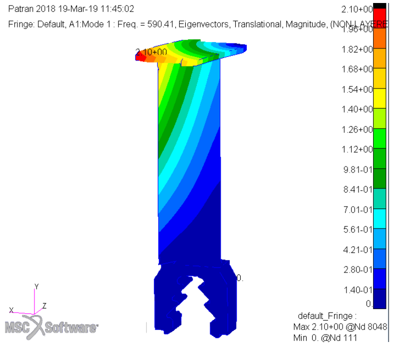




If CFD is infeasible

Internal optimization loop

$$\begin{cases} C(f_j(R_t, R_b, H_b)) > 0 \\ S_{eqv}(R_t, R_b, H_b) < 500\ [MPa] \end{cases} \textit{for each considering } (\gamma^i, \beta_l^i, \beta_t^i, \theta^i)$$



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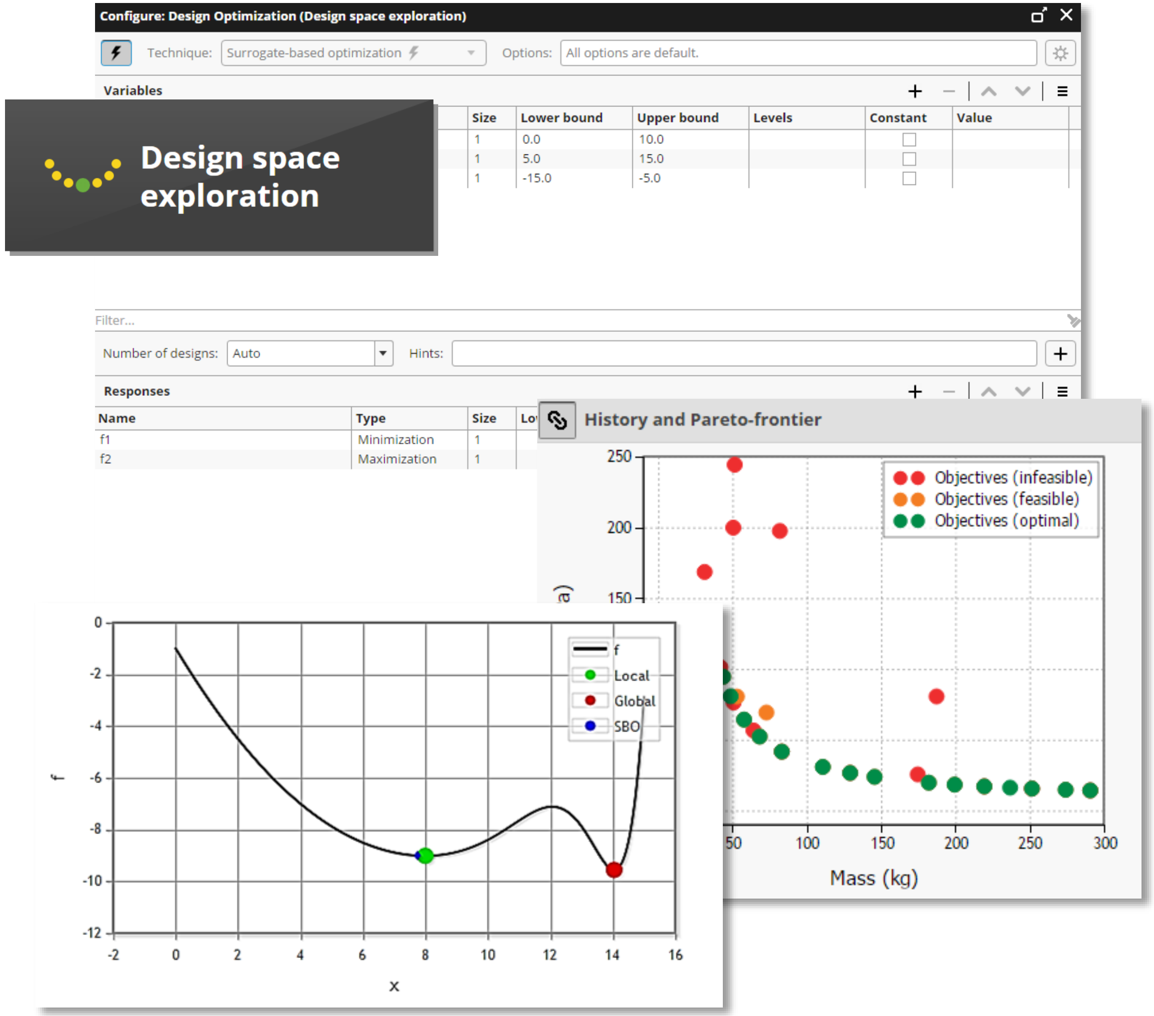
Design Optimization in pSeven

pSeven provides easy and effective solution for most of industry optimization problems:

- Single- or multi-objective, robust optimization
- Large dimensionality*
- Long model evaluation time**
- Continuous and discrete input variables
- Nonlinear, multimodal or noisy objective functions and constraints
- Presence of implicit constraints and domains of undefined behavior
- Presence of uncertainties

SmartSelection chooses the optimization algorithms automatically and adaptively!



* - Up to 100 design variables for nonlinear time-consuming models

** - For example, any CAE model

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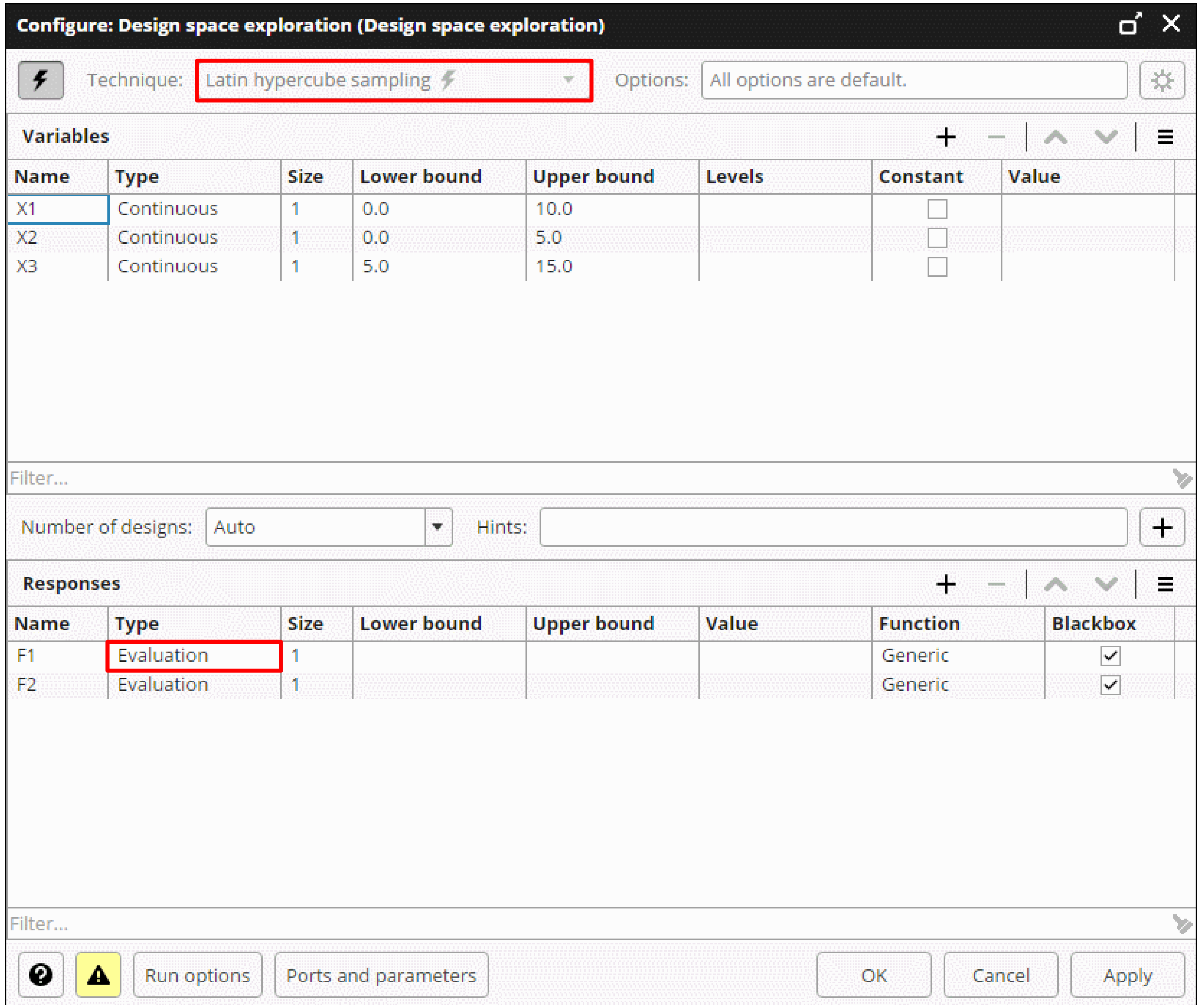
SmartSelection for Design Exploration

Design Exploration technique is chosen automatically with SmartSelection:

- Set of options and hints helps the user to describe a problem and desired solution:
  - Types of variables: continuous, discrete, categorical
  - Types of responses: evaluation, minimization, constraint etc.
  - Function of responses: generic, linear, quadratic etc.
  - Problem hints: noisy, expensive

Design Optimization algorithms' parameters are adaptively tuned during the solution:

- In the case of performance degradation solution process interrupts and restarts with the next suitable algorithm



Benchmark: Multi-Objective Gradient-Based Optimization

- Test problem: Well-known TP7
- Objective functions evaluations:
  - pSeven - 187
  - NSGA2 - 200

$$\min_{\vec{x}} \left(x_0, \frac{1+x_1}{x_0}\right),$$

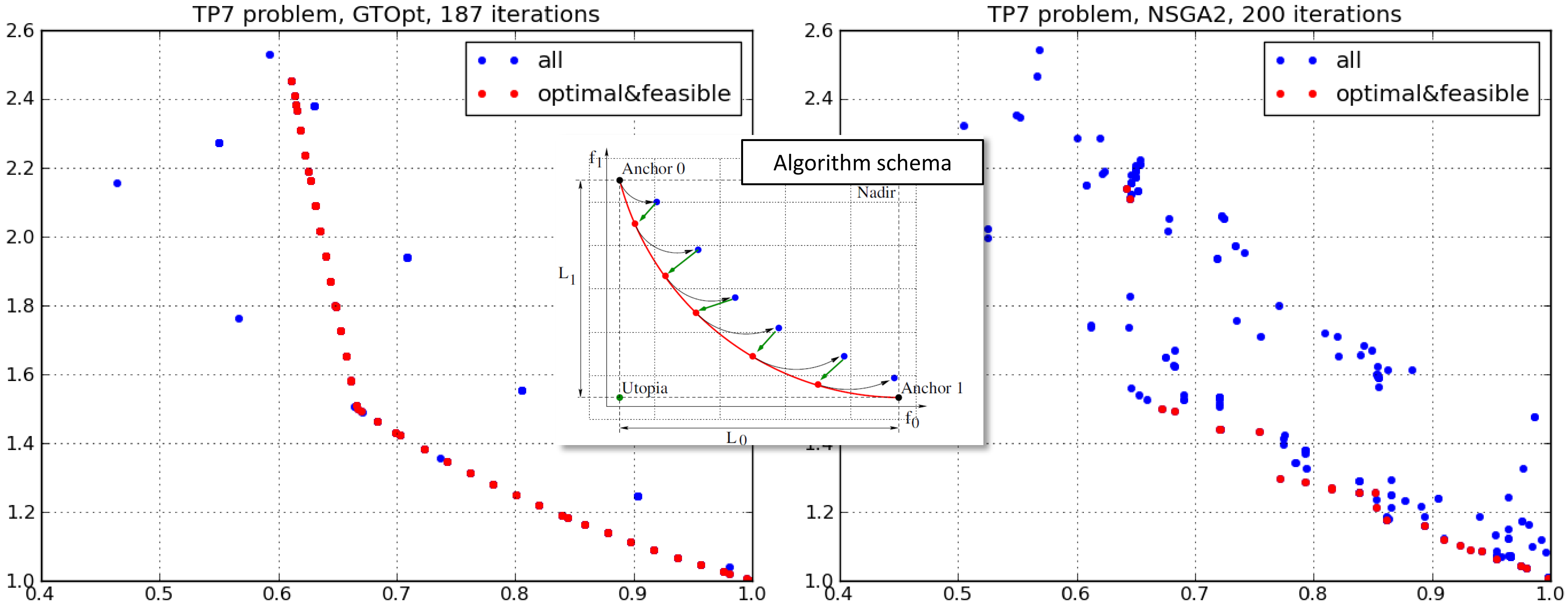
where

$$0.1 \le x_0 \le 1$$
$$0 \le x_1 \le 0.5$$

subject to

$$x_1 + 9\,x_0 \ge 6$$
$$-x_1 + 9\,x_0 \ge 1$$

- NSGA2 can't reconstruct Pareto frontier using the same number of evaluations



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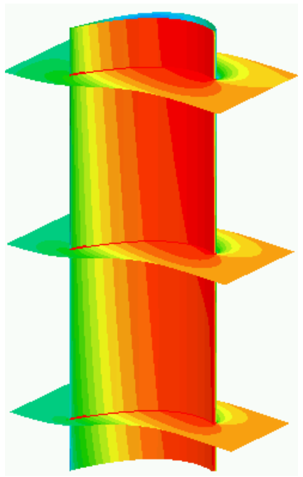
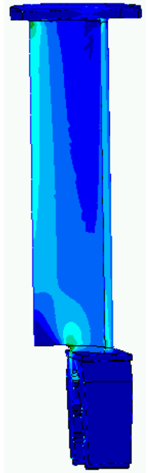
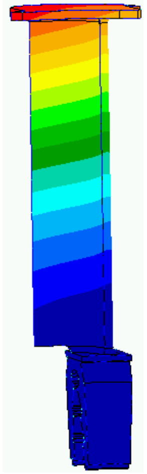
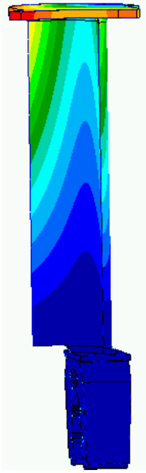
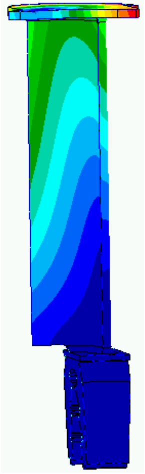
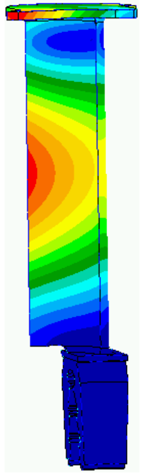
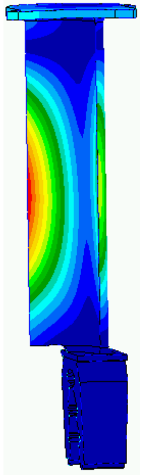
Optimization: Initial model

- Maximum stress is violated
- Second mode in resonance state (~300Hz)

Parameters	CFD in scTetra	Structural in Patran/Nastran					
$\gamma^1 = 35$ $\gamma^2 = 35$ $\gamma^3 = 35$ $\beta_l^1 = -35$ $\beta_l^2 = -35$ $\beta_l^3 = -35$ $\beta_t^1 = 65$ $\beta_t^2 = 65$ $\beta_t^3 = 65$ $\theta^1 = 15$ $\theta^2 = 15$ $\theta^3 = 15$ $R_t = 5$ $R_b = 5$ $H = 7$							
	Pressure field $\eta = 84.09\%$ $dP = 2628\ [Pa]$	*Stress field* $S_{eqv} = 689\ [MPa]$	*Eigen disp. field* f_1 =123.49 [Hz]	*Eigen disp. field* $f_2 = 294$ [Hz]	*Eigen disp. field* f_3 =408.03 [Hz]	*Eigen disp. field* $f_4 = 814.6$ [Hz]	*Eigen disp. field* $f_5 = 1435$ [Hz]

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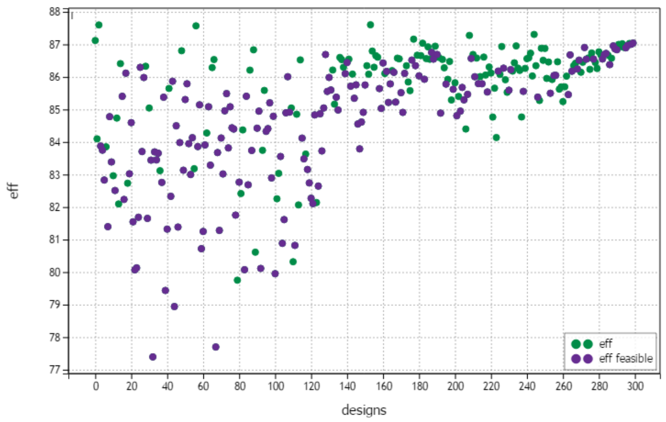
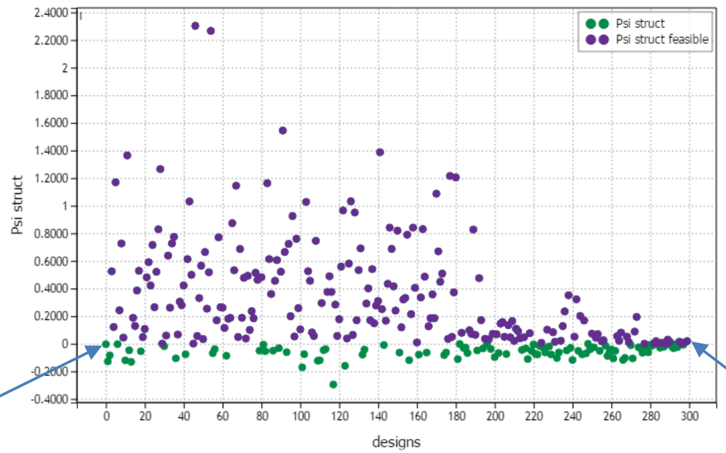
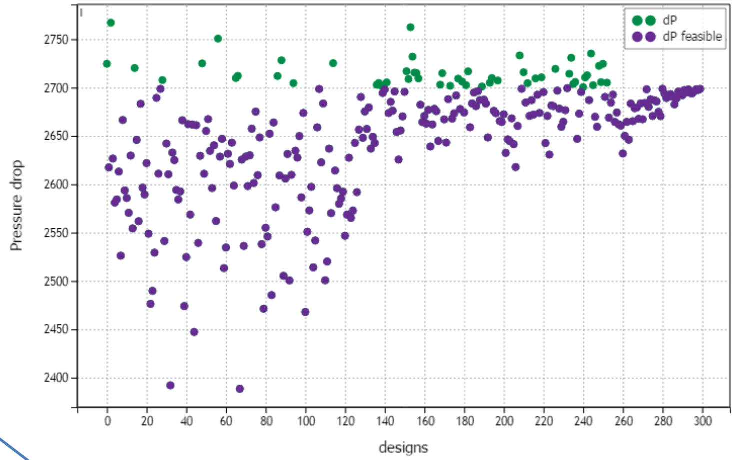
Optimization: History

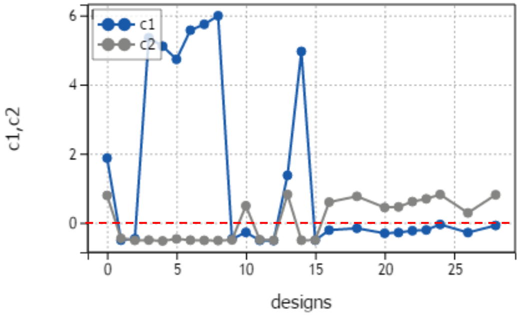
External optimization (300 CFD calls)

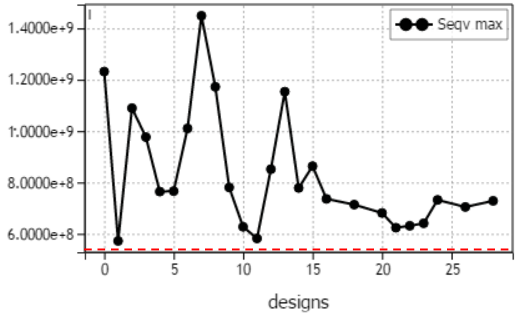




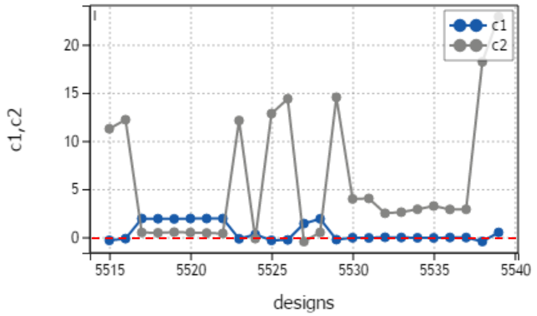


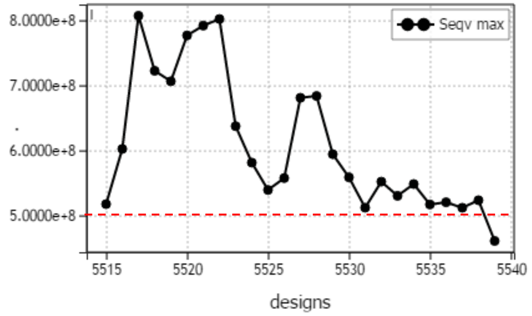
Internal optimizations





Internal optimization has infeasible status – blade's first mode stayed in resonance, maximum equivalent stress is above the limit

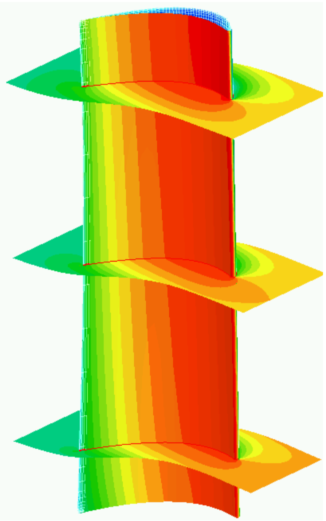
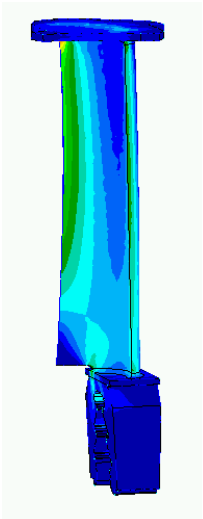
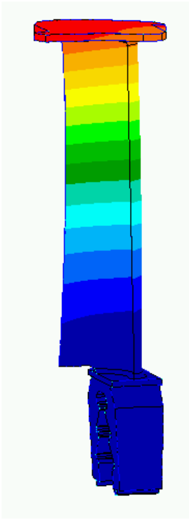
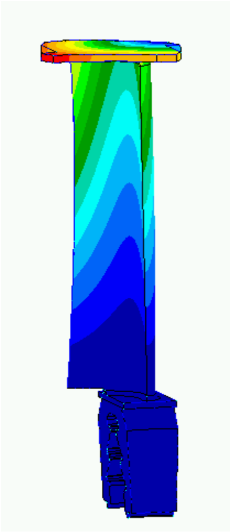
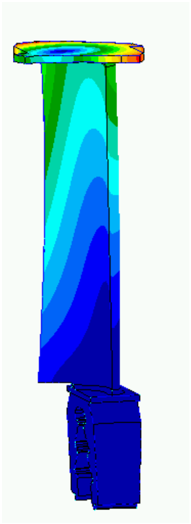
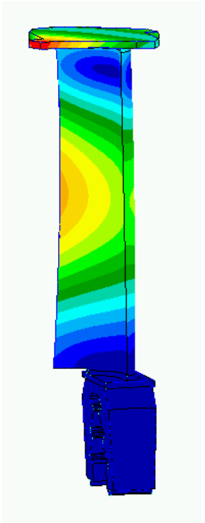
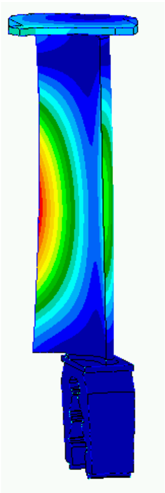




Internal optimization has feasible status

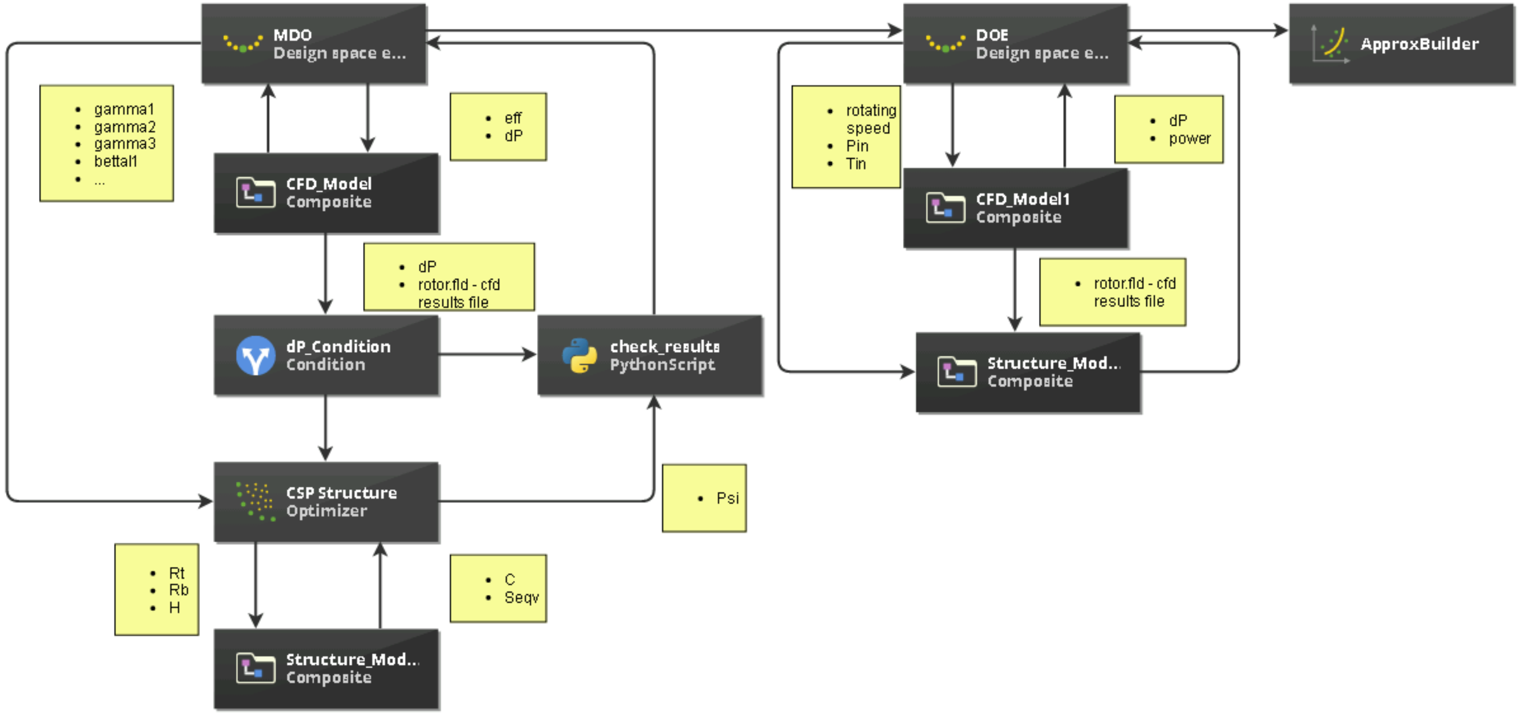
Optimization: Result

- *Used 300 evaluations of the CFD model and 5545 evaluations of the structure model (budget is 30 in each internal loop)*
- *These optimization budgets are selected on the basis of the entire optimization operating time estimation*
- *Efficiency increased by 3%, maximum stress decreased and eigenfrequencies were tuned*

Parameters	**CFD in scTetra**	**Structural in Patran/Nastran**					
$\gamma^1 = 34.5$ $\gamma^2 = 30$ $\gamma^3 = 30$ $\beta_l^1 = -34.5$ $\beta_l^2 = -40$ $\beta_l^3 = -36$ $\beta_t^1 = 65.3$ $\beta_t^2 = 62.7$ $\beta_t^3 = 60$ $\theta^1 = 20$ $\theta^2 = 19.5$ $\theta^3 = 20$ $R_t = 3.6$ $R_b = 6.4$ $H = 6$							
	Pressure field $\eta = 87.04\%$ $dP = 2698\ [Pa]$	*Stress field* $S_{eqv} = 466.5\ [MPa]$	*Eigen disp. field* f_1 =136.6 [Hz]	*Eigen disp. field* $f_2 = 318.5$ [Hz]	*Eigen disp. field* f_3 =482.95 [Hz]	*Eigen disp. field* $f_4 = 863.2$ [Hz]	*Eigen disp. field* $f_5 = 1637$ [Hz]

Predictive modelling

- Build a predictive model of gas-dynamic and structural characteristics of the optimal geometry in various operational regimes:
  - 3 input parameters:
    - $5000\ [Pa] \leq P_{tot}^{in} \leq 20000\ [Pa]$
    - $100\ [C] \leq T^{in} \leq 300\ [C]$
    - $20\ [Hz] \leq \omega \leq 50\ [Hz]$
  - 9 output parameters:
    - $CFD\colon dP, Power$
    - $Structural\colon S_{eqv}, f_i\ , i \in [0,5]$



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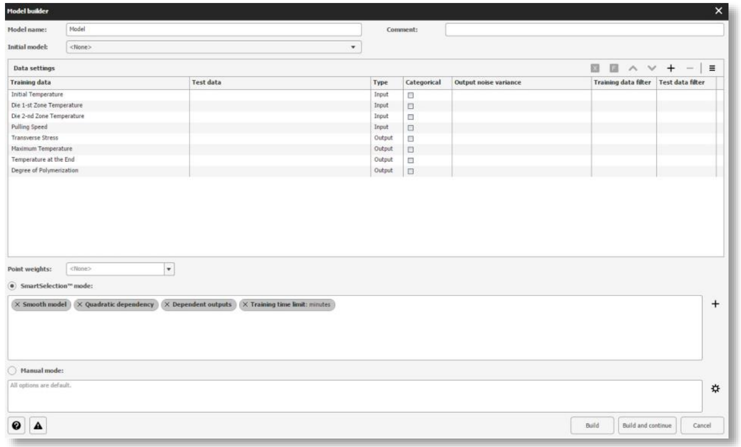
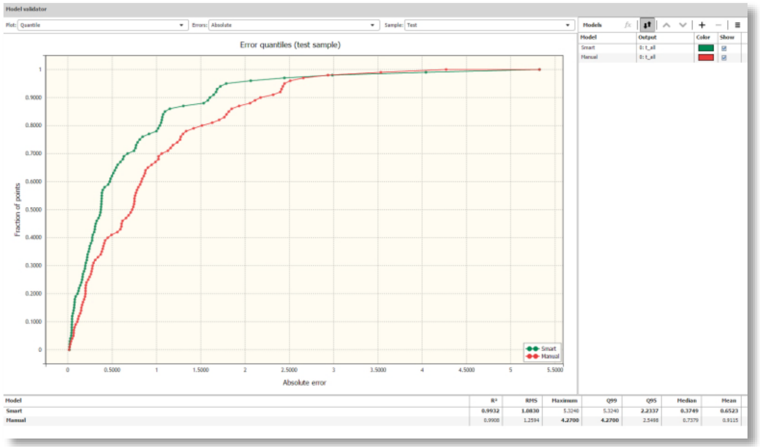
Tools for Predictive Modeling

pSeven includes a dedicated set of tools for building and managing predictive models that allows to:

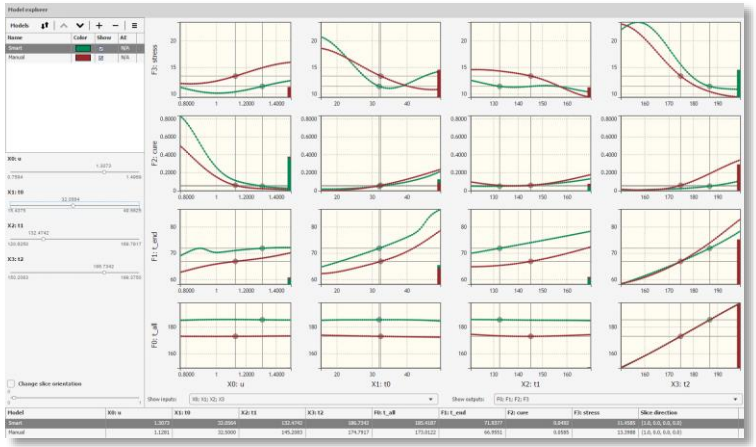
- Build fast and robust predictive models with automatic selection of technique (SmartSelection)
- Validate, test against reference data and compare models to find the best approximation quality
- Explore behavior of multidimensional models with studying input-output dependencies
- Export models to external file, including C source code, executable, Matlab/Octave, Excel and FMI



Model Builder



Model Validator

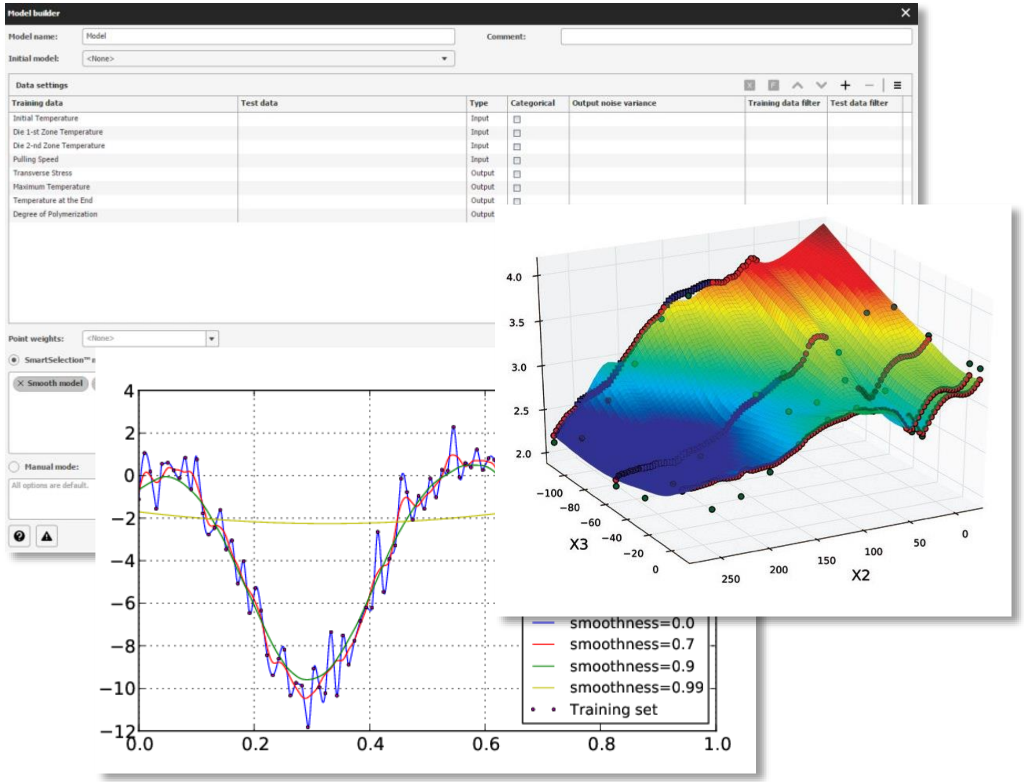


Model Explorer

Building Predictive Models

pSeven provides unbeatable capabilities and flexibility for building predictive models:

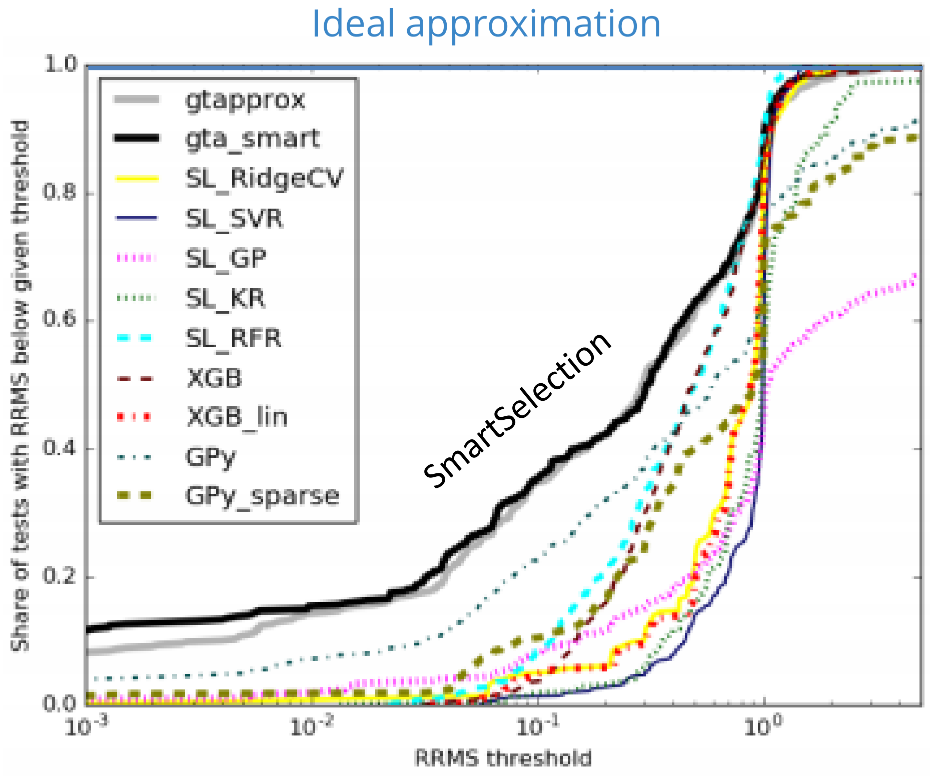
- Variety of industry-proven approximation techniques
- Full control of the model building time
- Accuracy and error estimation
- Dealing with oscillations and model smoothing
- Logarithm of outputs and exact fit
- Handling anisotropic data, discontinuities and inhomogeneous data, multi-fidelity data
- Updating existing models with new data & combining of the models



SmartSelection selects the most efficient technique for a given problem and data automatically!

Quality of predictive model built with SmartSelection:

- Even with default settings SmartSelection builds predictive models of better approximation quality than famous open algorithms, like Scikit-learn, XGBoost and GPy.

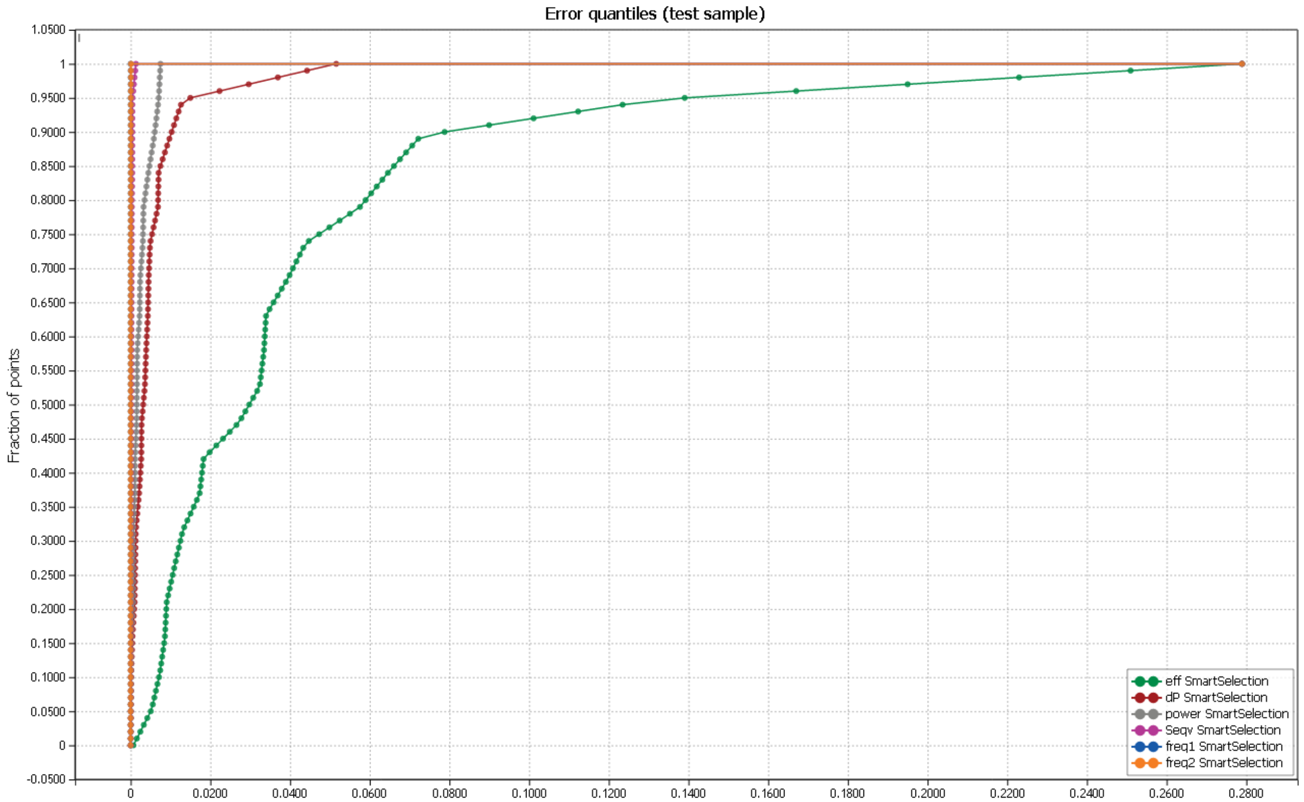


pSeven vs. open algorithms

Full benchmark can be found here: https://arxiv.org/abs/1609.01088

Surrogate model validation

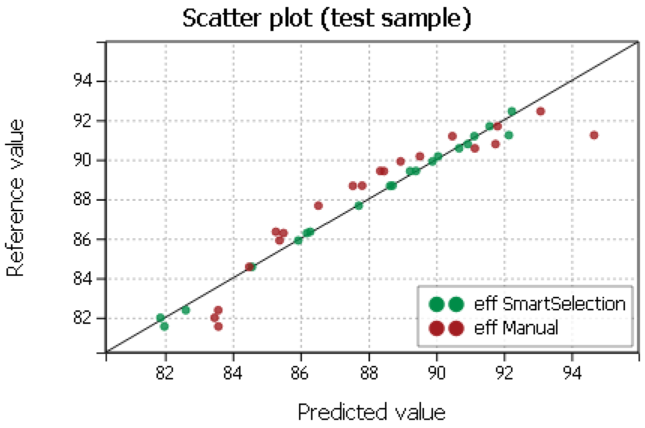
- Training sample: DoE with 30 designs was used to build the surrogate model
- Test sample: DoE with 20 designs
- The surrogate model allows to predict both CFD and structural responses with **RRMSE of <7%** (worst case)

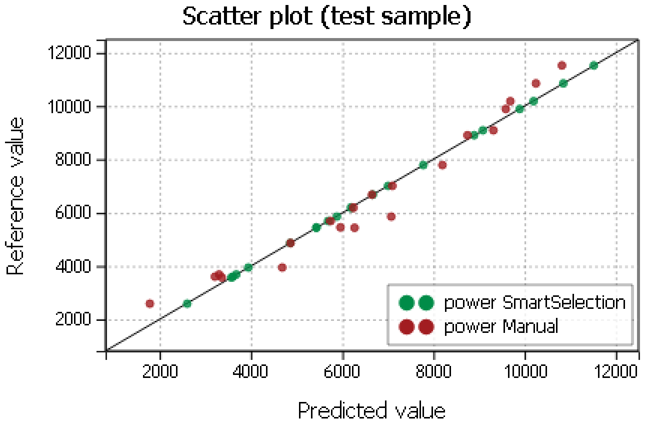


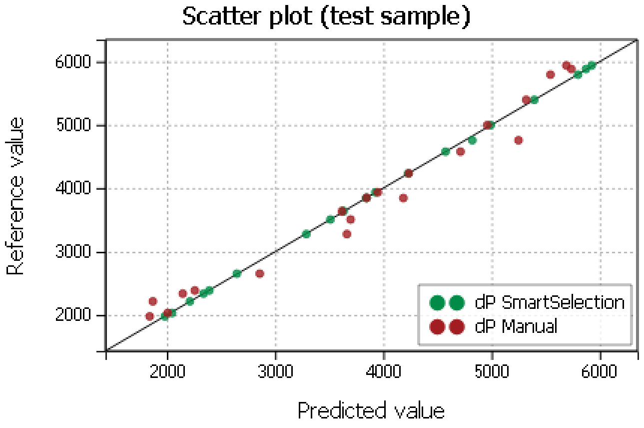
Model response	R^2	RRMS	Maximum	Q99	Q95	Median	Mean
eff	0.994	0.074	0.278	0.278	0.278	0.032	0.04534
dP	0.999	0.012	0.05	0.0515	0.051	0.0035	0.00607
power	0.999	0.003	0.0074	0.007	0.0074	0.0015	0.002260
Seqv	0.999	0.0003	0.0013	0.001	0.00138	0.00021	0.000254
freq1	0.999	3.88e-06	7.965e-06	7.965e-06	7.92e-06	3.24e-06	3.170e-06
freq2	0.999	3.10e-05	8.486e-05	8.486e-05	8.486e-05	1.74e-05	2.291e-05

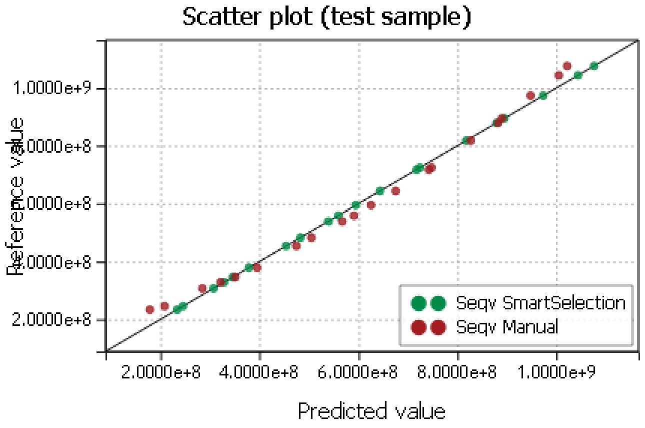
Surrogate model: Scatter plots

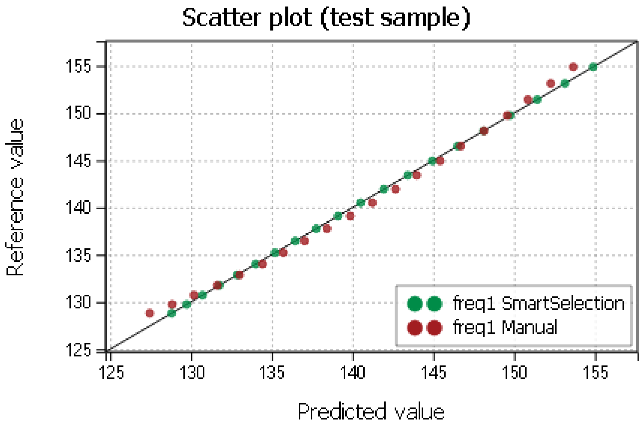
- Create more accurate Surrogate model using SmartSelection technology

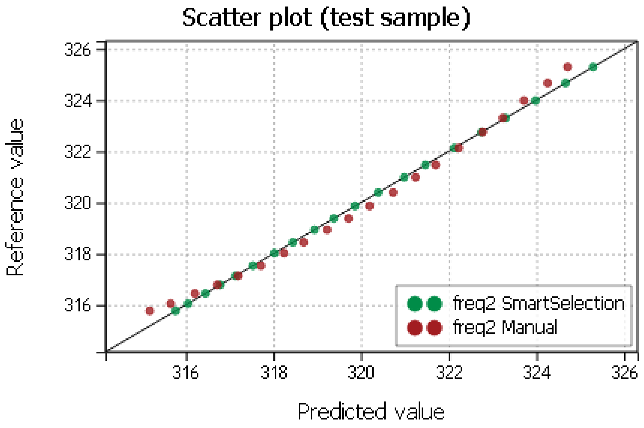












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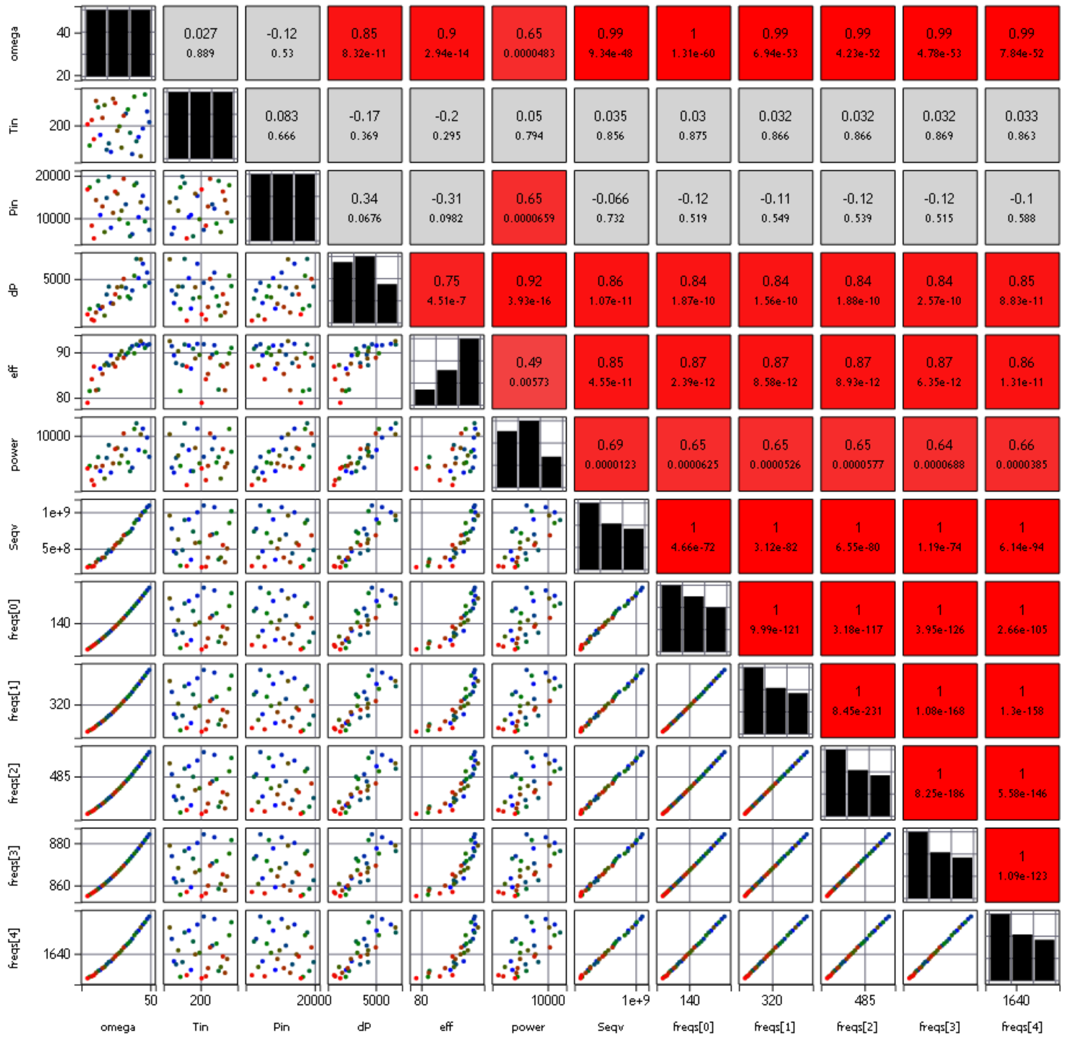
Surrogate model: Scatter plot matrix

- Analyze correlations between model responses and parameters using scatter plot matrix
- Detect linear and non-linear correlations
- Rate parameters influence



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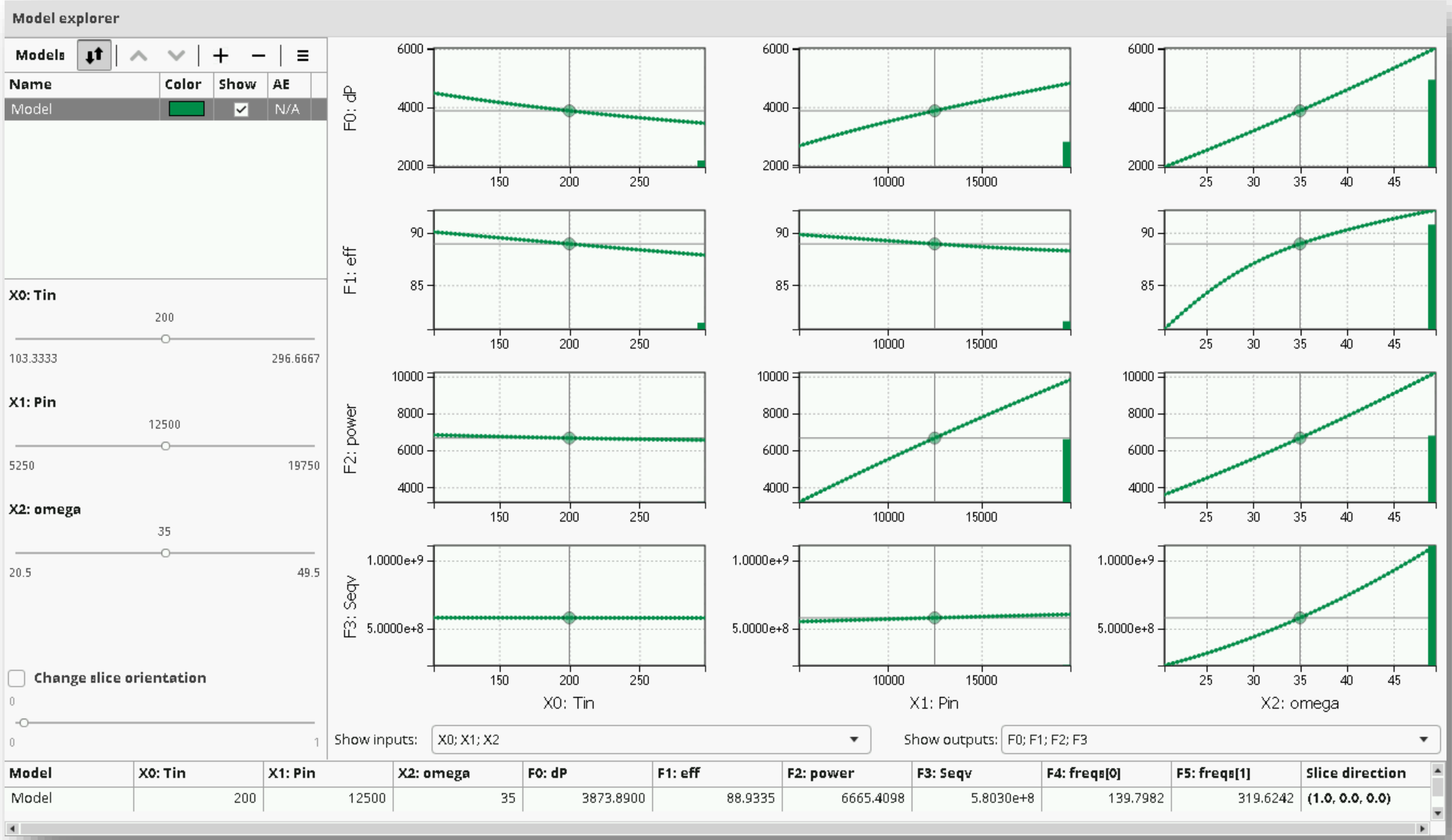
Surrogate model: Model Explorer

- Explore efficiency and safety on variety of operational regimes using Model explorer



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Summary

- Using the process integration capabilities provided by pSeven, we have managed to build a multidisciplinary workflow, which includes **8 CAD/CAE tools**: *Patran, Nastran, scTetra (Pre/Solver/Post), scConverter, BladeGen,* and *Turbogrid.*

- The result is a **run-ready workflow** for simultaneous calculation of turbine blade efficiency (CFD, Cradle) and preloaded eigenfrequencies (Structural Analysis, Patran/Nastran).

- pSeven's advanced workflow engine enabled the implementation of nested optimization loops in the workflow.

- The problem of blade optimization, frequency tuning and maximum stress reduction was solved in automatic mode.

- For rapid estimation of gas-dynamic and structural characteristics in non-nominal operating modes, an automatically trained surrogate model was used.

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info@datadvance.net

42 Avenue du Général de Croutte, 31100, Toulouse, FRANCE
Tel.: +33 (0)6 03-84-62-92

Nauchny proezd 17,
15 floor, 117246, Moscow, RUSSIA
Tel.: +7 (495) 669-68-15

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