Multi Objective Optimisation of an aeronautical vaporizer by coupling of Genetic Algorithms and CFD techniques

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Presentation Outline

- **EST - Fiatavio Research Programme**
- **Optimisation concepts and strategy**
  - DOE, MOGA, RSM, ANN
- **Basic CFD problem, design and logic setup**
  - Vaporiser initial run
  - Parametrisation
  - Design setup and logic
- **DOE and MOGA screening**
  - SOBOL screening
  - MOGA high mutation generations
- **MOGA and RSM optimisation**
  - Response surface fitting
  - MOGA and RSM blending Runs
- **MCDM final design**

RESEARCH PROGRAMME

- **Partners: Engin Soft Trading CAE company, FIATAVIO aerospace, University of Trieste**
  - Develop a programme to link CFD techniques and optimisation techniques.
    - needing the exploration of a **wide range of variability** for the design parameters
    - **involving several aspects** (MULTIDISCIPLINARY)
    - with **several**, may be conflicting, **objectives (MULTIOBJECTIVE)**
    - **respecting the "computation budget"** available for problems involving high CPU demands ie. 3D RANS CFD
  - Develop parametric test models:
    - gas turbine rotor blade
    - shroud sealing flows
    - fuel vaporiser (Fiatavio supplies a typical vaporiser design to be optimised within the framework of technological innovation of the combustor product)

Optimisation

- **Optimisation techniques can roughly be divided in three classes**
  - screening techniques: DOE (Design Of Experiment) methods which are intelligent ways to minimize the experiments getting the maximum of information out of them
  - Gradient or Genetic Algorithm techniques to:
    - find the optimal solution on a N-dimensional surface with gradient methods
    - find the optimal solution after N-generations of genetically selected experiments
  - Interpolating techniques
    - Finding optimal solution without running CFD analysis, but on an interpolating surface of previously run solutions: RSM (Response Surface Method)
    - Finding optimal solution without running CFD analysis, but on an interpolating neural network of transfer functions between input parameters and output objectives: ANN (Artificial Neural Networks)

FRONTIER Product Properties

- ALL platforms are supported
  - Browser based technology
  - JAVA,CORBA,XML)
- Capability of handling any computing services
  - files or API (Application Protocol Interface) …
  - from CFD to MS-EXCEL
- Optimisation Algorithms
  - Multi-Objective Genetic Algorithm,
  - Simplex
  - Gradient based methods
  - DOE (Design of Experiments)
  - RSM
  - ANN
- Decision Support tools
  - Pareto Filters
  - MCDM
  - Statistical charts
  - Parallel charts
- The order of magnitude is:
  - 100 analysis automatic analysis for typically 20 variables, 3 objectives, 3 constraints
- FRONTIER allows the user to extract the maximum of information allowed by the user-defined CPU budget

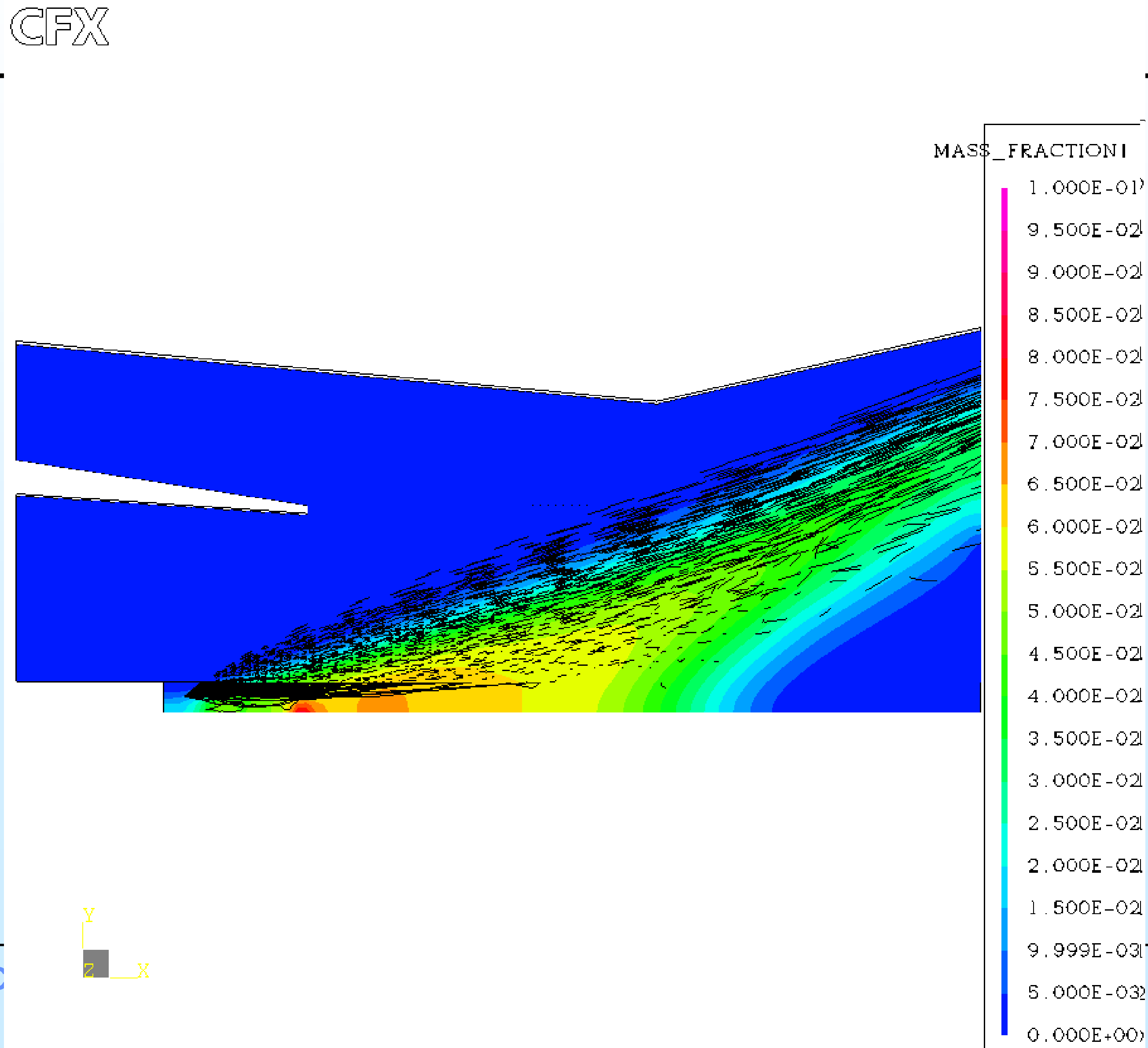
Basic CFD

- **Set up in CFX4.3:**
  - **geometry 3d in cylindrical coordinates**
  - **fully compressible model**
  - **mass fraction 1 for vaporised fuel**
  - **mass fraction 2 for recirculating products from combustor can**
  - **lagrangian tracking for particle phase**
  - **spray model employed with turbulent dispersion**
  - **Reynolds Stress Model for turbulence**
  - **Two numeric procedure to guarantee convergence**
    - **15 X 100 it with k-epsilon**
    - **15 X 100 it with RSM but restart from K-epsilon**
  - **100 maximum down to 50 minimum fluid iterations for each particle coupling, dynamically set by USRCVG**

Basic CFD

- Boundary conditions
- Inlet 1
  - T = 900 Kelvin
  - Air mass flow = 40% total
  - Swirl angle = 40 degrees
- Inlet 2
  - T = 900 Kelvin
  - Air mass flow = 60% total
  - Swirl angle = 40 degrees
- Atomiser (fuel droplet inlet)
  - SMD 45 microns
  - Rosin Rammler exponent 3.0
  - Fuel/Air mass flow ratio = 5.0%

Basic CFD


CFX
MASS_FRACTION
1.000E-01
9.500E-02
9.000E-02
8.500E-02
8.000E-02
7.500E-02
7.000E-02
6.500E-02
6.000E-02
5.500E-02
5.000E-02
4.500E-02
4.000E-02
3.500E-02
3.000E-02
2.500E-02
2.000E-02
1.500E-02
9.999E-03
5.000E-03
0.000E+00
Y
Z
X

Design Problem

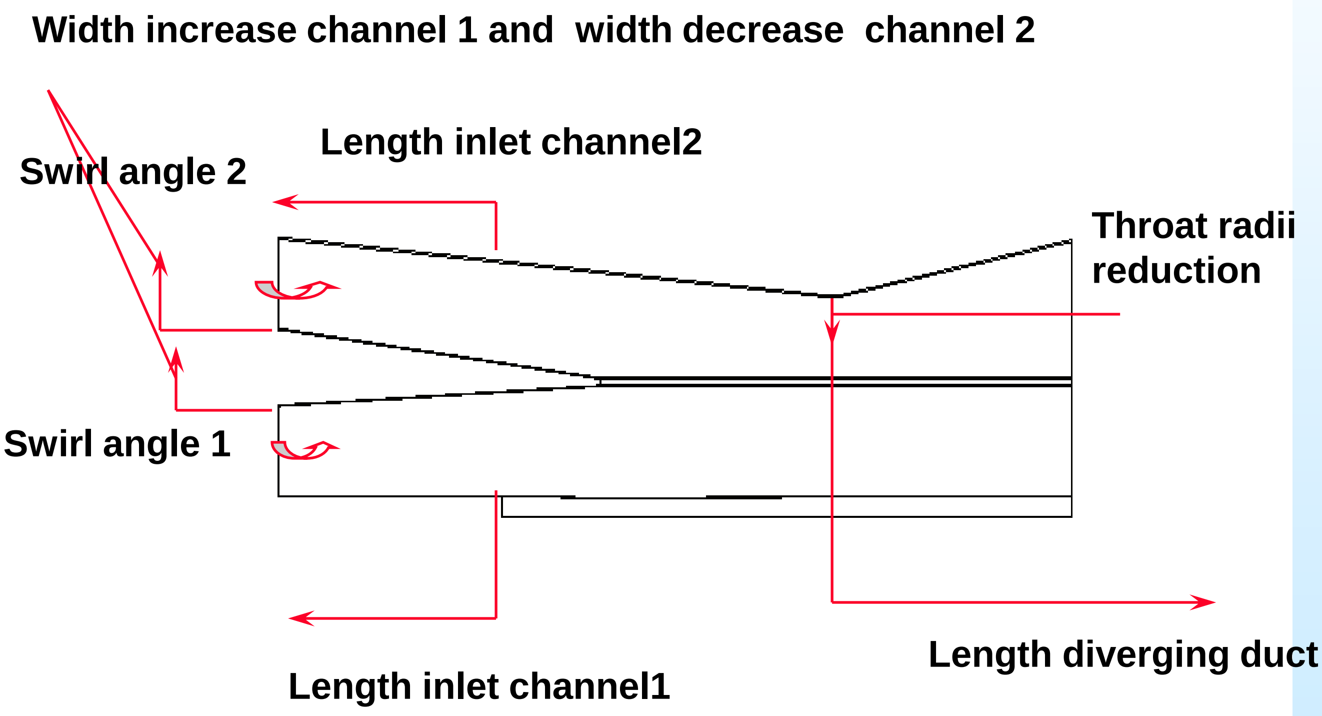
- The basic fuel vaporiser must be improved:

  - inlet air and fuel mass flow are given
  - inlet swirl angles and air mass ratios are free
  - dimensions are limited

  - pressure drop must be minimised
  - recirculation must minimised
  - fuel vaporisation must be maximised
  - length must be minimised

  - recirculating combustion products must not go upstream the throat
  - swirl number at exit is set to combustor requirements $Sw_{no}=0.50$
  - convergence must be obtained

Design Problem



ENGIN SOFT

Design Logic

FRONTIER

Input parameters

	Definition	Original	Minimum	Maximum
L1	Length channel 1	7.0	2.0	15.0
L2	Lengtht channel 2	7.0	2.0	15.0
B1=-B2	Increase Width channel 1 = decrease width cahnnel 2	0.0	0.0	5.0
Delta R1	Throat radius reduction	0.0	0.0	3.0
Length	Length diverging duct	15	10	30
Alfa1	Swirl angle channel 1	40.0	10	80
Alfa2	Swirl angle channel 2	40.0	10	80

Note: b1 and b2 change the area hence the mass flow rate ratios from the pressure plenum

Design Logic

The basic idea is illustrated in the following chart:

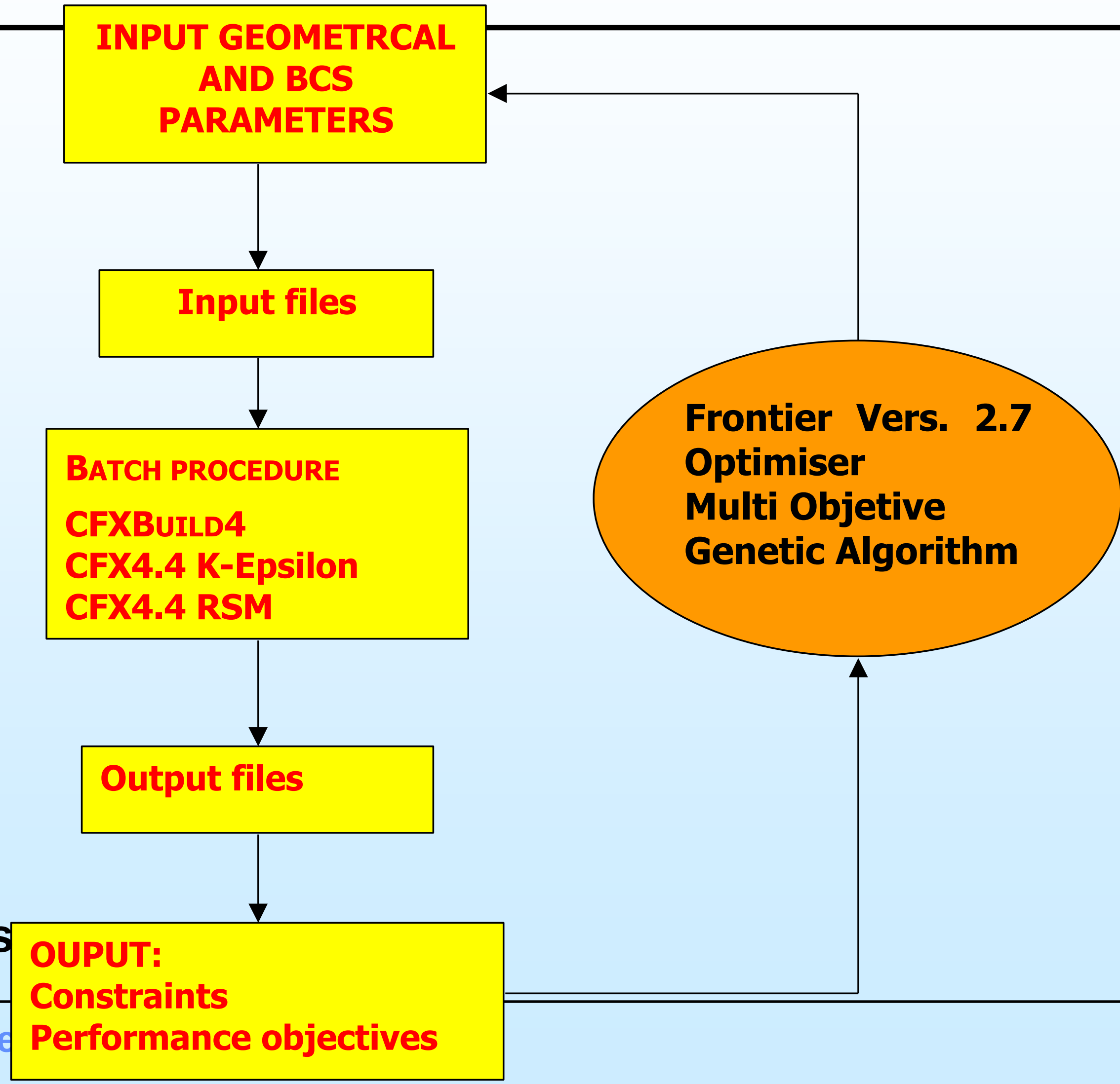
Logic Setup in Frontier2.7
Parametric input

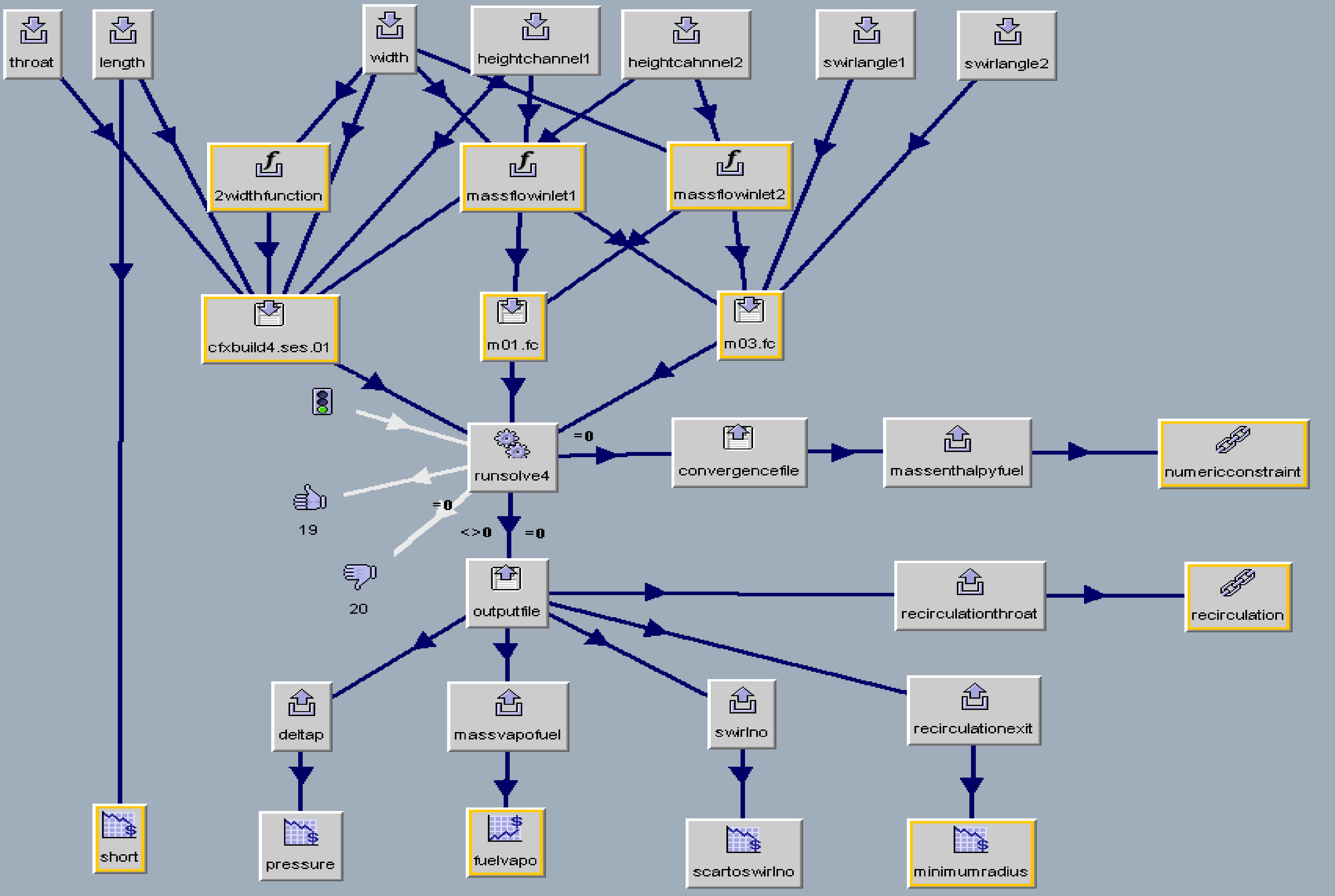
File input handling

Batch procedure

File output handling

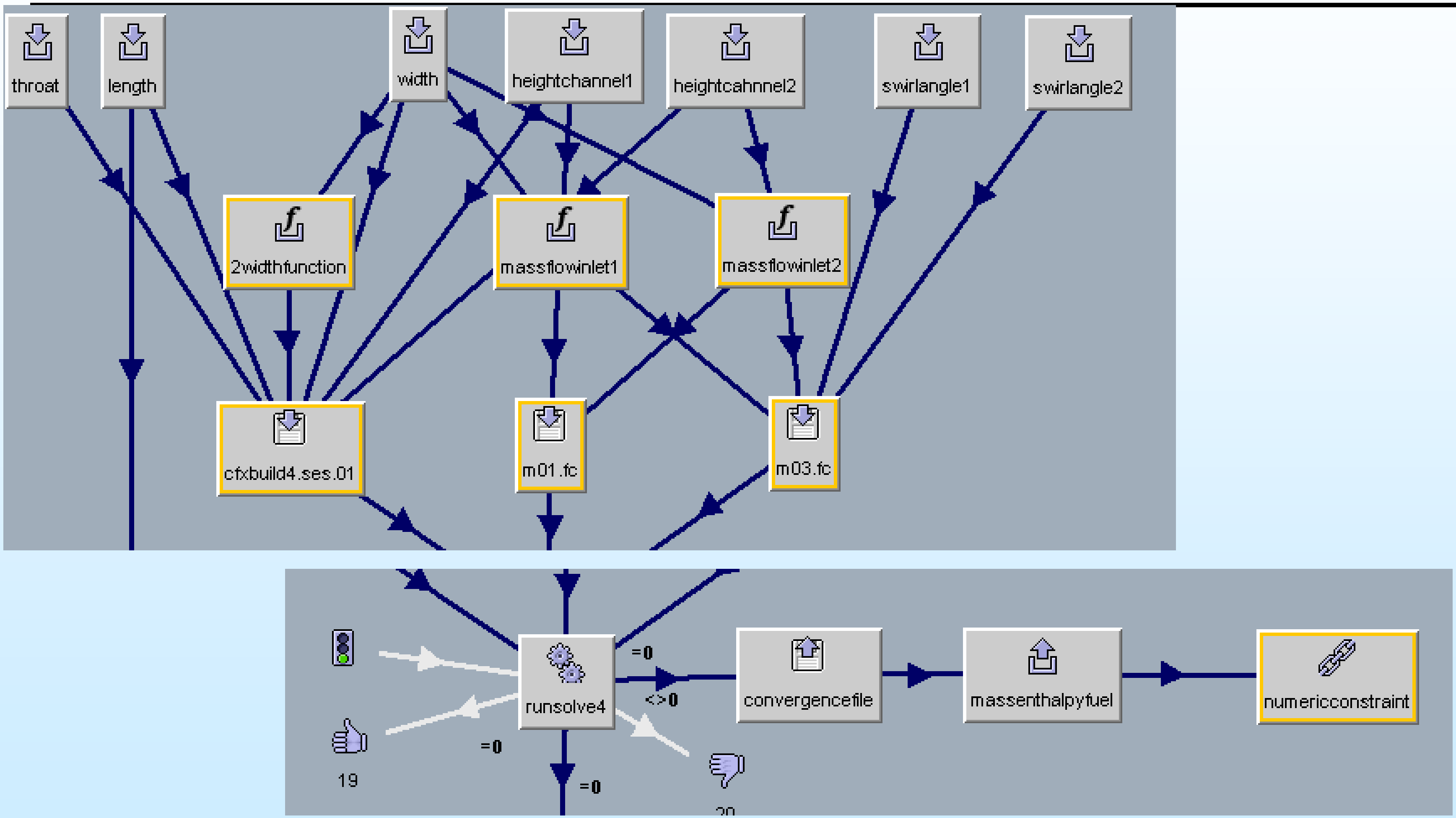
Output feedback-parameters





throat
length
width
heightchannel1
heightcahnnel2
swirlangle1
swirlangle2
2widthfunction
massflowinlet1
massflowinlet2
cfxbuild4.ses.01
m01.fc
m03.fc
runsolve4
=0
convergencefile
massenthalpyfuel
numericconstraint
19
=0
<>0
=0
20
outputfile
recirculationthroat
recirculation
deltap
massvapofuel
swirlno
recirculationexit
short
pressure
fuelvapo
scartoswirlno
minimumradius

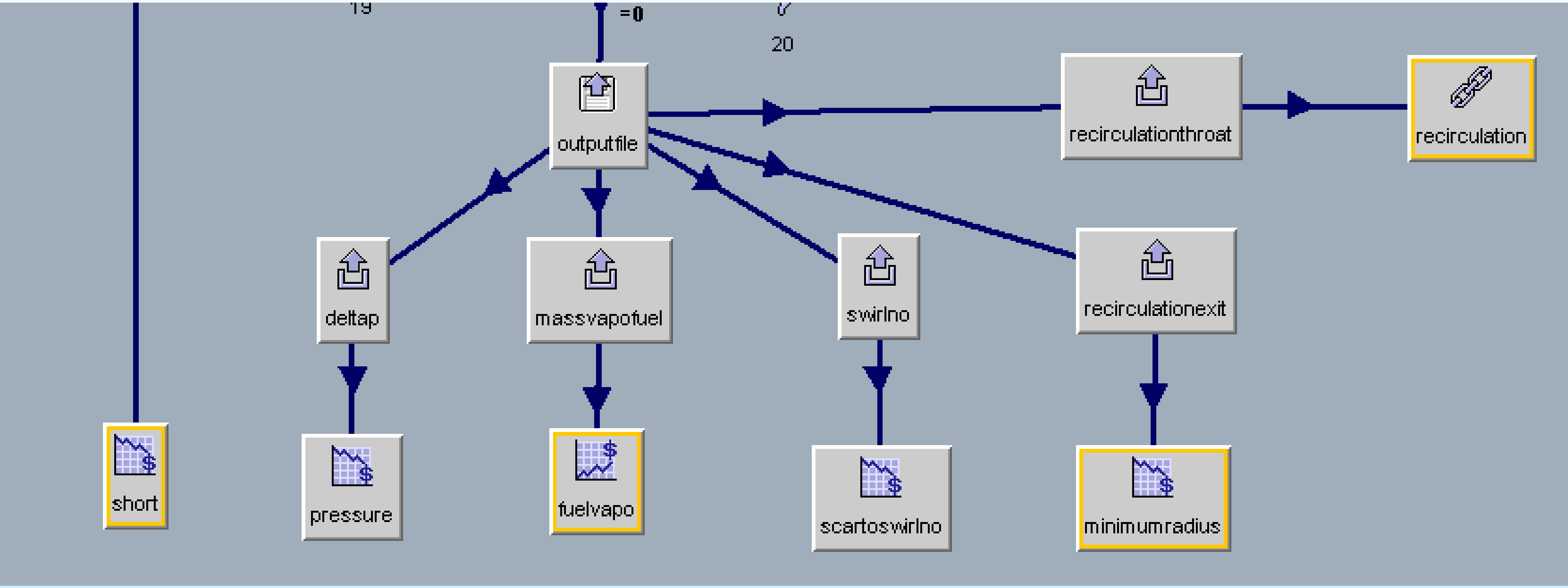
Design Logic



Design Logic

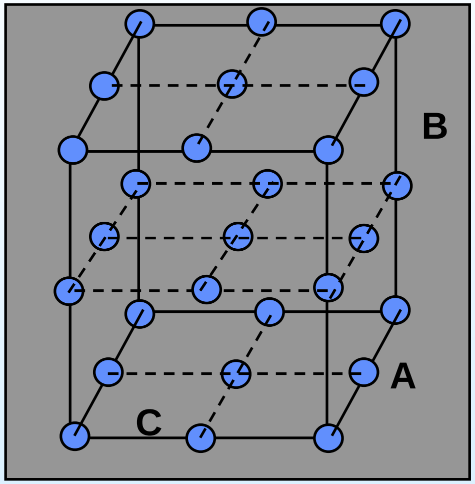
```
# ! /bin/sh
cp /users/engin/FRON/inizio_copiami.db ./inizio.db
cp /users/engin/FRON/m01.f .
runbuild4 -b -sfp cfxbuild4.ses.01
mv *geo* m01.geo
runmi -cylaxis -fe m01.geo
rm m01.geo inizio.db*
mv *geo* m01.geo
rm setting* volm* cfxbuild4.ses.02
runsolve4 -f m01.f -c m01.fc -g m01.geo -enviro 01
runsolve4 -f m01.f -c m03.fc -g m01.geo -r m01.dmp -enviro 03
cp ./m03.dir/param .
cp ./m03.dir/CONVERGENZA .
rm -r m01.dir m03.dir m01.fo *.trk m01.dmp *.log file*
compress *.*
```

Design Logic

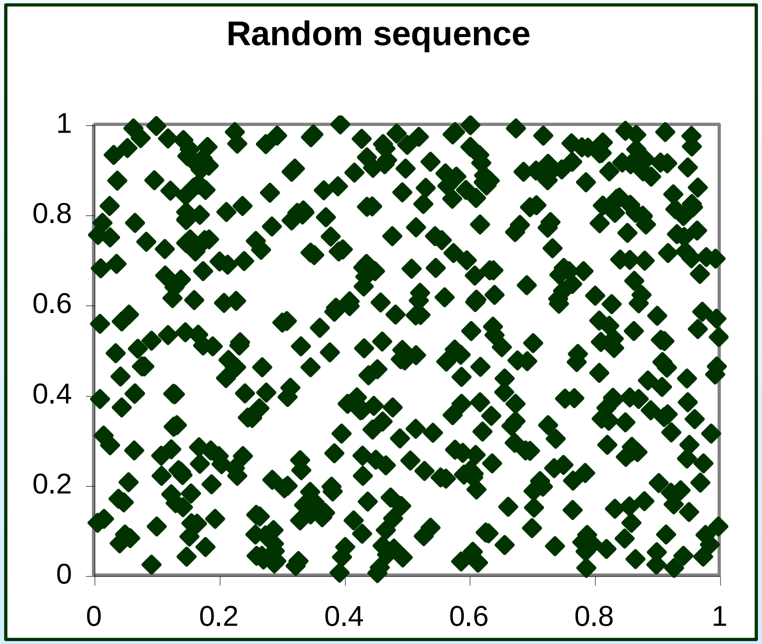


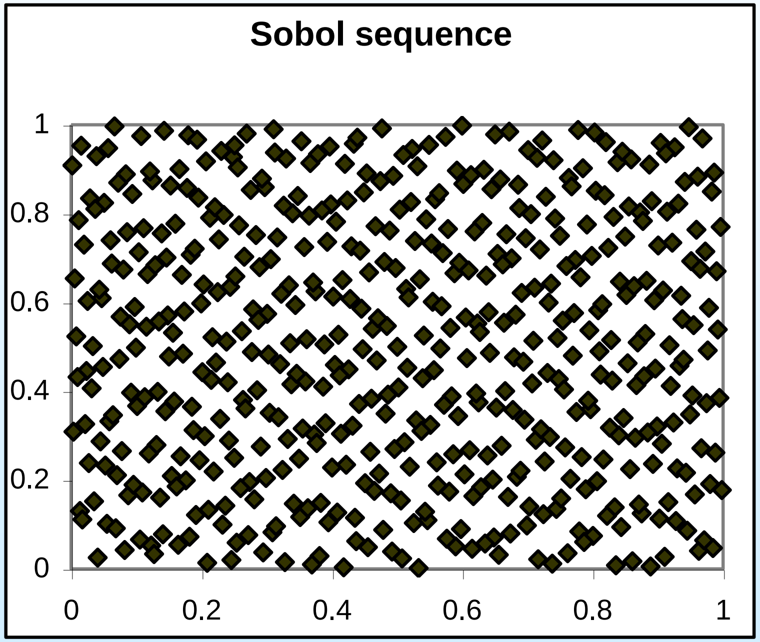
Initial Screening

- **DOE**
  - with 7 input parameters running a 3 level full factorial DOE (min, med,Max) would mean 3^7=2187 experiments!!!!! Or CFD analysis!!!
- **DOE reduction methods**
  - Box-Benhkem
  - Taguchi
  - MonteCarlo
  - Random
  - SOBOL (a uniform Random)



Initial Screening





Initial Screening

SOBOL

- In a 7 input parametric space with 5 objectives, needs 40-50 experiments for just a basic screening

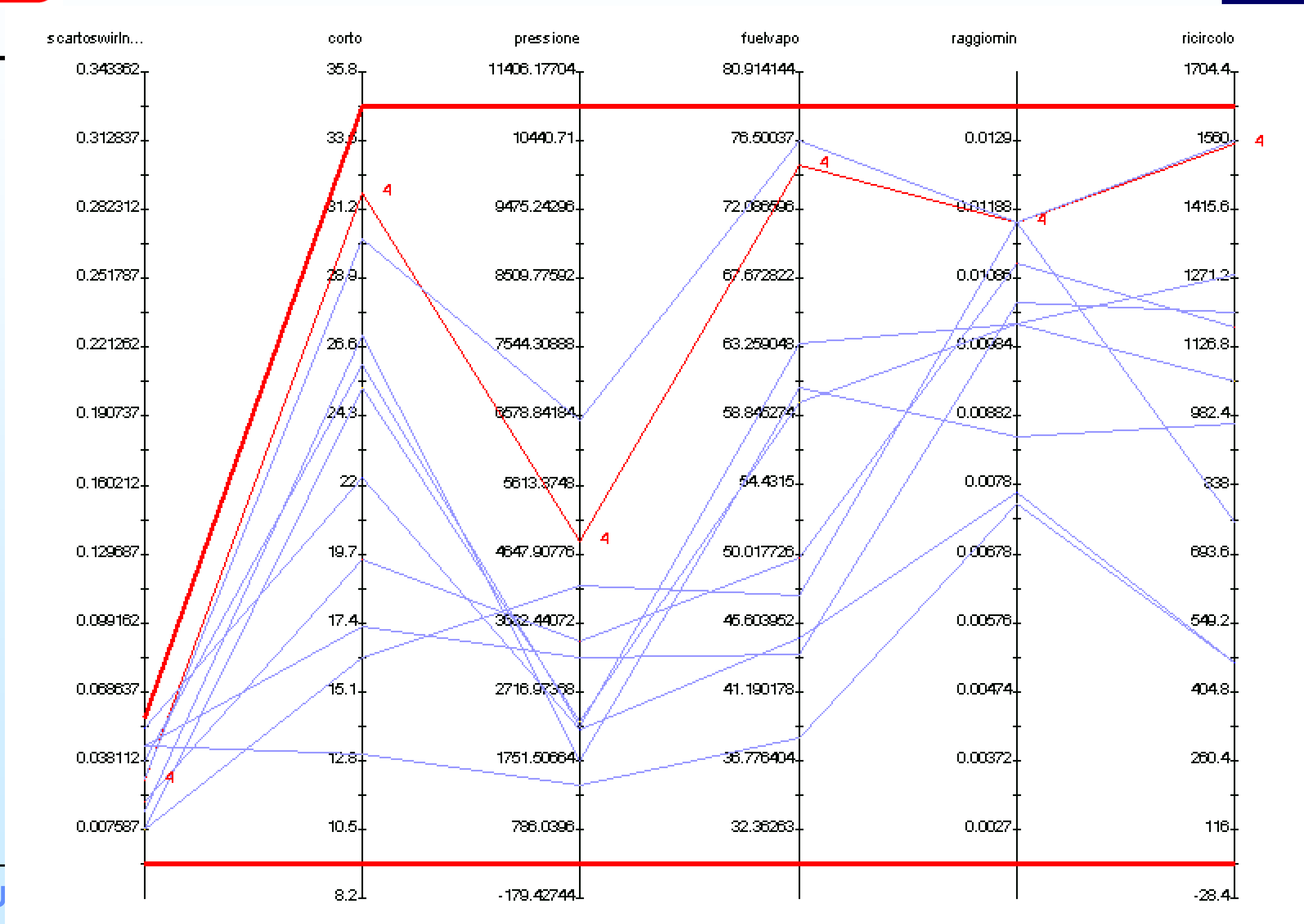
MOGA

- Multi Objective Genetic Algorithm searches for optimal solution after N-generations of genetically selected individuals by:
  - selection
  - cross-over
  - mutation

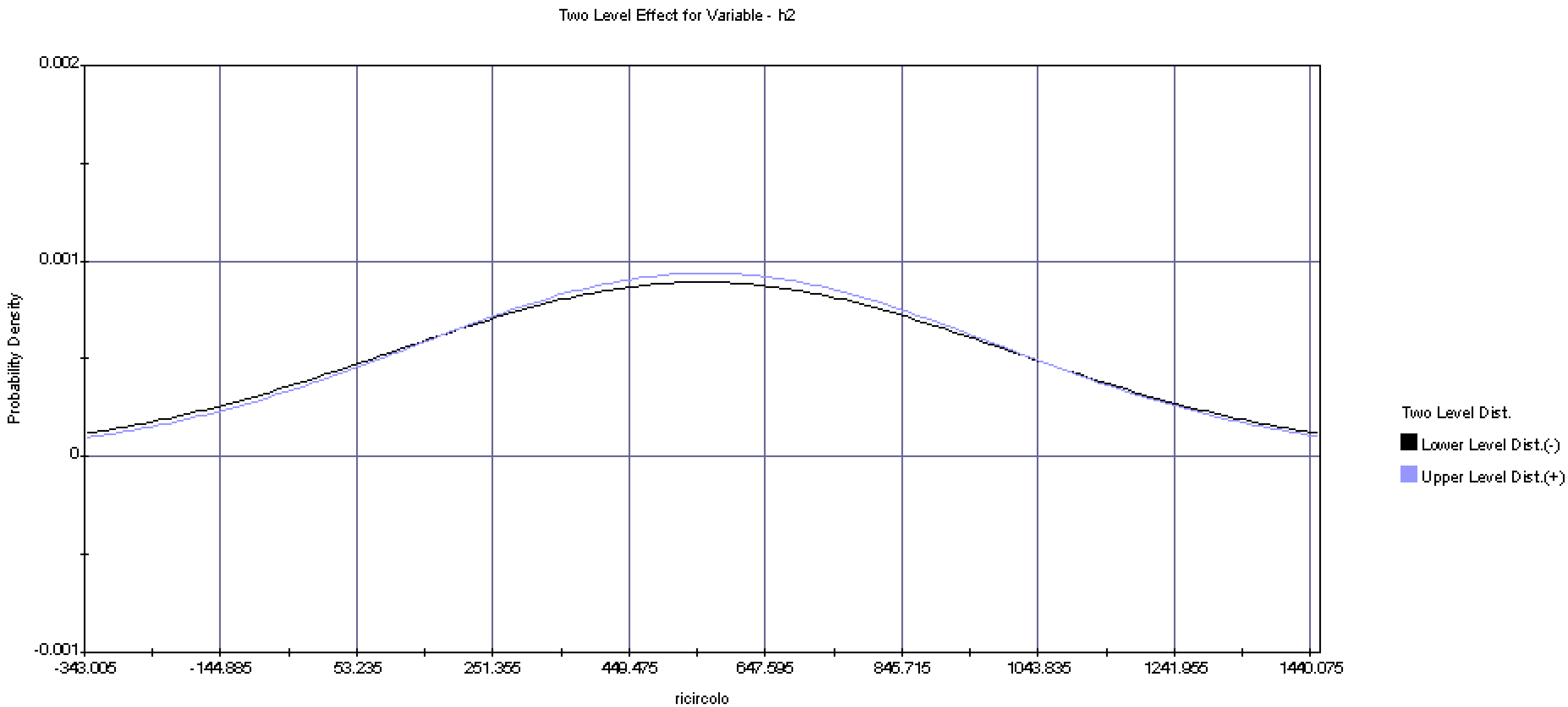
SOBOL and MOGA

- A first generation of 20 experiments (CFD analysis) is produced “randomly” in a SOBOL sequence
- MOGA runs 3 generation with high (respect to standard) mutation coefficient: 30%, hence 6 out of 20 experiments mutate each generation
- Total of 80 experiments are run: 20 are screening randomly, the other 60 evolute toward the optimal solutions with a mutation for 18 experiments

Initial Screening



Initial Screening



Level Moments				Student Parameters			
n-	39	n+	33	delta	6.569E0	mean std.dev.	1.034E2
mean-	5.555E2	mean+	5.620E2	t-Stud.	6.355E-2	significance	5.129E-2
std.dev-	4.47E2	std.dev+	4.249E2				

Shift + Drag Mouse to Zoom. Press 'r' to reset. Click on line to mark.

Final Optimisation

Parameter reduction

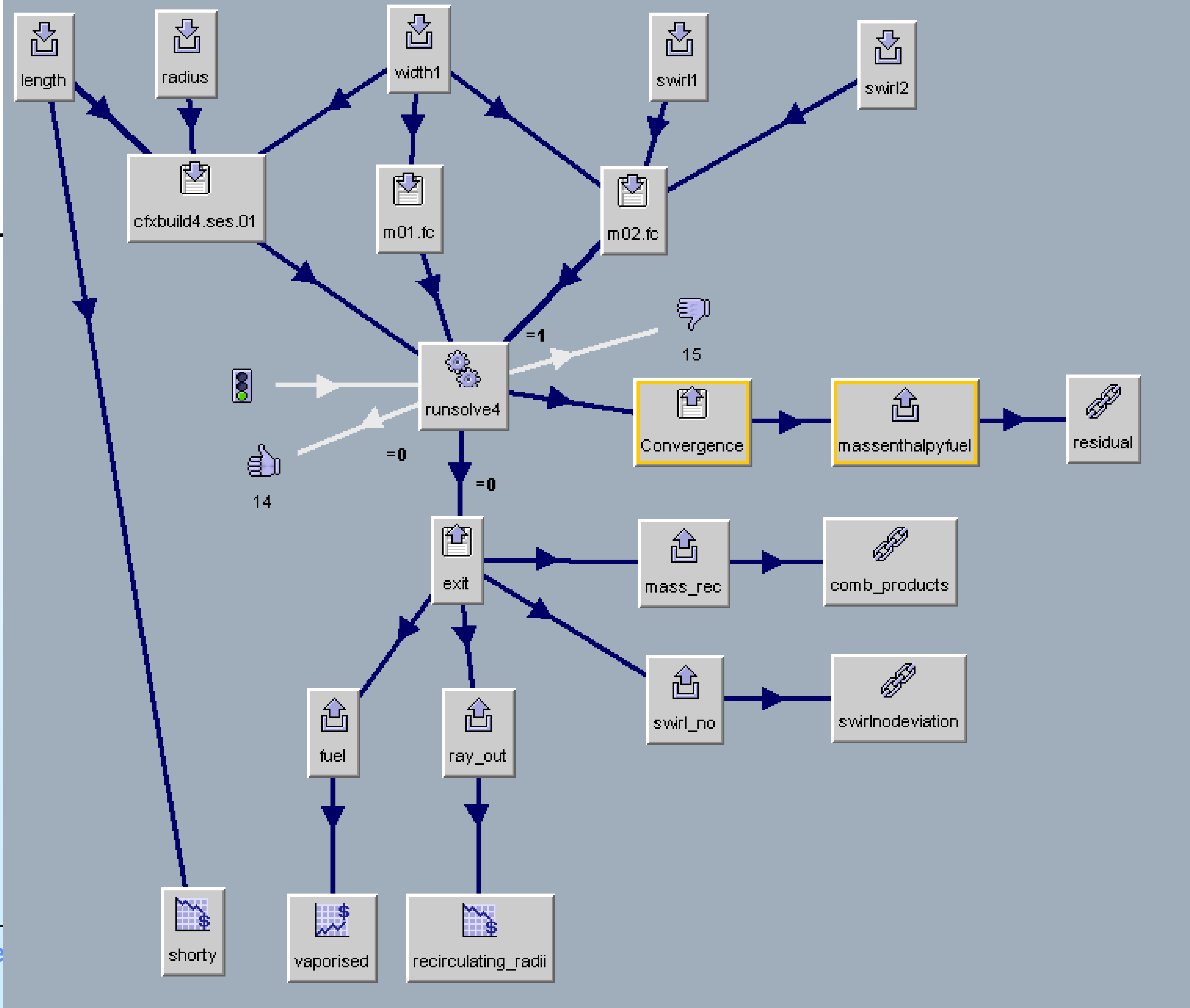
- The length of the inlet channels are fixed, since they do not heavily influence the output.
- Pressure loss is not considered an objective, since the pressure requirements can always be satisfied.
- The length parameter is extended to 50 mm
- Swirl number deviation is changed into a constraint
- 2 input parameters and 1 objective are eliminated
- Logic is reduced

RSM

- Response surface is fitted and trained to reduce CPU time

Multi Criteria Decision Method - post-processing

- MCDM functions are introduced to postprocess the final design
- weight of 3 objectives to obtain a single objective


length
radius
width1
swirl1
swirl2
cfxbuild4.ses.01
m01.fc
m02.fc
=1
15
runsolve4
Convergence
massenthalpyfuel
residual
=0
=0
14
exit
mass_rec
comb_products
fuel
ray_out
swirl_no
swirlnodeviation
shorty
vaporised
recirculating_radii

RSM - MOGA

MOGA RSM Blending

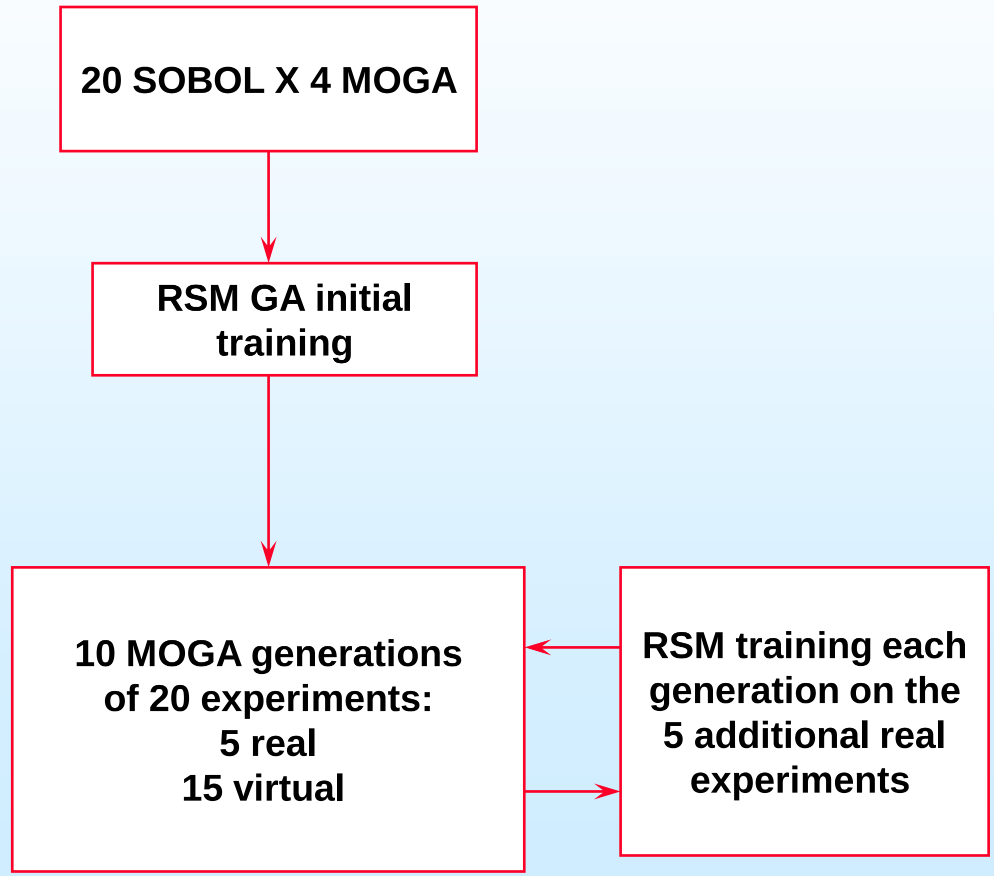
- The final optimisation is run on a blend of:
  - 75% RSM virtual
  - 25% MOGA real experiments

MOGA setting

- 4 generations of 20 experiments

RSM blend

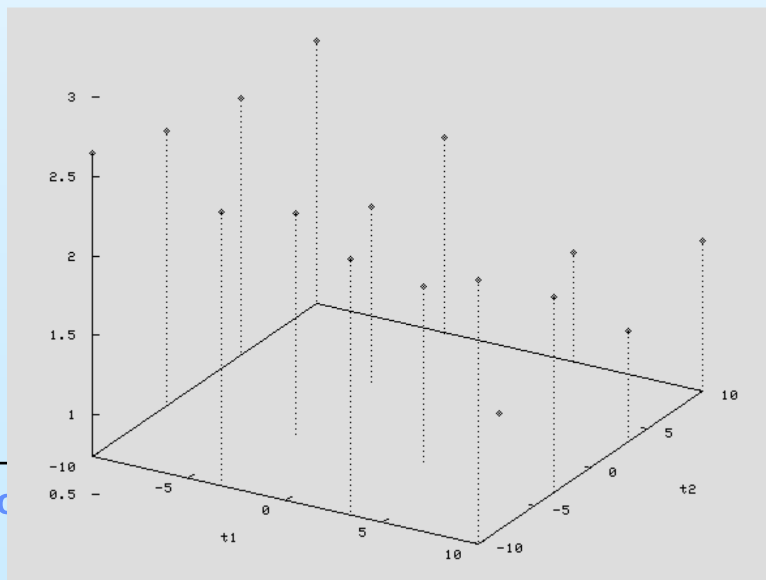
- 10 generations of 20 experiments
  - 50 real
  - 150 virtual
- is re-trained and updated each generation
- Total CPU time is reduced of 50%

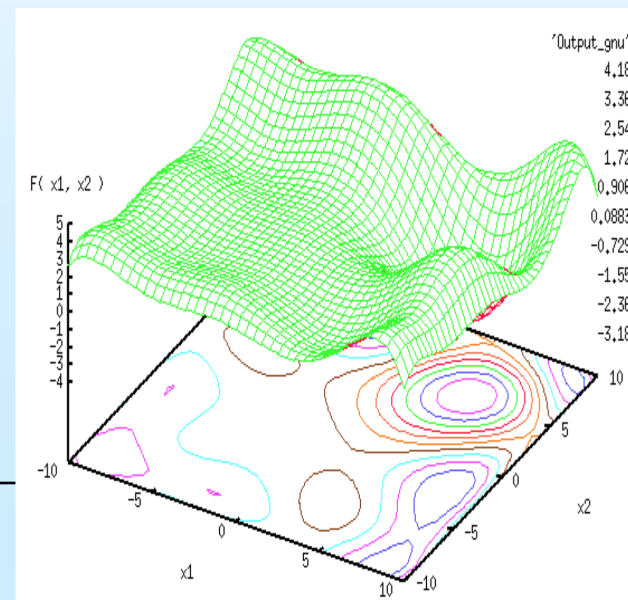


RSM Fitting

RSM

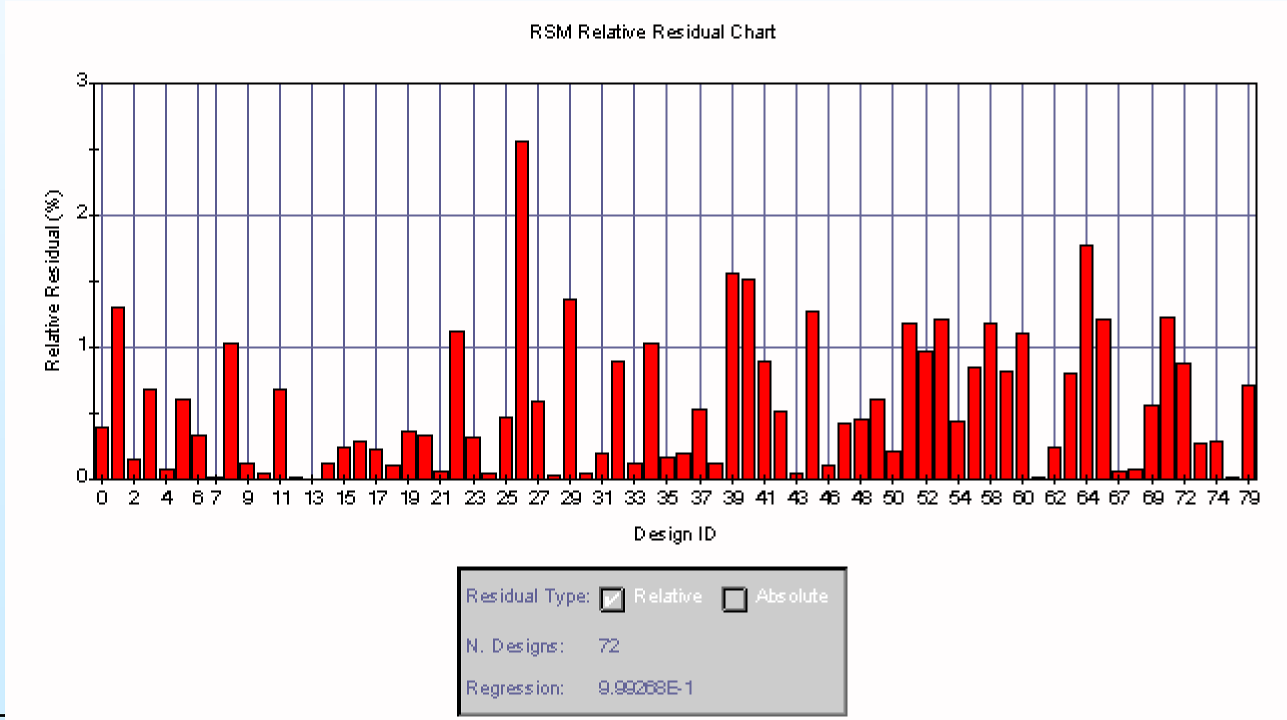
- On the 80 experiments SOBOL-MOGA, a response surface is fitted so that experiments can be performed virtually on the N -dimensions response surface instead of going through an explicit CFD run
- Basically an experiment on a RSM has CPU time of less than 1 sec while the average CFD run takes 90 minutes:
  - Advantage: ENORMOUS CPU TIME SAVING
  - Disadvantage: Response Surface must have low errors and virtual results (if chosen)must be validated by CFD



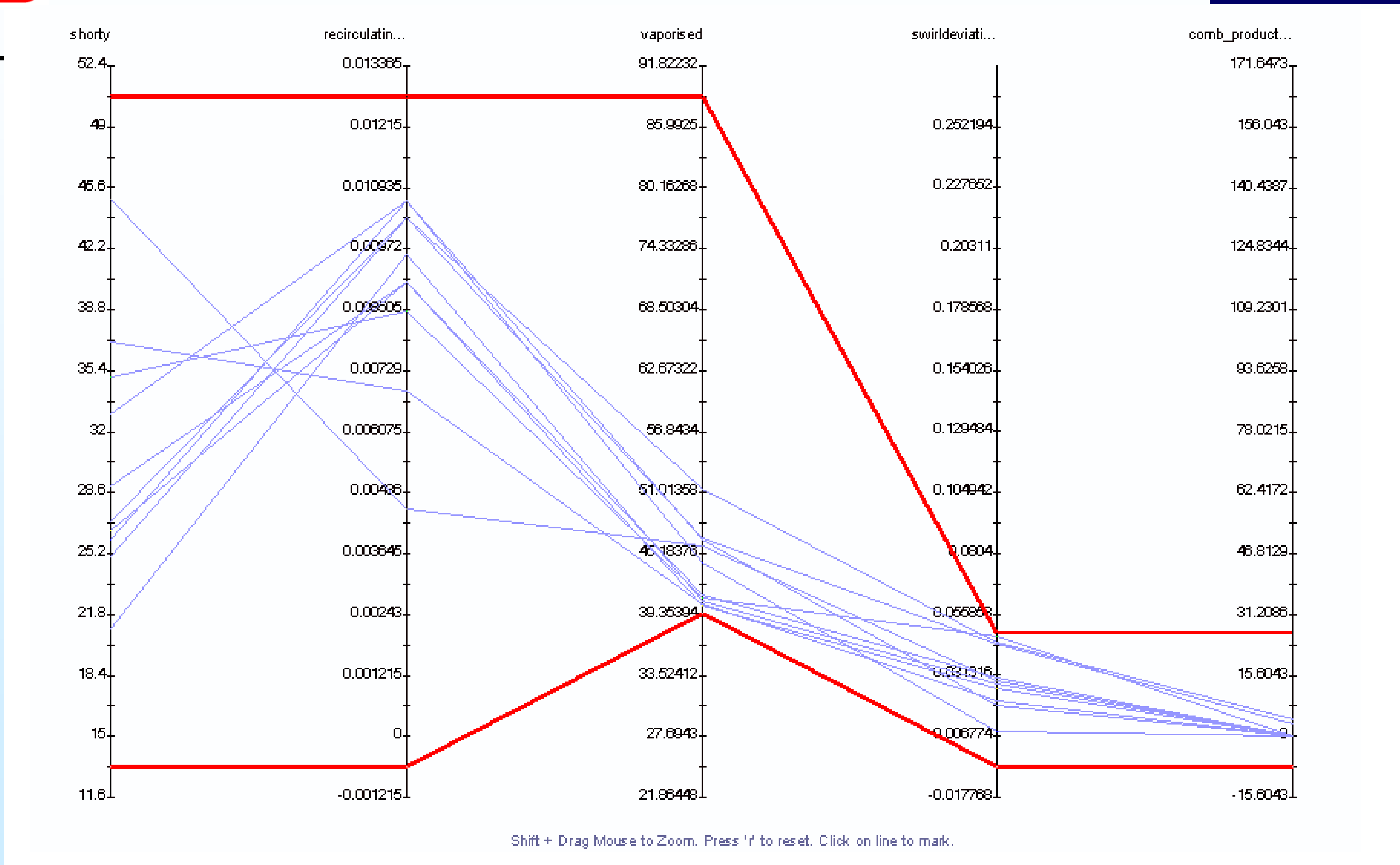


RSM Confidence

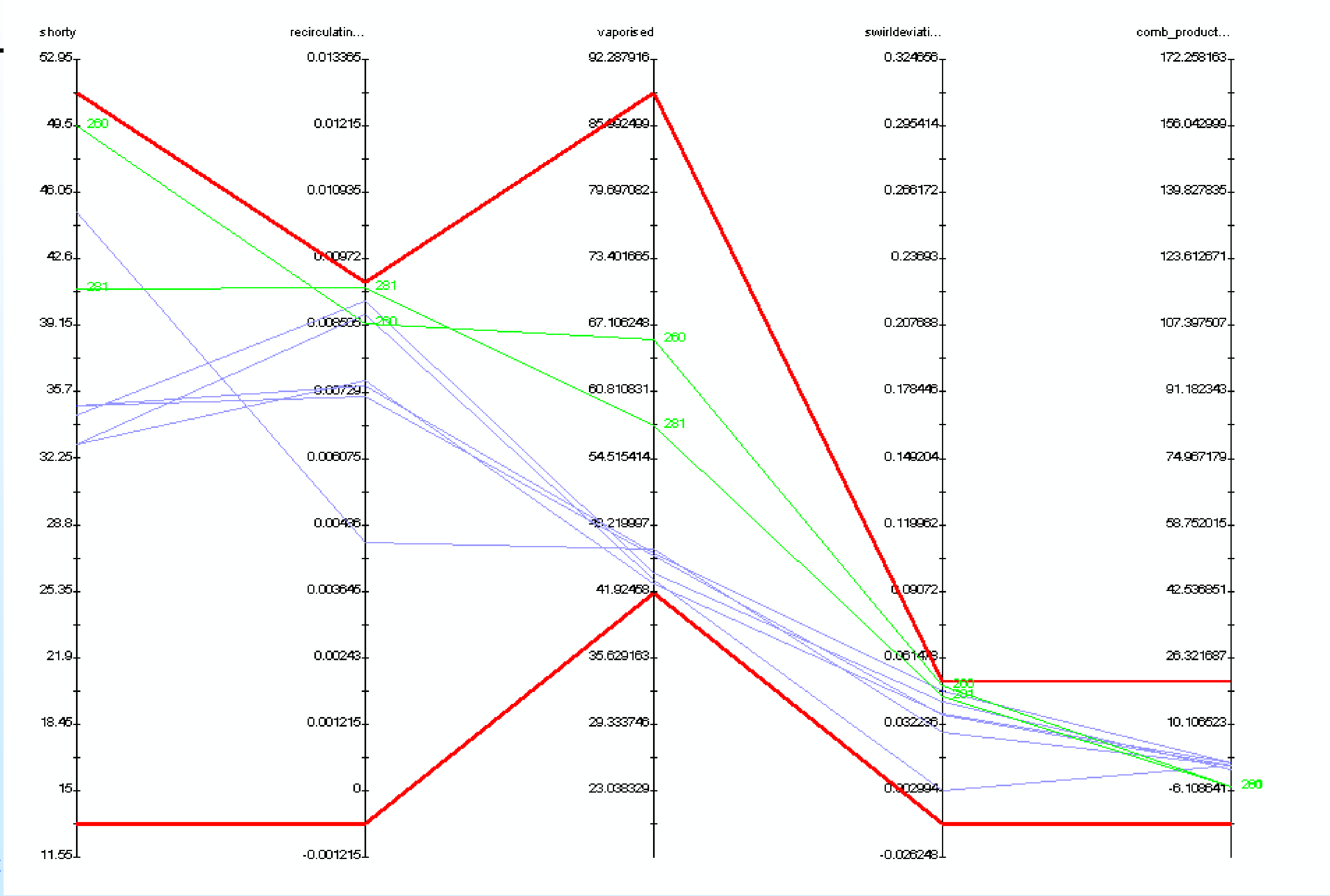
- **RSM**
  - a fitting is performed by gaussian interpolation
  - the errors are checked on all real experiments
  - sample surface on %fuel vaporised at 4th generation



Parallel Chart Convergence



Parallel chart postprocessing

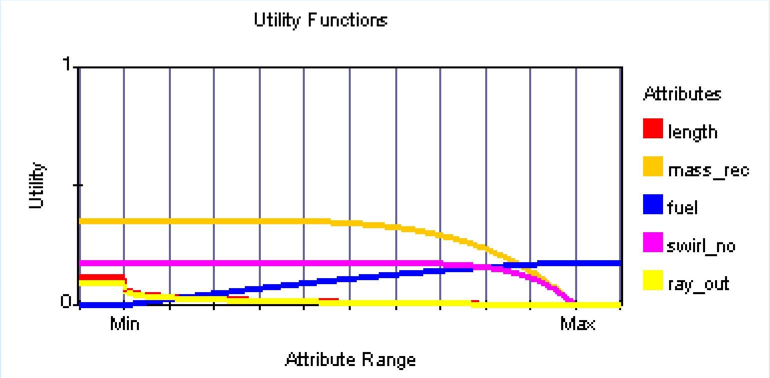


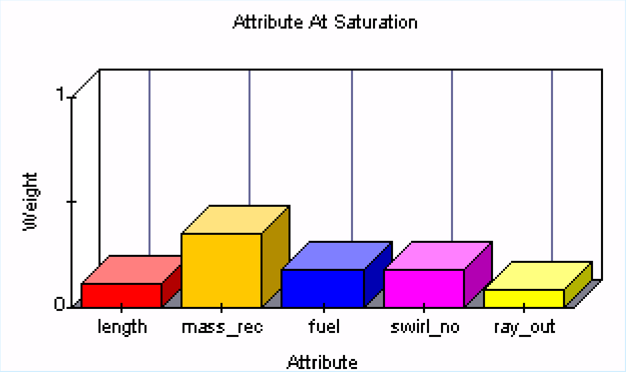
MCDM Postprocessing

- **Weights are introduced for each output variable**

Marked	First Attribute	Type	Weight	Second Attribute
☑	swirl_no	greater than	2.0	ray_out
☑	fuel	greater than	1.5	length
☑	swirl_no	equal to	1.0	fuel
☑	mass_rec	greater than	3.0	length

- **Non linear weighing functions are computed**





MCDM postprocessing

Design ranking

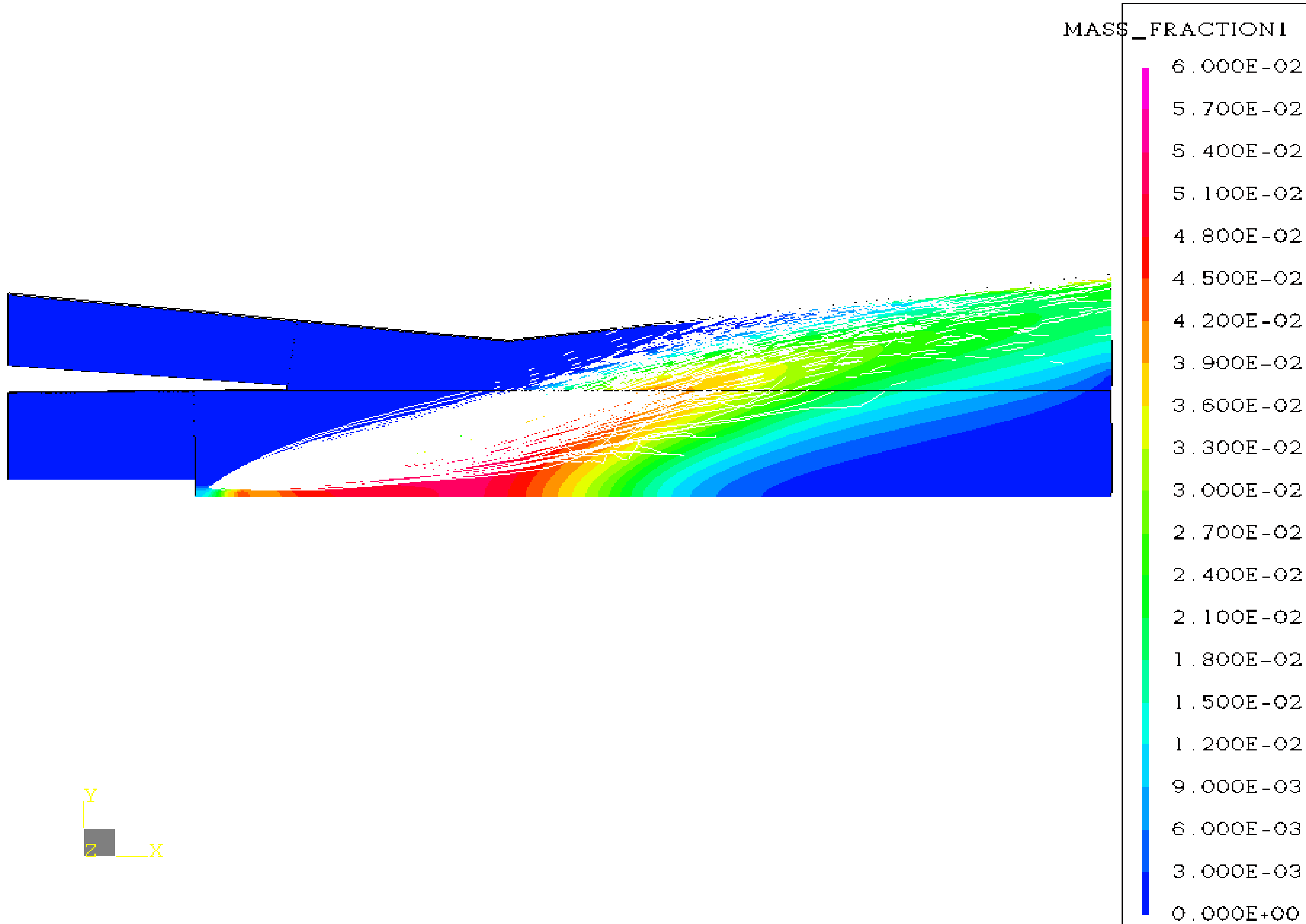
Design No.	length	mass_rec	fuel	swirl_no	ray_out	Rank Value
45	45.0	0.0	75.59436	0.2180011	0.00907218	0.696718006342...
18	49.0	0.9883296	72.13689	0.0544705	0.0106934	0.693395846394...
2	40.0	73.97912	72.97001	0.0462573	0.00996328	0.690309713192...
5	15.0	34.89241	39.2496	0.2459233	0.0106934	0.686747862539...
29	15.0	25.74149	39.1771	0.2476789	0.0103283	0.685246411073...
68	45.0	1.36824	67.624	0.0851953	0.0110585	0.684698460919...
260	49.5	-5.083780795681...	65.730085808563...	0.0488729864080...	0.0085448456882...	0.681538510871...
64	45.0	0.0	64.13435	0.109817	0.00961084	0.678128166238...

Design 260 is virtual on RSM : if chosen must be validated

FINAL Design CFD

Design	Length	% Fuel Vap.	Δ Swirl NO.	Recirculation	Rec. Radii
1 Real	30.00	41.10%	0.077	0.00	0.096
260 Virtual	49.50	65.71%	0.048	-5.08	0.085
260 Real	49.50	69.72%	0.047	0.00	0.09

CFX


MASS_FRACTION1
6.000E-02
5.700E-02
5.400E-02
5.100E-02
4.800E-02
4.500E-02
4.200E-02
3.900E-02
3.600E-02
3.300E-02
3.000E-02
2.700E-02
2.400E-02
2.100E-02
1.800E-02
1.500E-02
1.200E-02
9.000E-03
6.000E-03
3.000E-03
0.000E+00
Y
Z
X

Conclusion

- 3 Objectives have been simultaneously chased
  - minimising recirculating radii
  - minimising length
  - maximising % vaporised fuel
- Two main goals are obtained
  - Flashback is avoided (constraint of recirculation combustor products)
  - Desired swirl number is obtained
    - It means that a tuning of 2 mass flow rates and 2 swirl angles can make the same vaporiser yield different swirl numbers for different combustor can requirements
    - It has been tested with success on two similar vaporisers chasing different swirl numbers