

OpenTURNS and its graphical interface

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OpenTURNS: www.openturns.org

OpenTURNS

An Open source initiative for the Treatment of Uncertainties, Risks'N Statistics

- ▶ Multivariate probabilistic modeling including dependence
- ▶ Numerical tools dedicated to the treatment of uncertainties
- ▶ Generic coupling to any type of physical model
- ▶ Open source, LGPL licensed, C++/Python library

OpenTURNS: www.openturns.org



AIRBUS



- ▶ Linux, Windows
- ▶ First release : 2007
- ▶ 5 full time developers
- ▶ Users \approx 1000, mainly in France (208 000 Total Conda downloads)
- ▶ Project size (2018) : 720 classes, more than 6000 services

OpenTURNS: content

Data analysis

Visual analysis: QQ-Plot, Cobweb

Fitting tests: Kolmogorov, Chi2

Multivariate distribution: kernel smoothing (KDE), maximum likelihood

Process: covariance models, Welch and Whittle estimators

Bayesian calibration: Metropolis-Hastings, conditional distribution

Reliability, sensitivity

Sampling methods: Monte Carlo, LHS, low discrepancy sequences

Variance reduction methods: importance sampling, subset sampling

Approximation methods: FORM, SORM

Indices: Spearman, Sobol, ANCOVA

Importance factors: perturbation method, FORM, Monte Carlo

Probabilistic modeling

Dependence modelling: elliptical, archimedean copulas.

Univariate distribution: Normal, Weibull

Multivariate distribution: Student, Dirichlet, Multinomial, User-defined

Process: Gaussian, ARMA, Random walk.

Covariance models: Matern, Exponential, User-defined

Functional modeling

Numerical functions: symbolic, Python-defined, user-defined

Function operators: addition, product, composition, gradients

Function transformation: linear combination, aggregation, parametrization

Polynomials: orthogonal polynomial, algebra

Meta modeling

Functional basis methods: orthogonal basis (polynomials, Fourier, Haar, Soize Ghanem)

Gaussian process regression:

General linear model (GLM), Kriging

Spectral methods: functional chaos (PCE), Karhunen-Loeve, low-rank tensors

Numerical methods

Integration: Gauss-Kronrod

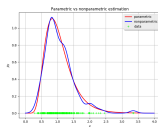
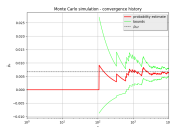
Optimization: NLOpt, Cobyla, TNC

Root finding: Brent, Bisection

Linear algebra: Matrix, HMat

Interpolation: piecewise linear, piecewise Hermite

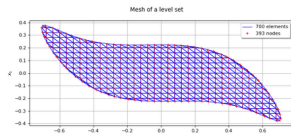
Least squares: SVD, QR, Cholesky



OpenTURNS: documentation

LevelSetMesher

(Source code, png, hires.png, pdf)



`class LevelSetMesher(*args)`

Creation of mesh of box type.

Available constructor:

`LevelSetMesher(discretization)`

Parameters: **discretization**: sequence of int, of dimension ≤ 3 .

Discretization of the levelset bounding box.

solver: `OptimizationAlgorithm`

Optimization solver used to project the vertices onto the level set. It must be able to solve nearest point problems. Default is `RobustKaczmarz`.

Notes

The meshing algorithm is based on the `IntervalMesher` class. First, the bounding box of the level set (provided by the user or automatically computed) is meshed. Then, all the simplices with all vertices outside of the level set are rejected, while the simplices with all vertices inside of the level set are kept. The remaining simplices are adapted the following way:

- The mean point of the vertices inside of the level set is computed
- Each vertex outside of the level set is projected onto the level set using a linear interpolation
- If the project flag is `True`, then the projection is refined using an optimization solver.

Examples

Create a mesh:

```
>>> import openturns as ot
>>> mesher = ot.LevelSetMesher([5, 10])
>>> level = 1.0
>>> function = ot.SymbolicFunction([x0', x1'], ['x0'^2+x1'^2'])
>>> levelSet = ot.LevelSet(function, level)
>>> mesh = mesher.build(levelSet)
```

Methods

| | |
|----------------------------------|-----------------------------------|
| <code>build(*args)</code> | Build the mesh of level set type. |
| <code>getClassname()</code> | Accessor to the object's name. |
| <code>getDiscretization()</code> | Accessor to the discretization. |

- Content: programming interface, examples, theory.
- The doc is generated: *all* classes and methods are documented, partly automatically.
- Examples are automatically tested at *each* update of the code and outputs are checked.

OpenTURNS: estimate the mean sequentially

Two sequential algorithms based on asymptotic statistics: the mean and Sobol' sensitivity indices.

Part 1 : Estimate the mean with an sequential algorithm.

- ▶ The "classical" way of estimating the mean : set the sample size n , then use the sample mean $\mu = (1/n) \sum_{j=1}^n y^{(j)}$.
- ▶ The sample mean is asymptotically gaussian:

$$\mu \rightarrow \mathcal{N}\left(E(Y), \frac{V(Y)}{n}\right).$$

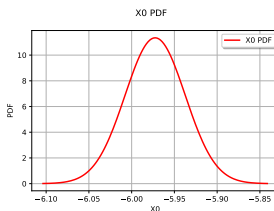
- ▶ The absolute accuracy of the estimate μ can be evaluated based on the sample standard deviation of the estimator $\frac{s}{\sqrt{n}}$
- ▶ Goal of the algorithm: use the smallest possible sample which achieves a given accuracy.
- ▶ To get good performances on distributed supercomputers and multi-core workstations, the size of the sample increases by block.

OpenTURNS: estimate the mean sequentially

```
[... Define the Y RandomVector ...]
algo = ot.ExpectationSimulationAlgorithm(Y)
algo.setMaximumOuterSampling(1000)
algo.setBlockSize(10) # Sample size is 0, 10, 20, 30, 40, ...
algo.setMaximumCoefficientOfVariation(0.001)
algo.run()
result = algo.getResult()
expectation = result.getExpectationEstimate()
print("Mean = %f" % expectation[0])
meanDistr = result.getExpectationDistribution()
View(meanDistr.drawPDF())
```

Output:

Mean = -5.972516



Asymptotic distribution of the sample mean.

OpenTURNS: estimate Sobol' indices sequentially

Part 2 : Estimate Sobol' sensitivity indices with an incremental algorithm.

- Assume that the Sobol' estimator is

$$\bar{S} = \Psi(\bar{U})$$

where Ψ is a multivariate function, U is a multivariate sample and \bar{U} is its sample mean.

- Each Sobol' estimator (e.g. Saltelli, Jansen, etc...) can be associated with a specific choice of function Ψ and vector U .
- Therefore, the multivariate delta method implies:

$$\sqrt{n}(\bar{U} - \mu) \rightarrow \mathcal{N}(0, \nabla\psi(\mu)^T \Gamma \nabla\psi(\mu))$$

where μ is the expected value of the Sobol' indice, $\nabla\psi(\mu)$ is the gradient of the function Ψ and Γ is the covariance matrix of \bar{U} .

- An implementation of the exact gradient $\nabla\psi(\mu)$ was derived for all estimators in OpenTURNS.

OpenTURNS: estimate Sobol' indices sequentially

```
[... Define the X Distribution , define the g Function ...]
estimator = ot.SaltelliSensitivityAlgorithm()
estimator.setUseAsymptoticDistribution(True)
algo = ot.SobolSimulationAlgorithm(X, g, estimator)
algo.setMaximumOuterSampling(100) # number of iterations
algo.setBlockSize(50) # size of experiment at each iteration
algo.setIndexQuantileLevel(0.1) # the confidence interval level
algo.setIndexQuantileEpsilon(0.2) # length of confidence interval
algo.run()
```



Asymptotic distribution of the first order Sobol' indices for the first variable.

PERSALYS, the graphical user interface of OpenTURNS

- ▶ Main goal : provide a graphical interface of OpenTURNS in the SALOME integration platform
- ▶ Features
 - ▶ Uncertainty quantification : definition of the probabilistic model (including dependence), distribution fitting (including copulas), central tendency, sensitivity analysis, probability estimate, meta-modeling (polynomial chaos, kriging), screening with Morris, optimization, design of experiments
 - ▶ Generic (not dedicated to a specific application)
 - ▶ GUI language : English, French
- ▶ Partners : EDF, Phiméca
- ▶ Licence : LGPL
- ▶ Schedule :
 - ▶ Since summer 2016, one EDF release per year
 - ▶ On the internet (free) : SALOME_EDF since 2018 on <https://www.salome-platform.org>

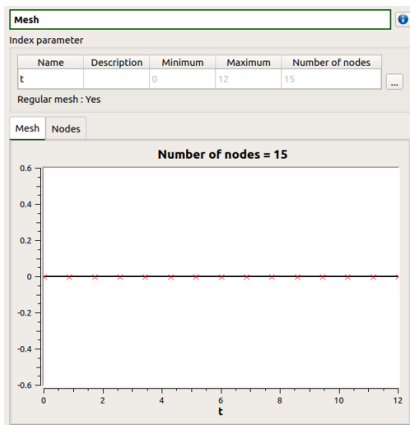
PERSALYS: define the dependence

- ▶ Dependence is defined using copulas
- ▶ Define arbitrary groups of dependent variables
- ▶ Available copulas (same as in OT): gaussian, Ali-Mikhail-Haq, Clayton, Farlie-Gumbel-Morgenstern, Frank, Gumbel
- ▶ Dependence inference from a sample : Bayesian Information Criteria (BIC) or Kendall plot



PERSALYS: 1D fields

- ▶ Mesh definition and visualization
- ▶ Import from text or csv file



PERSALYS: 1D fields

- ▶ Functional model definition and probabilistic model
- ▶ Python or symbolic

Python model

```
from numpy import maximum, exp
def _exec(z0,v0,m,c):
    g = 9.81
    zmin = 0.
    tau = m / c
    vinf = -m * g / c

    # mesh nodes
    t = getMesh().getVertices()

    z = [maximum(z0 + vinf * t_i[0] + tau
    return z
```

Definition Differentiation

Inputs

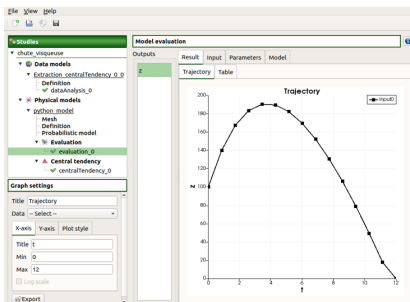
| Name | Description | Value |
|------|-------------|-------|
| 1 z0 | | 100 |
| 2 v0 | | 55 |
| 3 m | | 80 |
| 4 c | | 16 |

Index parameter: t

Outputs

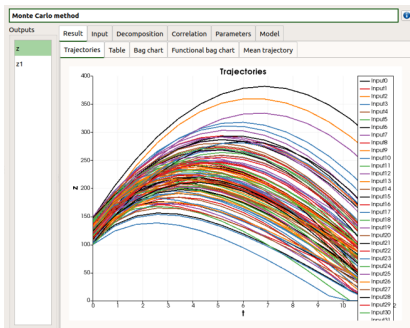
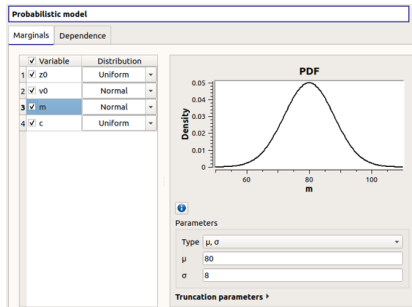
| <input checked="" type="checkbox"/> Name | Description |
|--|-------------|
| 1 <input checked="" type="checkbox"/> z | |

☒ Enable multiprocessing



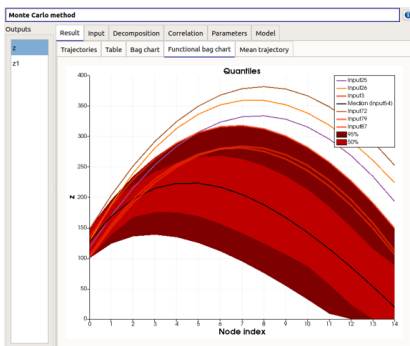
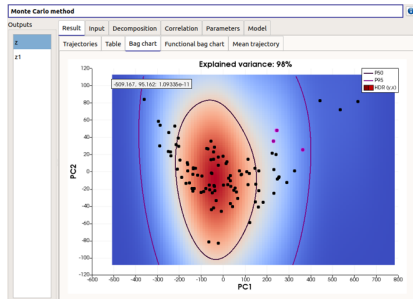
PERSALYS: 1D fields

- Probabilistic model
- Uncertainty propagation with simple Monte-Carlo sampling



PERSALYS: 1D fields

- ▶ BagChart and Functional Bagchart (from Paraview) based on High Density Regions (Hyndman, 1996).
- ▶ To do this, Paraview uses OpenTURNS to perform the Karhunen-Loève decomposition.
- ▶ Linked selections in the views



What's next ?

PERSALYS Roadmap :

- ▶ Calibration
- ▶ 2D Fields, 3D Fields
- ▶ In-Situ fields based on the MELISSA library (with INRIA):
when we cannot store the whole sample in memory or on the hard drive, update the statistics (e.g. the mean, Sobol' indices) sequentially, with distributed computing.



The end

Thanks !

Questions ?

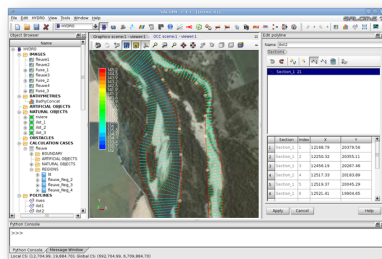
PERSALYS: estimate the parameters of the copulas

- Inference of the dependence of the multivariate sample
- Guided choice according to the BIC and Kendall plot



SALOME

- ▶ Integration platform for pre and post processing, and 2D/3D numerical simulation
- ▶ Features : geometry, mesh, distributed computing
- ▶ Visualization, data assimilation, uncertainty treatment
- ▶ Partners : EDF, CEA, Open Cascade
- ▶ Licence : LGPL
- ▶ Linux, Windows
- ▶ www.salome-platform.org



OpenTURNS: estimate Sobol' indices sequentially

Part 2 : Estimate Sobol' sensitivity indices with an incremental algorithm.

- ▶ Let us denote by Φ_k^F (resp. Φ_k^T) the cumulated distribution function of the gaussian distribution of the first (resp. total) order sensitivity indice of the k-th input variable.
- ▶ We set $\alpha \in [0, 1]$ a quantile level and $\epsilon \in (0, 1]$ a quantile precision.
- ▶ The algorithms stops when, on all components, first and total order indices have been estimated with enough precision.

The precision is said to be sufficient if

$$\Phi_k^F(1 - \alpha) - \Phi_k^F(\alpha) \leq \epsilon$$

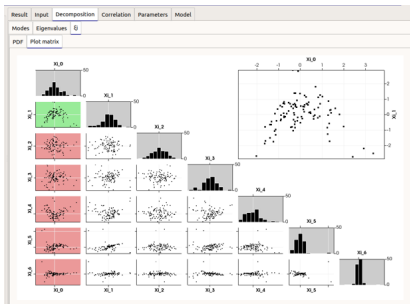
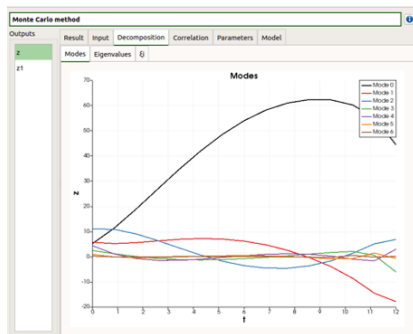
and

$$\Phi_k^T(1 - \alpha) - \Phi_k^T(\alpha) \leq \epsilon$$

for $k = 1, \dots, n_X$.

PERSALYS: 1D fields

- ▶ Karhunen Loeve decomposition
- ▶ Show modes, eigenvalues and projection coefficients



Interactive uncertainty visualization with Paraview



Methodology



Software architecture

Two entry points:

- ▶ interactive,
- ▶ Python.

Advantages of the Python programming of the GUI:

- ▶ unit tests,
- ▶ going beyond the GUI



Symbolic physical model

The screenshot shows the OTGui application window. The left sidebar displays a tree view with the following structure:

- Crue Analytique
 - physicalModel_0
 - Deterministic study
 - Probabilistic study
 - Probabilistic Model
 - Designs of experiment

The main area is divided into two sections: Inputs and Outputs.

Inputs

| | Name | Description | Value |
|---|------|---------------------------------|-------|
| 1 | Q | Débit (m ³ /s) | 0 |
| 2 | Ks | Strickler (m ^{1/3} /s) | 30 |
| 3 | Zv | Côte aval (m) | 50 |
| 4 | Zm | Côte amont (m) | 55 |
| 5 | Hd | Hauteur de la digue (m) | 8 |
| 6 | Zb | Côte de la berge (m) | 55,5 |
| 7 | L | Longueur de la rivière (m) | 5000 |
| 8 | B | Largeur de la rivière (m) | 300 |

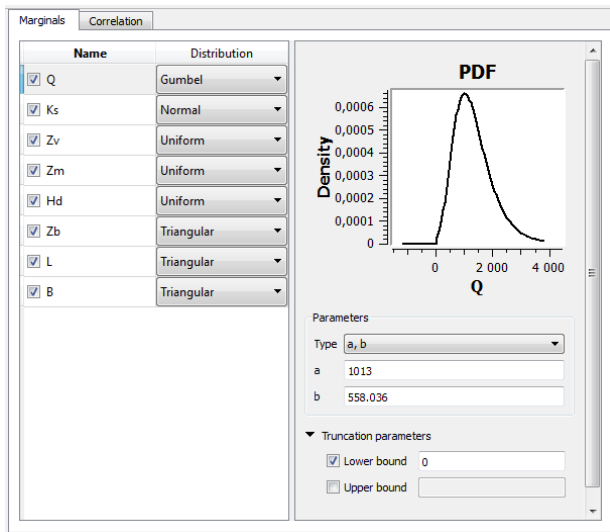
Below the inputs table are buttons for **+ Add** and **- Remove**.

Outputs

| | Name | Description | Formula | Value |
|---|------|--------------|--|-------|
| 1 | H | Surverse (m) | $(Q / (Ks * B * \sqrt{(Zm - Zv) / L}))^{(3.0 / 5.0)} + Zv - Zb - Hd$ | -13,5 |

Below the outputs table are buttons for **+ Add**, **- Remove**, and **Evaluate**.

Probabilistic model

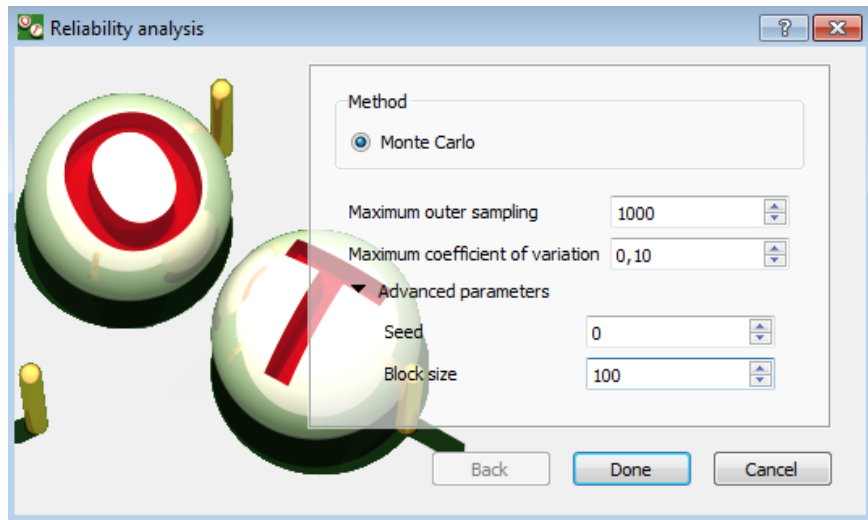


Limit state study : definition of the threshold

Definition of the failure event :

| Output | Operator | Threshold |
|--------|----------|-----------|
| H ▼ | < ▼ | -10 |

Limit state study : algorithm parameters



Limit state study : summary

Summary

Histogram

Convergence graph

Output H

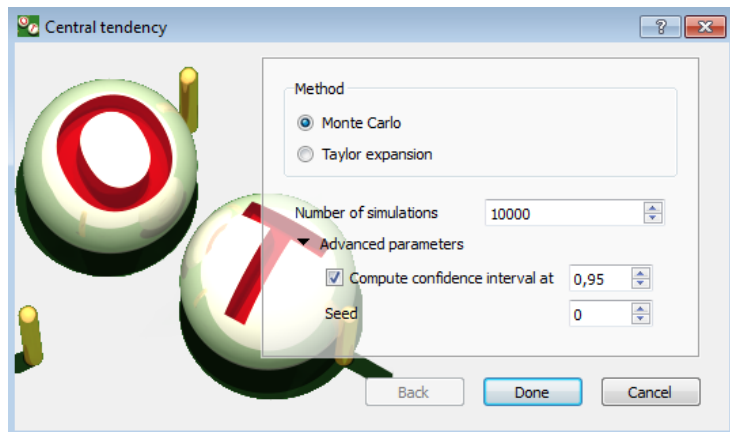
Number of simulations: 26

| Estimate | Value | Confidence interval at 95% | |
|--------------------------|-----------|----------------------------|-------------|
| | | Lower bound | Upper bound |
| Failure probability | 0.807692 | 0.656203 | 0.959182 |
| Coefficient of variation | 0.0956949 | | |

Limit state study : histogram



Central tendency : algorithm parameters



Central tendency : summary results

Moments estimate

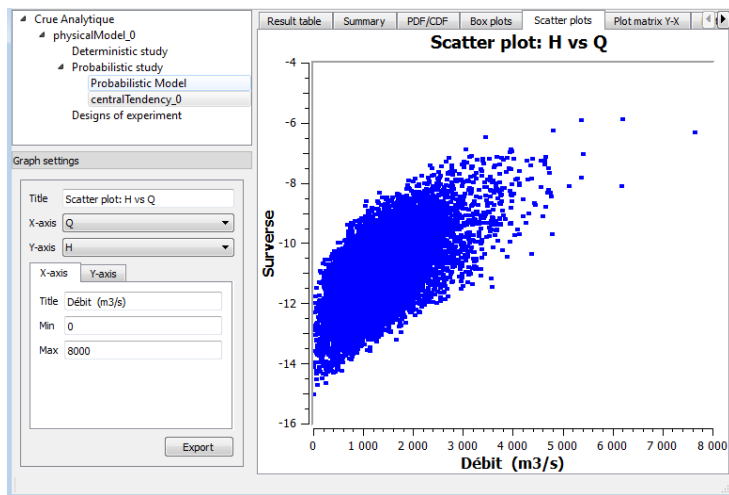
| Estimate | Value | Confidence interval at 95% | |
|--------------------|----------|----------------------------|-------------|
| | | Lower bound | Upper bound |
| Mean | -11.0178 | -11.0417 | -10.9938 |
| Standard deviation | 1.22309 | 1.20637 | 1.24028 |
| Skewness | 0.20005 | | |
| Kurtosis | 3.01907 | | |
| First quartile | -11.8721 | | |
| Third quartile | -10.2129 | | |

Probability
Quantile

Central tendency : summary results

| | | | | |
|------------------------------|----------|----------|-----------|---------------|
| Result table | Summary | PDF/CDF | Box plots | Scatter plots |
| Output H ▾ | | | | |
| Number of simulations: 10000 | | | | |
| Minimum and Maximum | | | | |
| | Variable | Minimum | Maximum | |
| Output | H | -15.0155 | -5.88758 | |
| Inputs at extremum | Q | 7.97827 | 6187.43 | |
| | Ks | 27.132 | 25.5926 | |
| | Zv | 49.1681 | 50.9071 | |
| | Zm | 54.5469 | 55.3994 | |
| | Hd | 8.76082 | 8.49391 | |
| | Zb | 55.5436 | 55.4935 | |
| | L | 4999.26 | 4997.37 | |
| | B | 303.187 | 300.871 | |

Central tendency : scatter plots



Sensitivity analysis : Sobol' indices



OpenTURNS: estimate the mean

See the Jupyter Notebook.

```
from openturns.viewer import View
import openturns as ot
from math import sqrt
```

```
ot.RandomGenerator.SetSeed(0)
```

1. The function G

```
def functionCrue(X) :
    Q, Ks, Zv, Zm = X
    alpha = (Zm - Zv)/5.0e3
    H = (Q/(Ks*300.0*sqrt(alpha)))*(3.0/5.0)
    S = [H + Zv - (55.5 + 3.0)]
    return S
```

Creation of the problem function

```
g = ot.PythonFunction(4, 1, functionCrue)
g = ot.MemoizeFunction(g)
```

OpenTURNS: estimate the mean

2. Random vector definition

```
myParamQ = ot.GumbelAB(1013., 558.)
Q = ot.ParametrizedDistribution(myParamQ)
otLOW = ot.TruncatedDistribution.LOWER
Q = ot.TruncatedDistribution(Q, 0, otLOW)
Ks = ot.Normal(30.0, 7.5)
Ks = ot.TruncatedDistribution(Ks, 0, otLOW)
Zv = ot.Uniform(49.0, 51.0)
Zm = ot.Uniform(54.0, 56.0)
```

3. View the PDF

```
Q.setDescription(["Q□ (m3/s)"])
View(Q.drawPDF()).show()
```



OpenTURNS: estimate the mean

```
# 4. Create the joint distribution function ,
# the output and the event.
X = ot.ComposedDistribution([Q, Ks, Zv, Zm])
Y = ot.RandomVector(g, ot.RandomVector(X))

# 5. Estimate expectation with simple Monte-Carlo
sampleSize = 10000
sampleX = X.getSample(sampleSize)
sampleY = g(sampleX)
sampleMean = sampleY.computeMean()
print ("Mean=%f" % (sampleMean[0]))
```

Output:

Mean by MC = -5.937845

GUI : the demo

Demo time.

GUI : outline

- ▶ From scratch : 3 inputs, 2 outputs, sum, central dispersion study with default parameters
- ▶ Open axialStressedBeam-python.xml : central dispersion with sample size 1000, Threshold $P(G < 0)$ with $CV=0.05$
- ▶ Import crue-4vars-analytique.py : S.A. with sample size 1000, sort by size

UQ, the easy way

Main goal : make UQ easy to use

- ▶ classical user-friendly algorithms with a state-of-the-art implementation,
- ▶ default parameters of the algorithms whenever possible,
- ▶ an easy access to the HPC resources,
- ▶ an automated connection to the computer code.

Produce standard results :

- ▶ numerical results e.g. tables,
- ▶ classical graphics.

Overview (1/2)

Inputs from the user :

- ▶ Physical model : symbolic, Python code or SALOME component
- ▶ Probabilistic model : joint probability distribution function of the input.

Then :

- ▶ Central dispersion: estimates the central dispersion of the output Y (e.g. mean).
- ▶ Threshold probability: estimates the probability that the output exceeds a given threshold S .
- ▶ Sensitivity analysis: estimates the importance of the inputs to the variability of the output.

Overview (2/2)

Probabilistic modeling :

- ▶ Distribution fitting from a sample
- ▶ Dependence modeling (Gaussian copula)

Meta-modeling :

- ▶ Polynomial chaos (full or sparse)
- ▶ Kriging