

**Global Sensitivity Analysis:  
Elementary Effects Method of Morris  
using Sampling for Uniformity (SU)  
MatLab code manual**

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# Morris SU (Sampling Uniformity) code

There are two Elementary Effects (EE) packages that complement the analysis: a) *EE Sampling* - to obtain the Morris samples based on a number of methods, including Sampling for Uniformity (SU); and b) *EE Measures and Plots* - after running the model with the EE samples it post-processes the results and provides Morris statistics and plots.

Download the Matlab code, sample inputs and documentation for the packages from the links below:

- [EE Sampling for Matlab](#) [10kB]
- [EE Measures and Plots for Matlab](#) [10kB]
- [This documentation in PDF](#) (2.9 MB)

Please click on the tabs below to see the documentation for each of the packages.

- [EE Sampling](#) |
- [EE Measures and Plots](#)

## Elementary Effects (EE) Sampling Package

### Description

EE\_Sampler\_Mapper Package is a set of MATLAB functions that generates input factor samples for the method of Elementary Effects or Morris method (Morris, 1991). The main function to run is 'Fac\_Sampler.m' (or its simplified command line form sampler.m). It generates input factor samples in a unit hyperspace and then transforms them according to the specified input probability distributions. Currently this tool gives five options for sampling strategy: (a) the method of Optimized Trajectories [OT] (Campolongo et al. 2007); (b) the Modified Optimized Trajectories [MOT] (Ruano et al., 2012); (c) Sampling for Uniformity [SU] (Khare et al., 2015); and (d) Enhanced Sampling for Uniformity [eSU] (Chitale et al., 2017); and (e) RadialeSU/ReSU (Chitale et al.) (in preparation).

### Program Usage & Outputs

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#### Syntax

```
Fac_Sampler('facfile', 'SS', OvrSamSiz, NumLev, NumTraj, 'SamFileType')
```

A command line shell (sampler.m) is provided for those interested in compiling the program for use in mixed environments (i.e. unix scripts and others). The program can be compiled in the Matlab environment with 'mcc -m sampler.m'. This will produce a command line executable that can be run outside Matlab, or in another machine command line environment provided that the same runtime library version as the compiler is installed in the client machine (see Matlab Compiler Runtime download and instructions [here](#)). An example of use for this tool (inside and outside Matlab) would be:

```
sampler 'try.fac' 'eSU' 1 8 16 'Text'
```

#### Inputs:

(1) facfile: This is an ASCII '.fac' file that follows the format (and can be generated) from SimLab v2.2.1 (Saltelli et al. 2004). For exact file formatting and distribution characteristics please refer SimLab v2.2 manual App. C ([available here](#)) (Saltelli et al. 2004). The file contains the following information:

- (a) number of input factors (NumFact)
- (b) default distribution truncation values
- (c) distribution type and distribution characteristics for each input factor.

(2) SS: Sampling Strategy. Currently we provide five options:

- (a) 'OT' - Campolongo et al. (2007) - Method of Optimized Trajectories
- (b) 'MOT' - Ruano et al. (2012) - Method of Modified Optimized Trajectories
- (c) 'SU' - Khare et al. (2015) - Sampling for Uniformity
- (d) 'eSU' - Chitale et al. (2017) – Enhanced Sampling for Uniformity
- (e) 'RadialeSU' - Chitale et al. (in preparation) – Radial eSU

(3) OvrSamSize: Oversampling Size.

For OT and MOT the recommended oversampling size is 500-1000. For SU recommended oversampling size is 300. For eSU oversampling is not necessary i.e. we recommend OvrSamSize = 1. The current version of this EE\_SamplerMapper tool interactively guides user to choose appropriate Oversampling size based on literature recommendations.

(4) NumLev: Number of input factor levels

In EE literature various values for number of levels have been suggested. However, the standard practice is to use even number of levels usually 4, 6 or 8. For SU/eSU and RadialeSU user can choose from NumLev = {4,6,8,10,12,14,16}. If user specifies NumLev that does not belong to this set, then it will be set to 4 by default.

(5) NumTraj: Number of trajectories to be generated

In EE literature recommended value for number of trajectories vary from as little as 2 to as large as 100. However, a number of studies have reported that 10-20 trajectories are sufficient. Chitale et al. (2017) indicates that for eSU the number of trajectories should be multiple of the number of levels to get better results. The current version of this EE\_SamplerMapper tool interactively guides user to change/select number of trajectories whenever necessary. Presence of factor/s with 'Nominal' type of distribution needs further consideration while selecting NumTraj. This tool guides the user in adjusting NumTraj in such cases.

(6) SamFileType: Sample File Format. Currently we provide two options:

- (a) 'Excel'
- (b) 'Text' (comma separated file with .sam extension)

**Outputs:**

(1) Factor\_Sample: Input factor sample [ncol,nrows], where ncol = NumFact and nrows = NumTraj\*(NumFact+1). Each column corresponds to one input factor

(2) \*\_FacSample.xlsx or \*\_FacSample.sam:

If user sets SamFileType = 'Excel' then Factor samples are written to an excel file '\*\_FacSample.xlsx', where \* i.e. first part of the file name is same as the first part of the '.fac' file. (e.g. Factor sample for the input file 'Example.fac' will be saved in 'Example\_FacSample.xlsx'). If user sets SamFileType = 'Text' then Factor samples are written to a text file '\*\_FacSample.sam', where \* (i.e. first part of the file name) is the same as the first part of the '.fac' file. In both types of files each column corresponds to a factor. Factor name is specified on the first row

(3) \*\_FacSamChar.txt: Characteristics used for generating the sample are written to a text file '\*\_FacSamChar.txt', where \* i.e. first part of the file name is same as the first part of the '.fac' file. (e.g. FacSamChar file for the input file 'Example.fac' will be saved as 'Example\_FacSamChar.txt'). Details of \*\_FacSamChar.txt file are as follows

First Line: Sampling Strategy – OT, MOT, SU, eSU or RadialeSU

Second Line: Oversampling Size

Third Line: Number of levels

Fourth Line: Number of trajectories

Fifth Line: Number of factors

Remaining Lines: Elementary Effects multiplication matrix, arranged by factors in rows and trajectories in columns. This matrix is useful for the cases when model has a Uniform Discrete factor/s with number categories different than NumLev.

**Folder Structure:**

There are 6 Matlab functions (i.e. m files) and five folders (Campolongo, Ruano, Khare, Enhanced\_Khare, and Radial\_Khare) included in this package (EE\_Sampler\_Mapper). Generated factor/input factor sample file \*\_FacSample.xlsx or \*\_FacSample.sam and \*\_FacSamChar.txt will be stored in the folder same as 'Fac\_sampler.m'.

**Input Factor Probability Distributions for facfile:**

For the details about distribution characteristics please refer SimLab v2.2 user manual App A (available [here](#)) (Saltelli et al. 2004). Currently the following parameter distributions can be generated using this package:

- (1) 'Uniform'
- (2) 'LogUniform'
- (3) 'Normal'
- (4) 'LogNormal'
- (5) Discrete (for categorical factors)

'Nominal' - uniform discrete for nominal factors

'NUDiscrete' – non-uniform discrete for nominal and ordinal factors

'UDiscrete' – uniform discrete for ordinal factors.

- (6) 'Constant'
- (7) 'Triangular'
- (8) 'Weibull'
- (9) 'Beta'
- (10) 'Gamma'
- (11) 'Exponential'
- (12) 'Log10Uniform'

**Note on Discrete Distributions.** To make EE\_SamplerMapper tool more flexible in its usage, we replaced the original Simlab (Saltelli et al. 2004) 'Discrete' distribution by the three types presented above ('Nominal', 'NUDiscrete', and 'UDiscrete').

- (A) '*Nominal*' uniform distribution for discrete nominal factors. A nominal variable (sometimes called a categorical variable) is one that has two or more categories, but there is no intrinsic ordering to the categories (for example "colors", "gender", etc.). For the 'Nominal' type factors it is necessary to ensure that all combinations of discrete levels are considered to get reliable EE based sensitivity measures. However, this increases the number of trajectories. Current version of the EE\_SamplerMapper guides users to select appropriate number of trajectories i.e. NumTraj when it encounters the presence of 'Nominal' factors. Example: If modeler is to choose from a number of sub-models to be used to simulate a particular mechanism then that 'sub-model' is a factor for EE analysis with nominal discrete type of distribution. There is no restriction on number of discrete values/categories/options to be selected. However, larger the number of categories larger is the number of trajectories needed.
- (B) '*UDiscrete*' distributions are used for ordinal discrete factors with equiprobable categories. A discrete variable is ordinal when there is a clear ordering of the values, either numerical (i.e. \$5, \$10, \$15) or non-numerical (i.e. "low", "medium" and "high"). An example of usage of this type of distribution would be the usage of application of EE sampling for design of experiments in ecotoxicology (Rodea-Palomares et al., 2016). Successful generation of sample for such a factor depends on number of categories used. If number of categories are not equal to the NumLev then it is not possible to get UDiscrete distribution due to mismatch between the two. In such cases instead of using NumLev defined by the user, this tool samples corresponding factor with NumLev = number of categories. Sampling is done with procedure consistent with the continuous distribution factors. However, this modification has implications on sensitivity indices calculations in such cases. The Elementary Effects multiplication matrix is calculated and used for this purpose. The multiplication factors are calculated as

If number of categories is even

$$\frac{\Delta_{\text{NumLev}}}{\Delta_{\text{NC}}}$$

If number of categories is odd

$$\frac{\Delta_{\text{NumLev}} \times 2(\text{NC} - 1)}{(\text{NC} \pm 1)}$$

Where NC is the number of categories and  $\Delta x$  is  $x/[2(x-1)]$ .

We have demonstrated this with an example (example 5) later in this manual.

- (C) '*NUDiscrete*' distributions can be used for ordinal discrete factors with non-uniform distributions. However, we want to warn users to be cautious about usage of this option. Accuracy of generated factor distributions depends on NumLev, number of

categories, and corresponding weights/probability configuration assigned to such factor. E.g. for SU/eSU/RadialeSU if NumLev is 4, and factor has 3 categories, then only three non-uniform probability configurations can be generated for NUDiscrete factors without any issues for EE analysis – (1) {0.25, 0.5, 0.25}, (2) {0.5, 0.25, 0.25}, and (3) {0.25, 0.25, 0.5}. Note that if weights/probability configurations are not assigned properly this distribution can result in trajectories where NUDiscrete factors do not change values, and potentially result in inaccurate EE measures/ EE Screening. E.g. In case NumLev = 4 and there are two discrete categories with unequal probabilities, e.g. {0.25, 0.75} or {0.75, 0.25}, half of the trajectories will result in EEs being 0 and will result in inaccurate values of sensitivity measures. Hence, modelers should be careful while interpreting corresponding results. We strongly recommend checking if it is possible to generate a representative sample when NUDiscrete factor is present and potentially adjust NumLev and/or weights assigned to individual categories of NUDiscrete factor/s.

The use of the three discrete distributions is restricted to SU, eSU and RadialeSU. EE\_Sampler\_Mapper tool prompts user to choose appropriate sampling method when these types of distributions are present. We are currently expanding our tool to improve its utility in generation one more distribution – non-uniform nominal/NUNominal distribution. Please contact the authors for additional information if this feature is needed.

### ***Probability distribution truncation***

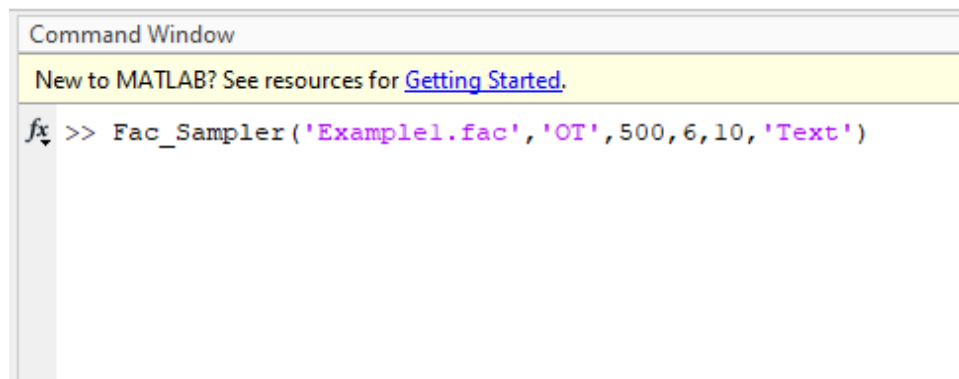
- (A) When parameter distribution/distributions have long tails (Normal, LogNormal, Weibull, Gamma, Exponential), to get accurate results/ factor rankings consistent with variance-based SA methods (e.g. Sobol'), experience has shown that truncated distributions perform better. SimLab v2.2 truncates distributions at 12.5% and 87.5% i.e. overall 25% truncation. Though, ideal truncation may vary from model to model, we recommend 2.5% to 5% truncation from either side.
- (B) If the user wants to use different truncations for different factors/parameters lower and upper percentiles (expressed as fractions) should be edited in the .fac' (please refer to App. C of SimLab v2.2 manual SimLab v2.2 manual App. C [available here](#)) (Saltelli et al. 2004). By default SimLab v2.2 sets these values these values at 0.001 and 0.999. See Example 2 in the following sections for additional details.

## **Examples**

---

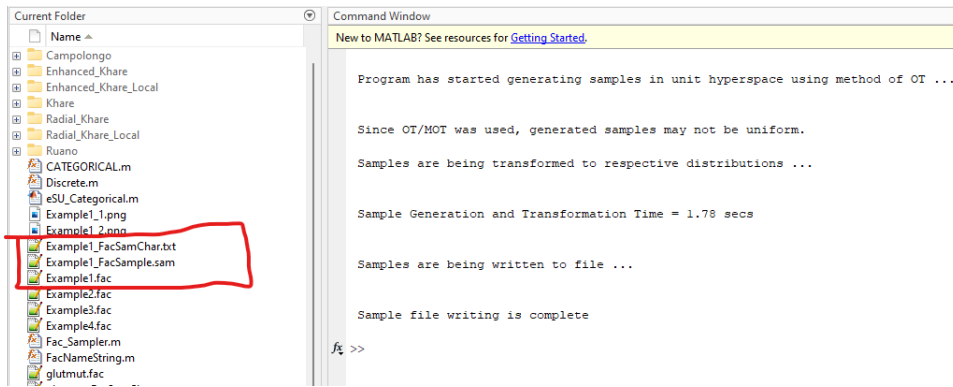
### **Example 1**

Generate 10 trajectory samples for factor file 'Example1.fac' (see package distribution) with OT method. Use oversampling size of 500 and 6 factor levels. Save outputs in text format (Example1\_FacSample.sam). Type following in the Matlab Command window making sure that you are in EE\_Sampler\_Mapper folder.



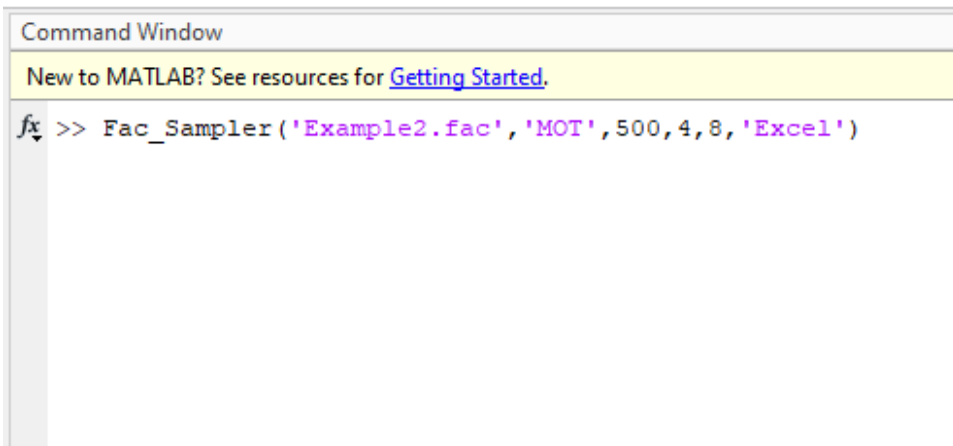
```
Command Window
New to MATLAB? See resources for Getting Started.
fx >> Fac_Sampler('Example1.fac', 'OT', 500, 6, 10, 'Text')
```

Output (notice new files Example1\_FacSamChar.txt and Example1\_FacSampler.sam on the left column)



## Example 2

Generate samples for factors in 'Example2.fac' (see package distribution) using method of MOT. Generate 8 trajectories with 500 oversampling size, NumLev = 4. Save sample in excel format. Note that Example2.fac contains 'Nominal' and 'UDiscrete' type factors. Type following in Matlab command window.



Output:



```
Command Window
New to MATLAB? See resources for Getting Started.

*****
ERROR: You have 3 categorical factors with multiple (> 2) categories
      Method of MOT does not handle this type of distributions
*****

-----
RECOMMENDATION: Consider SU/eSU/RadialeSU for sample generations
-----

Sample was not generated
fx >>
```

As expected, the sample was not generated and a warning is shown

Following the warning, we now generate the samples using eSU instead of MOT. Keep all other settings the same, except OverSamSiz = 1.

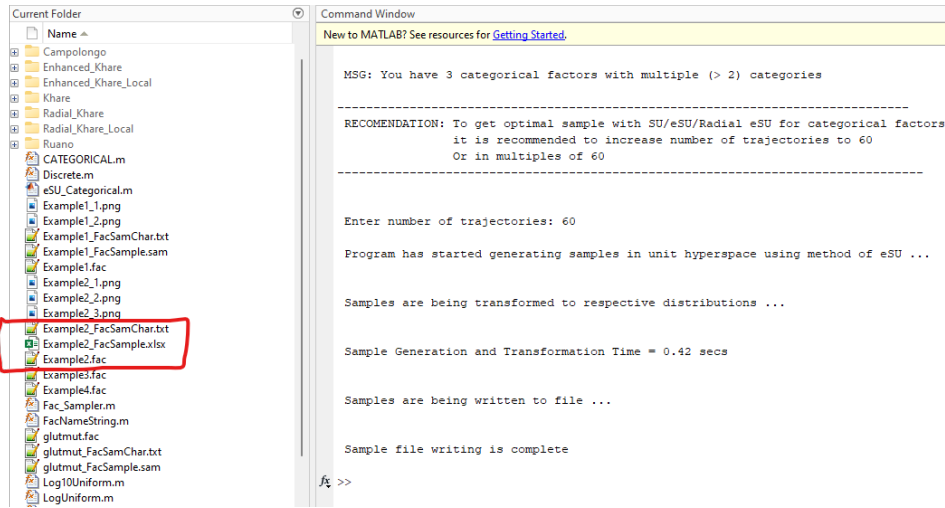
```
Command Window
New to MATLAB? See resources for Getting Started.

MSG: You have 3 categorical factors with multiple (> 2) categories

-----
RECOMENDATION: To get optimal sample with SU/eSU/Radial eSU for categorical factors
                it is recommended to increase number of trajectories to 60
                Or in multiples of 60
-----

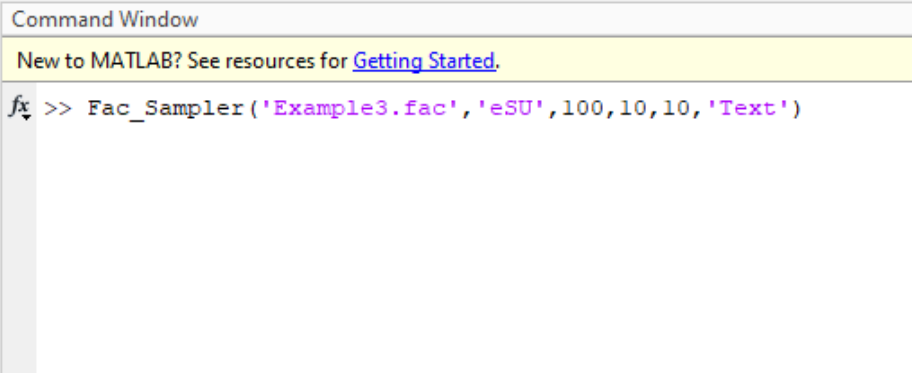
fx Enter number of trajectories:
```

In this case, due to the presence of Nominal and UDiscrete factors, user was asked to increase number of trajectories as shown. Let's increase number of trajectories to 60.



### Example 3

Generate samples for factors in 'Example3.fac' (see package distribution) using method of eSU. Generate 10 trajectories with 100 oversampling size, NumLev = 10. Save sample in text format. Type following in Matlab command window.



Output

```
Command Window
New to MATLAB? See resources for Getting Started.

For eSU Oversampling is not necessary. Reducing OvrSamSiz to 1
Program has started generating samples in unit hyperspace using method of eSU ...

Samples are being transformed to respective distributions ...

Sample Generation and Transformation Time = 0.28 secs

Samples are being written to file ...

Sample file writing is complete

fx >>
```

Let's try generating sample for Example3.fac file with eSU. Try NumLev = 12, NumTraj = 8, OvrSamSiz = 1. Below are input and output screenshots

```
Command Window
New to MATLAB? See resources for Getting Started.

fx >> Fac_Sampler('Example3.fac', 'eSU', 1, 12, 8, 'Text')
```

Since NumTraj = 8 is less than NumLev = 12, NumTraj will be increased to 12 to ensure uniformity of generated sample.

Output

```
Command Window
New to MATLAB? See resources for Getting Started.

SU/eSU/RadialeSU needs NumTraj to be a multiple of NumLev, increased NumTraj to 12
Program has started generating samples in unit hyperspace using method of eSU ...

Samples are being transformed to respective distributions ...

Sample Generation and Transformation Time = 0.24 secs

Samples are being written to file ...

Sample file writing is complete

fx >>
```

#### Example 4

Generate samples for factors in 'Example4.fac' (see package distribution) using method of RadialeSU. Generate 15 trajectories with 1 oversampling size, NumLev = 12. Save sample in text format. Type following in Matlab command window.

```
Command Window
New to MATLAB? See resources for Getting Started.

fx >> Fac_Sampler('Example4.fac', 'RadialeSU', 1, 12, 15, 'Text')
```

Since NumTraj is not multiple of NumLev, NumTraj will be increased to 24 (12x2)

Output

```
Command Window
New to MATLAB? See resources for Getting Started.

SU/eSU/RadialeSU needs NumTraj to be a multiple of NumLev, increased NumTraj to 24

Program has started generating samples in unit hyperspace using method of RadialeSU...

Samples are being transformed to respective distributions ...

Sample Generation and Transformation Time = 0.30 secs

Samples are being written to file ...

Sample file writing is complete

fx >>
```

### Example 5: Special Case 1 - UDiscrete factors with 3 categories and NumLev = 4

As discussed earlier, in the presence of discrete type of factors user needs to take cautious approach while generating sample for Elementary Effects analysis. One of such case is when we have one or more ordinal type discrete factors with 3 equiprobable categories (UDiscrete). This is a common situation in our experience. Also, using NumLev = 4 is also common and a common EE sample generation characteristic.

We have included an example 'SpCase.fac' file with 7 factors with this package. Among 7 factors p1 and p3 are UDiscrete and have 4 categories with (0.25, 0.25, 0.25, 0.25) configuration; p2, p4, and p5 are UDiscrete and have 3 categories with (0.3333, 0.3334, 0.3333) configuration; while p6 has Uniform distribution and p7 has 3 category Nominal distribution. For complete factor value details please see the actual SpCase.fac file.

```

SpCase fac
1 Default Truncations:
2 0.001 0.999
3
4 7 Distributions:
5 UDiscrete
6 p1
7
8 1 4
9 1 2 0.25
10 2 3 0.25
11 3 4 0.25
12 4 5 0.25
13
14 UDiscrete
15 p2
16
17 1 3
18 1 2 0.3333
19 2 3 0.3334
20 3 4 0.3333
21
22 UDiscrete
23 p3
24
25 1 4
26 0.125 1.125 0.25
27 0.25 1.25 0.25
28 0.375 1.375 0.25
29 0.5 1.5 0.25
30
31 UDiscrete
32 p4
33
34 1 3
35 1 2 0.3333
36 2 3 0.3334
37 3 4 0.3333
38
39 UDiscrete
40 p5
41
42 1 3
43 3 4 0.3333
44 10 11 0.3334
45 90 91 0.3333
46

```

When this tool encounters the situation of factor/s with UDiscrete distribution, but NumLev not being multiple of number of discrete categories, it samples those factors with Number of Categories as NumLev and calculates Elementary Effects multiplication matrix as explained earlier. EE adjustment matrix is used by Sensitivity Measures tool to multiply raw elementary effects.

To generate sample for this 'SpCase.fac' use, SS = 'eSU', OvrSamSiz = 1, NumLev = 4, NumTraj = 12, and 'Excel' output format

```

Command Window
New to MATLAB? See resources for Getting Started.
fx >> Fac_Sampler('SpCase.fac', 'eSU', 1, 4, 12, 'Excel')

```

## Outputs

```

Command Window
New to MATLAB? See resources for Getting Started.

Program has started generating samples in unit hyperspace using method of eSU ...

Samples are being transformed to respective distributions ...

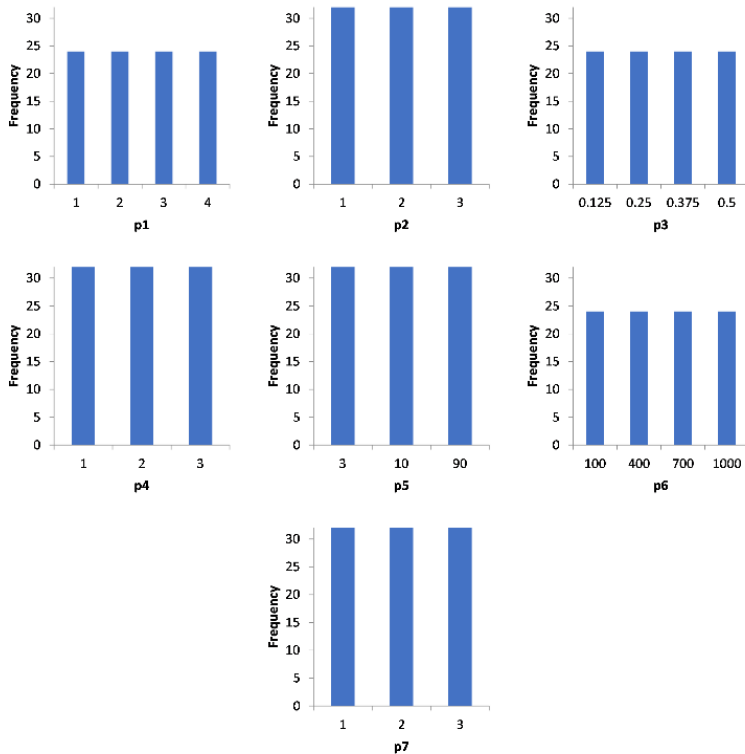
Sample Generation and Transformation Time = 0.20 secs

Samples are being written to file ...

Sample file writing is complete

fx >>
    
```

It can be observed that all factors have desired distributions



We can observe that p2, p4, and p5 (UDiscrete factors with 3 categories) have several EE multiplications values of calculated based on formulas presented earlier.

```

SpCase fac  SpCase_FacSamChart.txt
1  eSU
2  1
3  4
4  12
5  7
6  1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
7  1.3333,1.3333,1.3333,0.6667,1.3333,0.6667,1.3333,1.3333,1.3333,0.6667,1.3333,0.6667,
8  1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
9  0.6667,1.3333,1.3333,1.3333,1.3333,0.6667,0.6667,1.3333,1.3333,1.3333,1.3333,0.6667,
10 1.3333,0.6667,1.3333,1.3333,1.3333,0.6667,1.3333,0.6667,1.3333,1.3333,1.3333,0.6667,
11 1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
12 1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
13

```

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## Program License

These Matlab (R) packages were developed by Drs. Yogesh Khare and Rafael Muñoz-Carpena. This program is distributed as Freeware/Public Domain under the terms of GNU-License. If the program is found useful, the authors ask that acknowledgment is given to its use in any resulting publication and the authors notified. The source code is available from the authors upon request.

We highly encourage using these packages for EE (Morris) sampling and sensitivity measures calculations with the eSU ('enhanced Sampling for Uniformity') method. If you use this package, kindly acknowledge our effort. Also, if you have any question in usage of this package, please contact us on the email address below.

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# Morris SU (Sampling Uniformity) code

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Please click on the tabs below to see the documentation for each of the packages.

- [EE Sampling](#) |
- [EE Measures and Plots](#)

## Elementary Effects (EE) Measures and Plots Package

### Description

EE\_SensitivityMeasures\_Package is a set of Matlab functions that calculates sensitivity measures for the method of Elementary Effects/Morris method (Morris, 1991). Function 'EE\_SenMea\_Calc.m' is the main function that user needs to call from MATLAB command line. Calculated measures include modified sensitivity measures -  $\mu^*$  and  $\sigma$  based on (Campolongo et al. 2007) and original measure  $\mu$  proposed by Morris (1991), and additions by the SU authors (Khare et al., 2015; Chitale et al., 2017).

### Program Usage & Outputs

#### Syntax

```
EE_SenMea_Calc(FacFile,Fac_Sam_File,Fac_Sam_Char,Mod_Out_File,Per_Fac_Label)
```

#### Inputs:

(1) FacFile: This is an ASCII input factor '.fac' file that follows the format (and can be generated) from SimLab v2.2. For exact file formatting and distribution characteristics please refer SimLab v2.2 manual App. C ([available here](#)). Please see also the EE Sampling section for additional details pertaining the modifications introduced for Discrete distributions.

(2) Fac\_Sam\_File: This is an Excel(R)\*'.xlsx' or '\*.sam' file (a comma separated text file) containing factor/parameter samples. This file is generated by the [EE Sampling](#) package.

(3) Fac\_Sam\_Char: This file is generated along with '\*.xlsx' file or '\*.sam' by Factor\_Sampler\_Mapper package for factor sample generation. This is a '\*.txt' file which contains following information:

- (a) Sampling Strategy (line 1)
- (b) Over Sampling Size (line 2)
- (c) Number of factor levels (line 3)
- (d) Number of trajectories (line 4)
- (e) Number of factors (line 5)
- (f) Elementary Effects multiplication matrix (line 6 onwards)

(4) Mod\_Out\_File: This is a \*.xlsx' file or ASCII text file with '.out', '.dat' or '.txt' extensions. This tool can handle both scalar and time series outputs. The specific formats are as follows.

Scalar Outputs

If the model output/s of interest are scalar then arrange them column-wise (tab, space or comma delimited for text files). Output names should be specified in the first row.

Time Series Outputs

If the model output of interest are timeseries, the file format is as follows. The file name needs to start with 'Time', e.g. 'Time\_DummyModOut.out'. Note that only one output can be included in one file

Excel

	A	B	C	D	E	F
1	Dummy					
2	1	10	20			
3	-0.19753	0.802465	9.802465	Run1		
4	2.414359	3.414359	8.414359	Run2		
5	-29.5094	-29.5094	-25.5094	.		
6	-29.5094	-29.5094	-22.5094	.		
7	-29.5094	-28.5094	-18.5094	.		
8	2.414359	3.414359	12.41436	.		
9	2.414359	4.414359	5.414359	.		
10	8.136477	9.136477	10.13648	.		
11	8.016477	9.016477	14.01648	.		

ASCII File

For timeseries outputs saved in ASCII files, format is similar to Excel file. Columns can be tab, comma or space separated and the file extension could be any of '.out', '.txt', '.dat'.

(5) *Per\_Fac\_Label*: Percentage of factors to be labeled in EE Plots. Typically, relatively few factors are well separated from origin and are of interest, we suggest labeling top 20% to 40% of factors based on  $\mu^*$  values (i.e. use 20 or 40 on this input).

### **Outputs:**

(1) *EE\_SA\_Measures.txt*: Sensitivity measures based on the method of Elementary Effects/ Morris method are saved in this text file, for each model output. In case timeseries outputs, calculated measures are reported for each time.

(2) *Raw\_EE.txt*: This text file saves raw EEs for all outputs. For a given output, rows correspond to model factors while columns represent trajectories. These results can be used to verify accuracy of EEs or to perform any other analysis on Raw EEs as desired by the user.

(3) *Raw\_EE.mat*: Information in this file is same as *Raw\_EE.txt*, but is saved in '.mat' (Matlab) format for users with Matlab proficiency.

(4) *Plots*: Two figures/subplots are produced for each model output. The first subplot is a plot of  $\mu^*$  vs  $\sigma$  while the second one consists of  $\mu$  vs  $\sigma$ . Additionally, we plot  $\mu^* = \sigma$  line (dotted black line) on the first sub-plot and  $\mu = -/+ 2 \sigma/(\sqrt{r})$  lines (solid black line, with  $r$  number of sampling trajectories) on the second subplot. Factors above the lines in both plots are considered to have dominant interactions effects. The  $\mu = -/+2 \sigma/(\sqrt{r})$  lines were proposed by Morris (1991) to identify factors with dominant non-additive/non-linear effects. The 1:1 line (i.e.  $\mu^*=\sigma$ ) threshold is based on Chu-Agor et al. (2011) and Khare et al. (2019). Additionally, factors for which  $\mu^* = |\mu|$  holds true, i.e. factors with perfectly monotonic effects, are indicated by solid red circles while rest are indicated by blue asterisk. Also, bootstrapping based 95% CI for  $\mu^*$ ,  $\mu$ , and  $\sigma$  are indicated (golden color) on the subplots by horizontal error bars. Plots are automatically saved as PDF and JPG files. In case of timeseries outputs, a figure with three subplots ( $\mu^*$  vs time index,  $\mu$  vs time index, and  $\sigma$  vs time index) is generated in PDF and JPG format.

### **Folder Structure:**

This package consists of 7 Matlab functions (i.e. m files) namely (a) *EE\_SenMea\_Calc*, (b) *EE\_Plots*, (c) *Morris\_Measure\_Groups*, (d) *Morris\_Measures*, (e) *Morris\_Measure\_Radial*, (f) *EE\_Rad\_Traj*, and (g) *ReadFacDist* saved in folder '*EE\_SensitivityMeasures*'. Output files – '*EE\_SA\_Measures.txt*', '*EE\_Raw.txt*', '*EE\_Raw.mat*', and plots (PDFs and JPGs) will be saved in the package folder.

For demonstration purposes we have provided input files required for each of the examples presented in this documentation. Please note that if users generate their own samples with the EE Sampling package for these examples, they should also recalculate the example model outputs as the EE measures would differ from the ones presented below.

### **Examples of syntax:**

(a) If both sample and model output files are excel (.xlsx) files.

```
EE_SenMea_Calc('Example_FacFile.fac', 'Example_Sample.xlsx', 'Example_SampleChar.txt', 'Example_Output.xlsx', 20)
```

(b) If sample file is \*.sam and model output file is \*.out

```
EE_SenMea_Calc('Example_FacFile.fac', 'Example_Sample.sam', 'Example_SampleChar.txt', 'Example_Output.out', 20)
```

(c) If sample file is \*.sam and model output file is \*.xlsx

`EE_SenMea_Calc('Example_FacFile.fac', 'Example_Sample.sam', 'Example_SampleChar.txt', 'Example_Output.xlsx', 20)`

(d) If sample file is \*.xlsx and model output file is \*.dat

`EE_SenMea_Calc('Example_FacFile.fac', 'Example_Sample.xlsx', 'Example_SampleChar.txt', 'Example_Output.dat', 20)`

# Input/Output Example

## Example 1

This is based on Example1 sample generated in the EE\_Sampling package documentation.

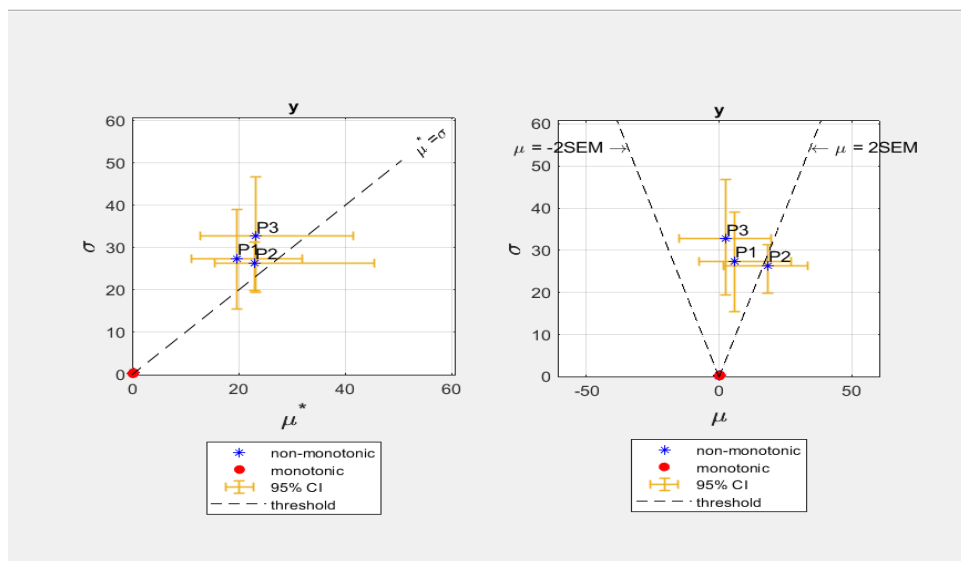
$$y = \prod_1^3 P_i + \prod_4^6 P_i$$

Model output:

Model outputs results were saved in 'Example1\_Mod\_Out.xlsx' file. To calculate EE measures, first copy previously generated 'Example1\_FacSample.sam' and 'Example1\_FacSamChar.txt' files to EE\_SensitivityMeasures Package. Then type the following in Matlab command window (make sure that EE\_SensitivityMeasures Package is the active Matlab folder):

```
Command Window
New to MATLAB? See resources for Getting Started.
>> EE_SenMea_Calc('Example1.fac', 'Example1_FacSample.sam', 'Example1_FacSamChar.txt', ...
fx: 'Example1_Mod_Out.xlsx', 40)
```

This will generate the figure below, which is automatically saved as a PDF file. EE sensitivity indices ( $\mu^*$ ,  $\mu$  and  $\sigma$ ) are also written to 'Example1\_EE\_Measures.txt'. Both files are saved in EE\_SensitivityMeasures\_Package directory.



Note that we specified to label top 40% of the factors. In this case there are 6 model factors and hence after rounding up ( $6 \times 0.4 = 2.4 \rightarrow 3$ ) top three factors were labeled.

```

Example1_EE_Measures.txt
1 Y
2 facname      mu*      mu      sigma
3 P1      1.9681e+01      5.9437e+00      2.7404e+01
4 P2      2.3007e+01      1.8460e+01      2.6405e+01
5 P3      2.3240e+01      2.6220e+00      3.2741e+01
6 P4      2.8000e-01      2.8000e-01      4.5412e-01
7 P5      1.8000e-01      1.8000e-01      2.2010e-01
8 P6      1.8000e-01      1.8000e-01      3.1958e-01
9 -----
10
    
```

```

Example1_EE_Raw.txt
1 y
2 facname      trajectory ->
3 P1 -4.3532e+00 -1.4454e+01 -2.6722e+01 -4.3532e+00 5.3206e+01 5.3206e+01 7.2592e+00 -4.3532e+00
4 P2 5.3206e+01 2.6722e+01 1.4454e+01 -4.3532e+00 5.3206e+01 4.3532e+00 -3.9265e+00 5.3206e+01
5 P3 5.3206e+01 1.1826e+00 1.4454e+01 -4.3532e+00 -4.3532e+00 -5.3206e+01 7.2592e+00 5.3206e+01
6 P4 -0.0000e+00 0.0000e+00 8.0000e-01 -0.0000e+00 1.0000e+00 0.0000e+00 -0.0000e+00 1.0000e+00
7 P5 -0.0000e+00 2.0000e-01 2.0000e-01 0.0000e+00 6.0000e-01 4.0000e-01 0.0000e+00 4.0000e-01
8 P6 0.0000e+00 -0.0000e+00 1.0000e+00 -0.0000e+00 0.0000e+00 2.4000e-01 4.0000e-01 1.6000e-01
9 -----
10
    
```

The two screenshots above show the *EE\_Measures.txt* and *EE\_Raw.txt* ASCII text files produced by the package that summarize the EE measures.

### Example 2

This is based on Example 2 sampling generated in the EE Sampling package documentation.

Model output:

$$y1 = \left( \sum_{i=1}^7 P_i \right) \left( \frac{P_8}{10} + \frac{P_9}{1000} + \frac{P_{10}}{100000} \right) + \prod_{i=11}^{16} P_i$$

$$y2 = P_1^2 + (P_2 * P_3) + \exp(P_4 + P_5 + P_6 + P_7)$$

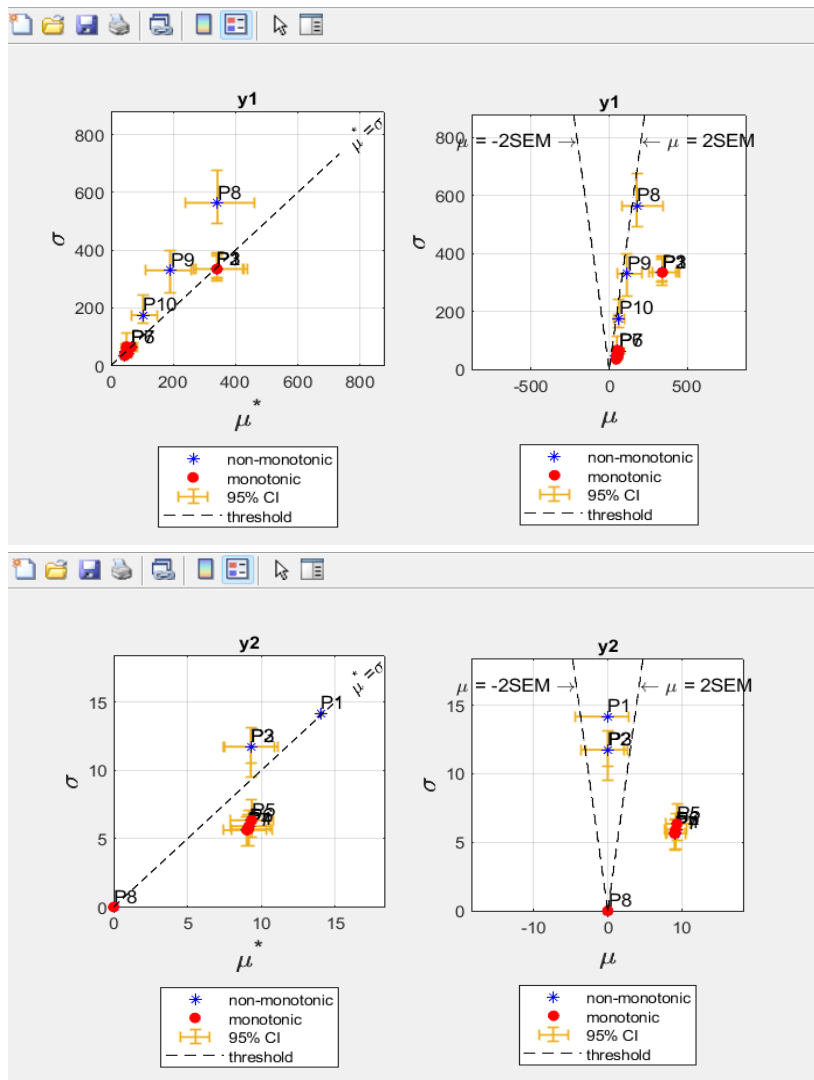
Model outputs results were saved in 'Example2\_Mod\_Output.txt' file (tab delimited). To calculate EE measures, first copy previously generated 'Example2\_FacSample.xlsx' and 'Example2\_FacSamChar.txt' files to the 'EE\_SensitivityMeasures\_Package' directory. Then type following in Matlab command window (make sure that

EE\_SensitivityMeasures\_Package is the active Matlab folder):

```

Command Window
New to MATLAB? See resources for Getting Started.
>> EE_SenMea_Calc('Example2.fac','Example2_FacSample.xlsx','Example2_FacSamChar.txt', ...
fx 'Example2_Mod_Output.txt',50)
    
```

Output:

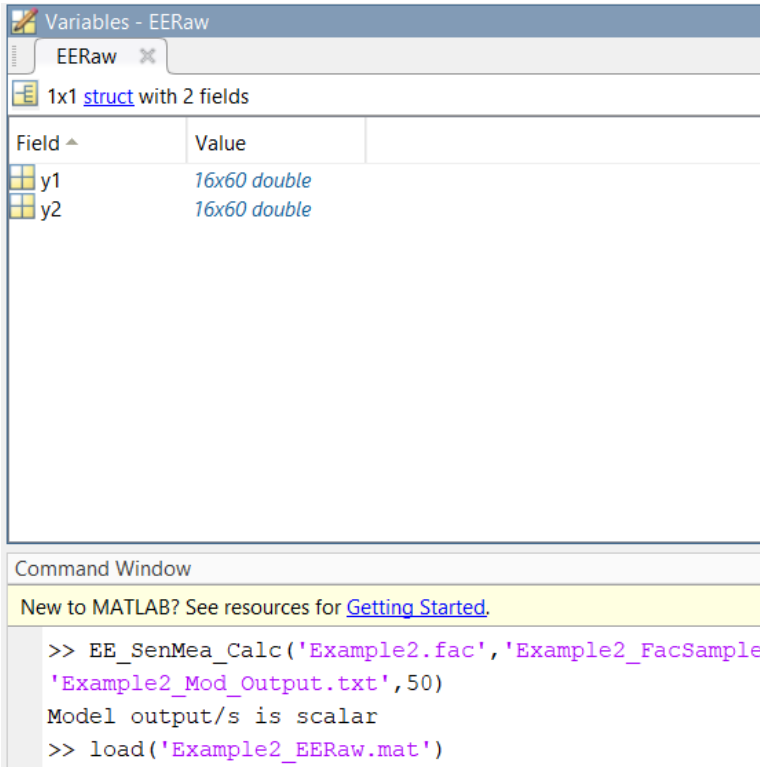


Example2_EE_Measures.txt				
y1				
	facname	mu*	mu	sigma
1				
2				
3	P1	3.3994e+02	3.3994e+02	3.3430e+02
4	P2	3.3994e+02	3.3994e+02	3.3430e+02
5	P3	3.3994e+02	3.3994e+02	3.3430e+02
6	P4	6.4382e+01	6.4382e+01	6.3313e+01
7	P5	6.4382e+01	6.4382e+01	6.3313e+01
8	P6	6.4382e+01	6.4382e+01	6.3313e+01
9	P7	6.4382e+01	6.4382e+01	6.3313e+01
10	P8	3.4150e+02	1.7611e+02	5.6342e+02
11	P9	1.8986e+02	1.1294e+02	3.2984e+02
12	P10	1.0295e+02	6.2096e+01	1.7429e+02
13	P11	4.9800e+01	4.9800e+01	6.5671e+01
14	P12	4.8675e+01	4.8675e+01	5.0125e+01
15	P13	4.4600e+01	4.4600e+01	3.4293e+01
16	P14	4.7850e+01	4.7850e+01	4.5128e+01
17	P15	4.9975e+01	4.9975e+01	5.0192e+01
18	P16	5.4550e+01	5.4550e+01	4.2320e+01
19	-----			
y2				
	facname	mu*	mu	sigma
20				
21				
22	P1	1.4047e+01	-6.5000e-10	1.4166e+01
23	P2	9.2930e+00	-1.0000e-09	1.1747e+01
24	P3	9.2930e+00	4.2500e-10	1.1747e+01
25	P4	9.1233e+00	9.1233e+00	5.6837e+00
26	P5	9.3566e+00	9.3566e+00	6.3521e+00
27	P6	9.1697e+00	9.1697e+00	5.9260e+00
28	P7	9.0212e+00	9.0212e+00	5.6344e+00
29	P8	0.0000e+00	0.0000e+00	0.0000e+00
30	P9	0.0000e+00	0.0000e+00	0.0000e+00
31	P10	0.0000e+00	0.0000e+00	0.0000e+00
32	P11	0.0000e+00	0.0000e+00	0.0000e+00
33	P12	0.0000e+00	0.0000e+00	0.0000e+00
34	P13	0.0000e+00	0.0000e+00	0.0000e+00
35	P14	0.0000e+00	0.0000e+00	0.0000e+00
36	P15	0.0000e+00	0.0000e+00	0.0000e+00
37	P16	0.0000e+00	0.0000e+00	0.0000e+00
38	-----			

Note: The sample for this example was generated with the eSU method. For the second output (y2), it was expected that (1) P8 to P16 will have zero sensitivity indices, (2) P2 and P3 should have identical sensitivity indices due to their distributions and nature of output function, (3) P4 to P7 should have identical indices, and (4) P1, P2 and P3 would be non-monotonic. From the calculated indices three of these four things were found to be true. Though sensitivity measures for P4 to P7 were not identical they were relatively close.

To import Raw EEs for this example, type `load Example2_EERaw.mat` in the Matlab command window, which will load `EERaw` in Matlab Workspace as shown below,





Variables - EERaw

EERaw

1x1 struct with 2 fields

Field	Value
y1	16x60 double
y2	16x60 double

Command Window

New to MATLAB? See resources for [Getting Started](#).

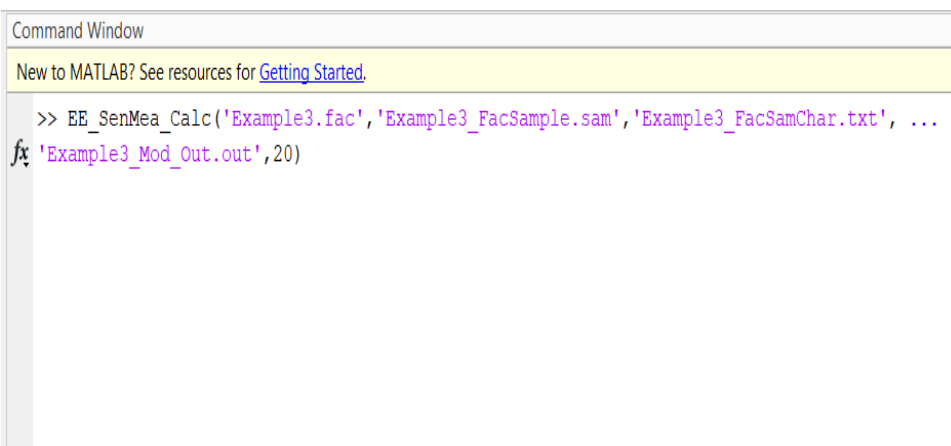
```
>> EE_SenMea_Calc('Example2.fac','Example2_FacSample
'Example2_Mod_Output.txt',50)
Model output/s is scalar
>> load('Example2_EERaw.mat')
```

### Example 3

This is based on Example 3 sample generated in the *EE Sampling* package documentation (please see details following the link on top of this page).

Model Output:  $y = P_1*(P_4+P_5) + P_2P_6 + P_3P_7 + [P_{10}/(P_8+P_9)]$

Model outputs results were saved in 'Example3\_Mod\_Out.out' file. To calculate EE measures, first copy previously generated 'Example3\_FacSample.sam' and 'Example3\_FacSamChar.txt' files to the 'EE\_SensitivityMeasures\_Package' directory. Then type the following in Matlab command window (make sure that EE\_SensitivityMeasures\_Package is the active Matlab folder):

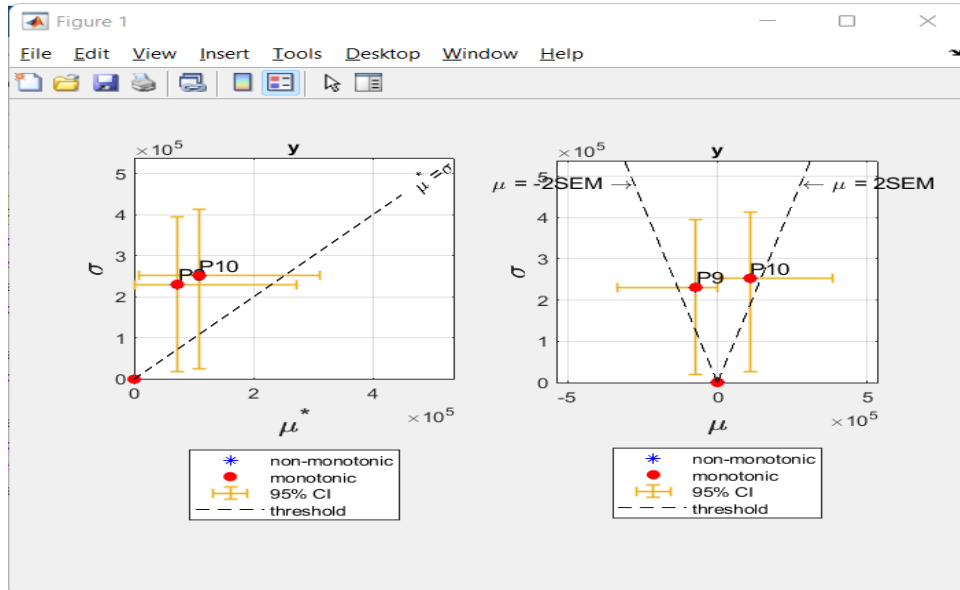


Command Window

New to MATLAB? See resources for [Getting Started](#).

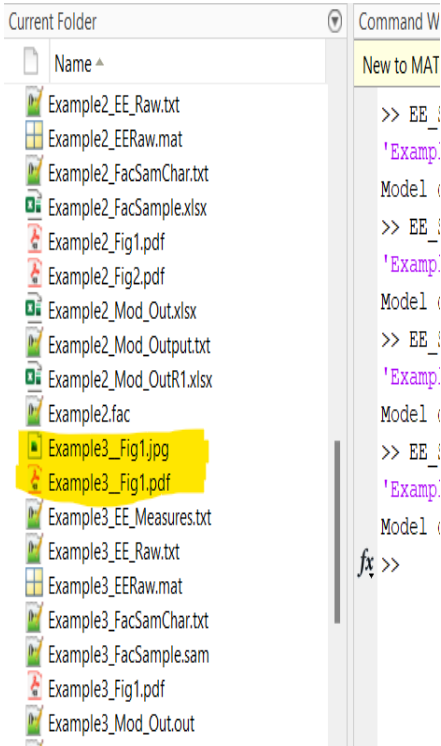
```
>> EE_SenMea_Calc('Example3.fac','Example3_FacSample.sam','Example3_FacSamChar.txt', ...
fx 'Example3_Mod_Out.out',20)
```

Package will produce following figure, which is automatically saved as PDF and JPG files. EE sensitivity indices ( $\mu^*$ ,  $\mu$  and  $\sigma$ ) are also written to 'Example3\_EE\_Measures.txt'. Both files are saved in EE\_SensitivityMeasures package along with Example3\_EERaw.mat and Example3\_EERaw.txt.



Example3\_EE\_Measures.txt

1	y			
2	facname	$\mu^*$	$\mu$	$\sigma$
3	P1	3.9719e+00	3.9719e+00	2.1104e+00
4	P2	1.8305e+00	1.8305e+00	1.5389e+00
5	P3	2.0260e+00	2.0260e+00	1.5980e+00
6	P4	1.0653e+00	-7.0583e-08	1.5158e+00
7	P5	1.0653e+00	7.0889e-08	1.5158e+00
8	P6	1.0653e+00	6.1111e-07	1.5158e+00
9	P7	1.0653e+00	-6.1111e-10	1.5158e+00
10	P8	8.9013e+01	-8.9013e+01	2.5342e+02
11	P9	7.2433e+04	-7.2433e+04	2.3092e+05
12	P10	1.0915e+05	1.0915e+05	2.5253e+05
13	-----			
14				



### Example 4

This is based on Example 4 sample generated based on 'RadialeSU' method in the EE Sampling package documentation.

Model Outputs:

$$Y1 = \sum_{i=1}^{10} \frac{1}{1 + P_i}$$

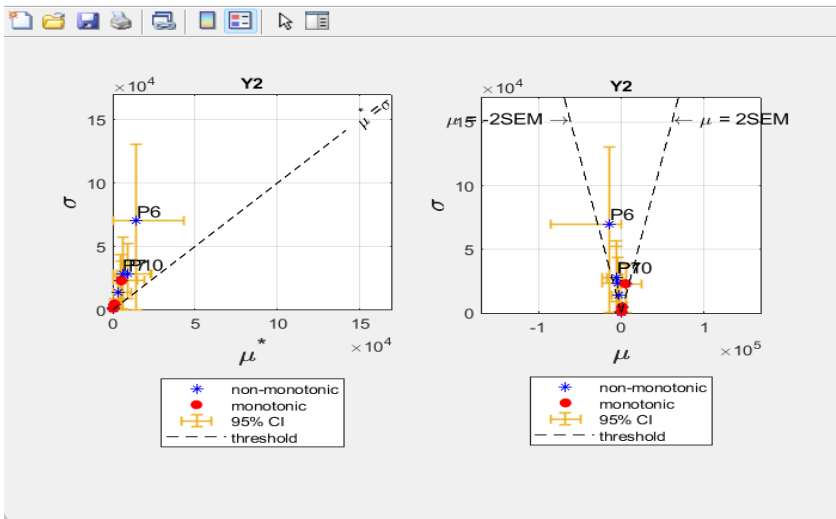
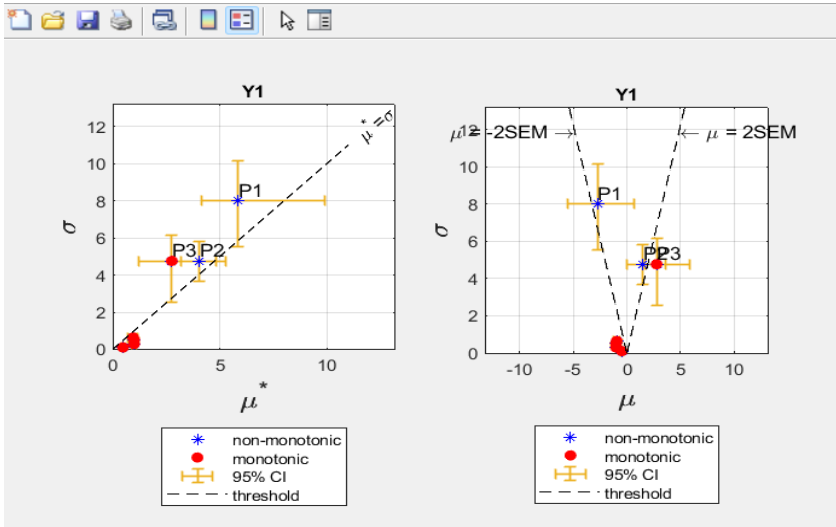
$$Y2 = \left( \sum_{i=1}^3 P_i \right) \left( \prod_{i=4}^7 P_i \right) \left( \sum_{i=8}^{10} \frac{P_i}{10^{i-8}} \right)$$

The model outputs results were saved in 'Example4\_Mod\_Out.dat' file (a comma separated ASCII file). To calculate EE measures, first copy previously generated 'Example4\_FacSample.sam' and 'Example4\_FacSamChar.txt' files to EE\_SensitivityMeasures\_Package directory. Then type the following in Matlab command window (make sure that EE\_SensitivityMeasures Package is the active Matlab folder):

```

Command Window
New to MATLAB? See resources for Getting Started.
>> EE_SenMea_Calc('Example4.fac', 'Example4_FacSample.sam', 'Example4_FacSamChar.txt', ...
fx: 'Example4_Mod_Out.dat', 25)
    
```

With output:



Example4_EE_Measures.txt				
1	Y1			
2	facname	mu*	mu	sigma
3	P1	5.8517e+00	-2.7067e+00	7.9975e+00
4	P2	4.0508e+00	1.5008e+00	4.7585e+00
5	P3	2.7614e+00	2.7614e+00	4.7671e+00
6	P4	4.7619e-01	-4.7619e-01	1.0583e-01
7	P5	4.7619e-01	-4.7619e-01	1.0583e-01
8	P6	4.7619e-01	-4.7619e-01	1.0583e-01
9	P7	4.7619e-01	-4.7619e-01	1.0583e-01
10	P8	9.9491e-01	-9.9491e-01	2.9426e-01
11	P9	1.0008e+00	-1.0008e+00	5.1883e-01
12	P10	9.5023e-01	-9.5023e-01	6.4551e-01
13	-----			
14	Y2			
15	facname	mu*	mu	sigma
16	P1	2.9825e+02	2.9825e+02	1.2082e+03
17	P2	1.0412e+03	1.0412e+03	4.5989e+03
18	P3	5.2051e+03	5.2051e+03	2.3003e+04
19	P4	3.2674e+03	-2.7576e+03	1.4081e+04
20	P5	4.9217e+03	-4.7259e+03	2.3362e+04
21	P6	1.4391e+04	-1.4245e+04	7.0057e+04
22	P7	5.8402e+03	-5.7185e+03	2.8020e+04
23	P8	1.8180e+02	3.7308e+01	4.8009e+02
24	P9	2.7094e+02	2.2753e+02	1.2096e+03
25	P10	9.1647e+03	-5.4600e+03	2.8009e+04
26	-----			
27				

### Example 5: Special case of constant model inputs

Sometimes the model output does not change due to multiple reasons including (a) the model is not a function of the factors that are being varied, (b) the output is a constant, (c) simulation errors. In such a case all Elementary Effects and hence sensitivity measures will be zero and the tool will issue a warning on the Matlab command window and plots.

To demonstrate this, we have modified Example 2 (presented earlier). The new model outputs are constants,  $y_1 = 0$  and  $y_2 = 3$ .

The new outputs were saved in 'Example2\_Mod\_OutR1.xlsx'. Please see the following figures for details,

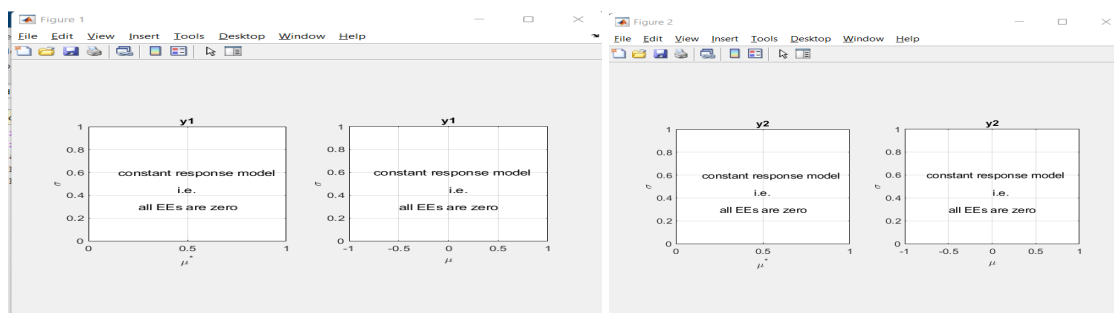
```
Command Window
New to MATLAB? See resources for Getting Started.
>> EE_SenMea_Calc('Example2.fac', 'Example2_FacSample.xlsx', 'Example2_FacSamChar.txt', ...
fx: 'Example2_Mod_OutR1.xlsx', 25)
```

```

Command Window
New to MATLAB? See resources for Getting Started.

>> EE_SenMea_Calc('Example2.fac', 'Example2_FacSample.xlsx', 'Example2_FacSamChar.txt', ...
'Example2_Mod_OutR1.xlsx', 25)
Model output/s is scalar
y1 is a constant response model. Please verify model and simulations for accuracy
y2 is a constant response model. Please verify model and simulations for accuracy
fx >>
    
```

With output:



### Example 6: Special Case – Udiscrete Factors

This is based on Special Case sample generated based on ‘eSU’ method in the EE Sampling package documentation. In this example we have several factors with UDiscrete distributions for which number of categories were not equal to NumLev = 4 that was defined to generate the factor sample.

Model Outputs:

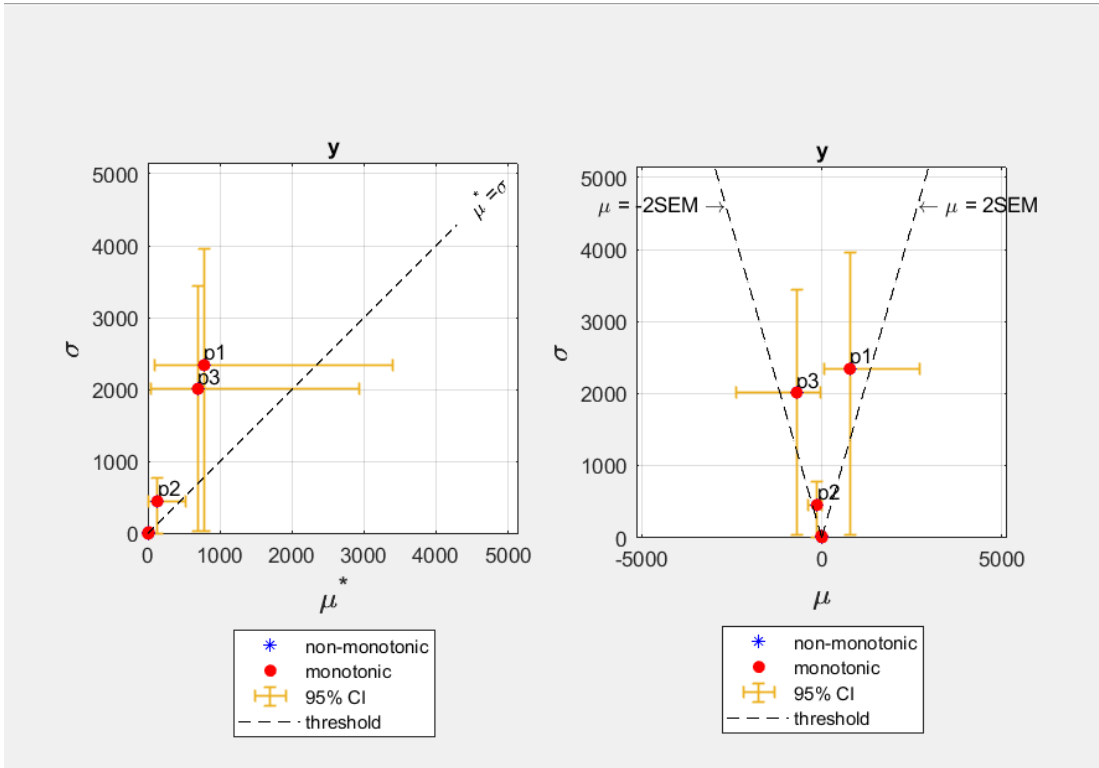
$$y = \frac{1}{(P2 \times P4) + P5} + \frac{P6}{100} + P7$$

As shown in the Sampler Mapper tool documentation, for P2, P4, and P5 Elementary Effects multiplication matrix has values different from 1. The model outputs results were saved in ‘SpCase\_Mod\_Out.xlsx’ file. To calculate EE measures, first copy previously generated ‘SpCase\_FacSample.xlsx’ and ‘SpCase\_FacSamChar.txt’ files to EE\_SensitivityMeasures\_Package directory. Then type the following in Matlab command window (make sure that EE\_SensitivityMeasures Package is the active Matlab folder):

```

Command Window
New to MATLAB? See resources for Getting Started.

>> EE_SenMea_Calc('SpCase.fac','SpCase_FacSample.xlsx','SpCase_FacSamChar.txt', ...
fx: 'SpCase_Mod_Out.xlsx',40)
    
```



### Example 7: Time Series Output

This timeseries output example is based on Example 1 sample generated in the EE Sampling package documentation. The model output is calculated using following function.

Model Outputs:

$$y(t) = \sum_{i=1}^3 \exp\left(\frac{-P_i}{i \times t}\right) + \prod_{i=4}^6 (i-3) \times t \times P_i$$

This model was evaluated for  $t = \{1, 2, 4, 8, 16\}$  and saved in an excel file 'Time\_Series\_Out.xlsx' as shown below. Please refer to the Syntax section of this documentation for time series output file format details. Note that timeseries output file name needs to start with 'Time'.

	A	B	C	D	E
1	Series				
2	1	2	4	8	16
3	4.459102	3.493692	3.201352	3.090628	3.042949
4	25.66398	7.300883	4.427884	3.593227	3.271676
5	29.47117	8.527415	4.930483	3.821954	3.380932
6	29.47117	8.527415	4.930483	3.821954	3.380932
7	29.47117	8.527415	4.930483	3.821954	3.380932
8	27.58909	7.812458	4.615921	3.67406	3.309181
9	27.58909	7.812458	4.615921	3.67406	3.309181
10	1.779694	3.061461	5.015186	8.267655	14.25613
11	1.059694	1.621461	2.135186	2.507655	2.736125
12	1.059694	1.621461	2.135186	2.507655	2.736125
13	1.924042	2.044289	2.345441	2.612638	2.788599
14	1.924042	2.044289	2.345441	2.612638	2.788599
15	3.166213	2.965751	2.948855	2.965163	2.980158
16	3.89716	3.411309	3.197179	3.096567	3.047789
17	6.731168	5.220508	5.47934	7.103981	10.8083
18	7.451168	6.660508	8.35934	12.86398	22.3283
19	6.529706	6.057094	8.006815	12.67242	22.22831
20	10.12971	13.25709	22.40681	41.47242	79.82831
21	8.246478	12.39275	21.98399	41.26217	79.72333
22	5.366478	6.632746	10.46399	18.22217	33.64333
23	3.484403	5.917789	10.14942	18.07427	33.57158
24	1.537229	1.876019	2.266911	2.574697	2.76995
25	1.537229	1.876019	2.266911	2.574697	2.76995
26	1.537229	1.876019	2.266911	2.574697	2.76995
27	2.779401	2.797482	2.870325	2.927222	2.961509

To calculate sensitivity measures for this output type following in Matlab command window

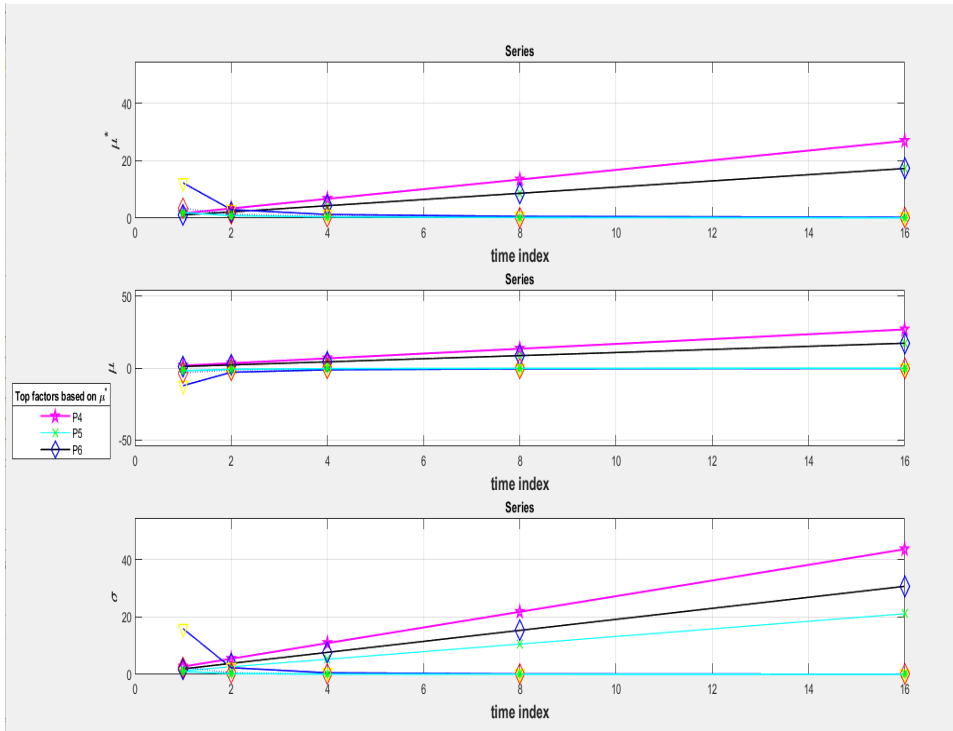
```

Command Window
New to MATLAB? See resources for Getting Started.

>> EE_SenMea_Calc('Example1.fac', 'Example1_FacSample.sam', 'Example1_FacSamChar.txt', ...
fx 'Time_Series_Out.xlsx', 40)
    
```

The sensitivity measures timeseries outputs are as shown





Sensitivity Measures text outputs

```

Example1_ts_SeriesEE_Measures.bt x
1 time1
2 facname      mu*      mu      sigma
3 P1      1.2265e+01      -1.2265e+01      1.5930e+01
4 P2      3.4406e+00      -3.4406e+00      2.5003e+00
5 P3      1.9310e+00      -1.9310e+00      1.0431e+00
6 P4      1.6800e+00      1.6800e+00      2.7247e+00
7 P5      1.0800e+00      1.0800e+00      1.3206e+00
8 P6      1.0800e+00      1.0800e+00      1.9175e+00
9 -----
10 time2
11 facname      mu*      mu      sigma
12 P1      2.9596e+00      -2.9596e+00      2.3367e+00
13 P2      1.3609e+00      -1.3609e+00      5.9940e-01
14 P3      8.6726e-01      -8.6726e-01      2.9850e-01
15 P4      3.3600e+00      3.3600e+00      5.4494e+00
16 P5      2.1600e+00      2.1600e+00      2.6412e+00
17 P6      2.1600e+00      2.1600e+00      3.8350e+00
18 -----
19 time4
20 facname      mu*      mu      sigma
21 P1      1.2571e+00      -1.2571e+00      5.5627e-01
22 P2      6.4017e-01      -6.4017e-01      1.9293e-01
23 P3      4.2193e-01      -4.2193e-01      1.1218e-01
24 P4      6.7200e+00      6.7200e+00      1.0899e+01
25 P5      4.3200e+00      4.3200e+00      5.2824e+00
26 P6      4.3200e+00      4.3200e+00      7.6700e+00
27 -----
28 time8
29 facname      mu*      mu      sigma
30 P1      6.1516e-01      -6.1516e-01      1.8028e-01
31 P2      3.1519e-01      -3.1519e-01      7.9459e-02
32 P3      2.0952e-01      -2.0952e-01      5.0650e-02
33 P4      1.3440e+01      1.3440e+01      2.1798e+01
34 P5      8.6400e+00      8.6400e+00      1.0565e+01
35 P6      8.6400e+00      8.6400e+00      1.5340e+01
36 -----
37 time16
38 facname      mu*      mu      sigma
39 P1      3.0899e-01      -3.0899e-01      7.6083e-02
40 P2      1.5698e-01      -1.5698e-01      3.7362e-02
41 P3      1.0458e-01      -1.0458e-01      2.4606e-02
42 P4      2.6880e+01      2.6880e+01      4.3595e+01
    
```

Normal text file | length : 2,061 | lines : 46 | Ln : 1 | Col : 1 | Pos : 1

Raw EE outputs

```

Example1_ts_SeriesEE_Raw.txt
1 time1
2 facname trajectory ->
3 P1 -3.5341e+01 -2.0703e+00 -3.1387e+00 -2.0703e+00 -3.5341e+01 -2.0703e+00 -3.1387e+00 -2.0703e+00 -2.0703e+00
4 P2 -6.3453e+00 -1.4406e+00 -1.5358e+00 -1.5358e+00 -6.3453e+00 -6.3453e+00 -1.5358e+00 -1.5358e+00 -6.3453e+00
5 P3 -3.1368e+00 -1.2182e+00 -3.1368e+00 -1.2182e+00 -3.1368e+00 -3.1368e+00 -9.4498e-01 -1.2182e+00 -9.4498e-01
6 P4 -0.0000e+00 0.0000e+00 4.8000e+00 -0.0000e+00 6.0000e+00 0.0000e+00 -0.0000e+00 6.0000e+00 0.0000e+00
7 P5 -0.0000e+00 1.2000e+00 1.2000e+00 0.0000e+00 3.6000e+00 2.4000e+00 0.0000e+00 2.4000e+00 -0.0000e+00
8 P6 0.0000e+00 -0.0000e+00 6.0000e+00 -0.0000e+00 0.0000e+00 1.4400e+00 2.4000e+00 9.6000e-01 -0.0000e+00
9 -----
10 time2
11 facname trajectory ->
12 P1 -6.3453e+00 -1.5358e+00 -1.4406e+00 -1.5358e+00 -6.3453e+00 -1.5358e+00 -1.4406e+00 -1.5358e+00 -1.5358e+00
13 P2 -2.0442e+00 -7.0471e-01 -1.0057e+00 -1.0057e+00 -2.0442e+00 -2.0442e+00 -1.0057e+00 -1.0057e+00 -2.0442e+00
14 P3 -1.1916e+00 -7.4260e-01 -1.1916e+00 -7.4260e-01 -1.1916e+00 -1.1916e+00 -4.6790e-01 -7.4260e-01 -4.6790e-01
15 P4 -0.0000e+00 0.0000e+00 9.6000e+00 -0.0000e+00 1.2000e+01 0.0000e+00 -0.0000e+00 1.2000e+01 0.0000e+00
16 P5 -0.0000e+00 2.4000e+00 2.4000e+00 0.0000e+00 7.2000e+00 4.8000e+00 0.0000e+00 4.8000e+00 -0.0000e+00
17 P6 0.0000e+00 -0.0000e+00 1.2000e+01 -0.0000e+00 0.0000e+00 2.8800e+00 4.8000e+00 1.9200e+00 -0.0000e+00
18 -----
19 time4
20 facname trajectory ->
21 P1 -2.0442e+00 -1.0057e+00 -7.0471e-01 -1.0057e+00 -2.0442e+00 -1.0057e+00 -7.0471e-01 -1.0057e+00 -1.0057e+00
22 P2 -8.3766e-01 -3.5043e-01 -5.8754e-01 -5.8754e-01 -8.3766e-01 -8.3766e-01 -5.8754e-01 -5.8754e-01 -8.3766e-01
23 P3 -5.2427e-01 -4.1387e-01 -5.2427e-01 -4.1387e-01 -5.2427e-01 -5.2427e-01 -2.3338e-01 -4.1387e-01 -2.3338e-01
24 P4 -0.0000e+00 0.0000e+00 1.9200e+01 -0.0000e+00 2.4000e+01 0.0000e+00 -0.0000e+00 2.4000e+01 0.0000e+00
25 P5 -0.0000e+00 4.8000e+00 4.8000e+00 0.0000e+00 1.4400e+01 9.6000e+00 0.0000e+00 9.6000e+00 -0.0000e+00
26 P6 0.0000e+00 -0.0000e+00 2.4000e+01 -0.0000e+00 0.0000e+00 5.7600e+00 9.6000e+00 3.8400e+00 -0.0000e+00
27 -----
28 time8
29 facname trajectory ->
30 P1 -8.3766e-01 -5.8754e-01 -3.5043e-01 -5.8754e-01 -8.3766e-01 -5.8754e-01 -3.5043e-01 -5.8754e-01 -5.8754e-01

```

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- Saltelli, A., S. Tarantola, F. Campolongo, and M. Ratto. 2004. *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models*. Chichester, U.K.: John Wiley and Sons. [with software [SIMLAB v2.2.1 available here](#)]

## Program License

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We highly encourage using these packages for EE (Morris) sampling and sensitivity measures calculations with the eSU ('enhanced Sampling for Uniformity') method. If you use this package, kindly acknowledge our effort. Also, if you have any question in usage of this package, please contact us on the email address below.

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APPENDIX A:  
PROBABILITY DISTRIBUTION FUNCTIONS FOR INPUT FACTORS USED  
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## Normal distribution

The density function of the Normal distribution has the following expression:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-1}{2} \left[\frac{x - \mu}{\sigma}\right]^2\right]$$

for  $x$  in  $(-\infty, \infty)$ .

Distribution  
parameters

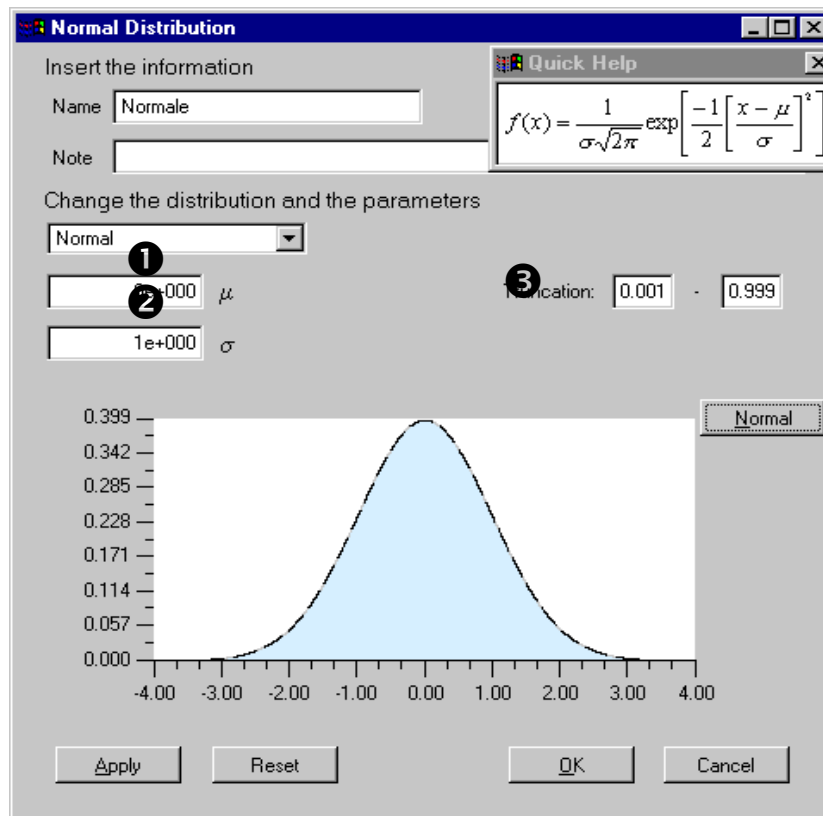


Figure 89 Normal distribution panel

- ❶ Mean value ( $\mu$ ), with  $\mu$  in  $(-\infty, \infty)$ ; the default value is  $\mu = 0e+000$ .
- ❷ Standard deviation value ( $\sigma$ ), with  $\sigma > 0$ ; the default value is  $\sigma = 1e+000$ .
- ❸ Truncation value; the default value is in  $[0.001, 0.999]$ .

There is the possibility to see the density formula through Quick Help by pressing the Normal button and close it by pushing again this button. The Quick Help functionality is the same for all distribution panels.

## LogNormal distribution

The density function of the LogNormal distribution has the following expression:

$$f(x) = \frac{1}{x \cdot \sigma \cdot \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left[\frac{\ln(x) - \mu}{\sigma}\right]^2\right] \cdot \mathbf{1}_{(0, \infty)}(x)$$

for  $x$  in  $(0, \infty)$ .

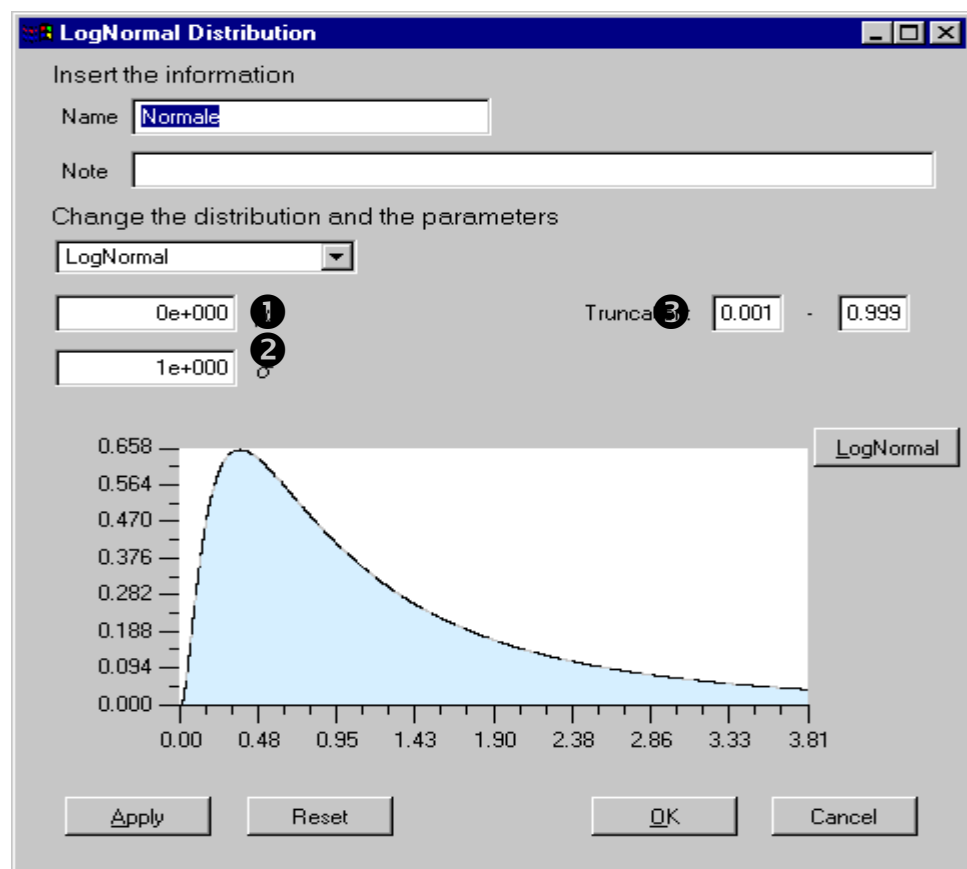


Figure 90 Log-Normal distribution panel

### Distribution parameters

- ①  $\mu$  parameter; the default value for  $\mu$  is 0.
- ②  $\sigma$  parameter; the default value for  $\sigma$  is 1.
- ③ Truncation value; the default value is in  $[0.001, 0.999]$ .

Mean value:  $\exp\left(\mu + \frac{1}{2}\sigma^2\right)$

Standard deviation:  $\exp(2\mu + 2\sigma^2) - \exp(2\mu - \sigma^2)$

## Uniform distribution

The density function of the Uniform distribution has the following expression:

$$f(x) = \sum_{i=1}^n \frac{Weight_i}{RightVal_i - LeftVal_i}$$

with  $n$  number of intervals.

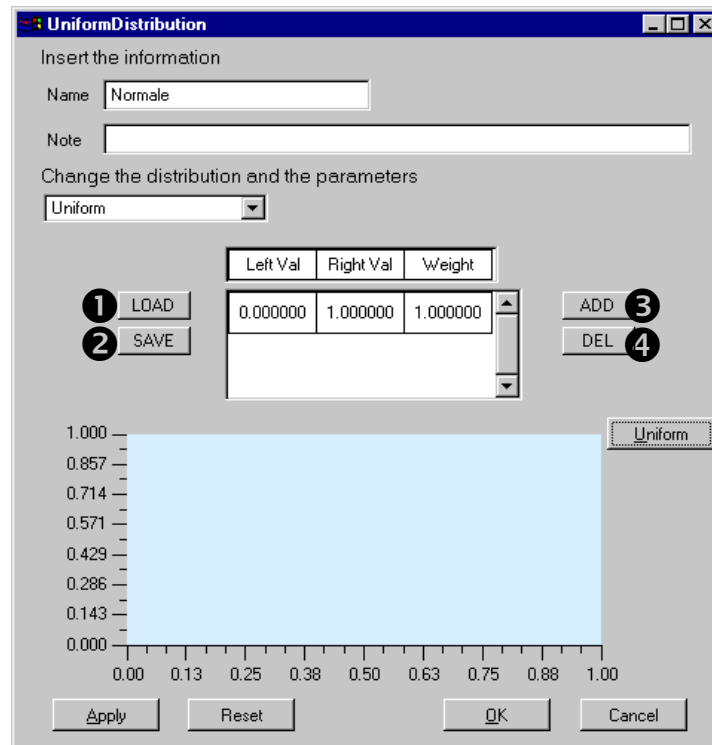


Figure 91 Uniform distribution panel

- Buttons description**
- ① **LOAD button.** The user can select this button to load a set of intervals for the current uniform distribution. This list of intervals will overwrite any previous list of intervals present in the matrix.
  - ② **SAVE button.** This button allows the user to save in a file the current intervals for the uniform distribution.
  - ③ **ADD button.** This button is used to insert a new interval for the current uniform distribution. For each interval, the user has to insert the left bound, the right bound and the relative weight of the interval. The intervals can't overlap and the sum of the weights must be equal to 1.
  - ④ **DEL button.** With this button the user may delete any interval present in the matrix. The user must select one interval before pressing the DEL button. After deleting an interval, the weight of the remaining elements must be corrected.

**Parameters area**

This area contains the parameters that characterise the uniform distribution:  $RightVal_i$  and  $LeftVal_i$  are the extreme values of  $i$ -th subinterval so that

$(RightVal_i - LeftVal_i) > 0$  for each  $i$ ;

$Weight_i$  is the weight of the  $i$ -th subinterval, the sum of all the weights must be equal to 1.

The user can modify each value double clicking the matrix item.

$$\text{Mean Value: } \sum_{i=1}^n \left( \frac{LeftVal_i + RightVal_i}{2} \right) * w_i$$

$$\text{Standard deviation: } \sqrt{\sum_{i=1}^n \left( \frac{(LeftVal_i^3 - RightVal_i^3)}{LeftVal_i - RightVal_i} * \frac{1}{3} * w_i \right)}$$



## LogUniform distribution

The density function of the LogUniform distribution has the following expression:

$$f(x) = \sum_{i=1}^n \frac{Weight_i}{x \cdot (\ln(RightVal_i) - \ln(LeftVal_i))}$$

with  $n$  number of intervals.

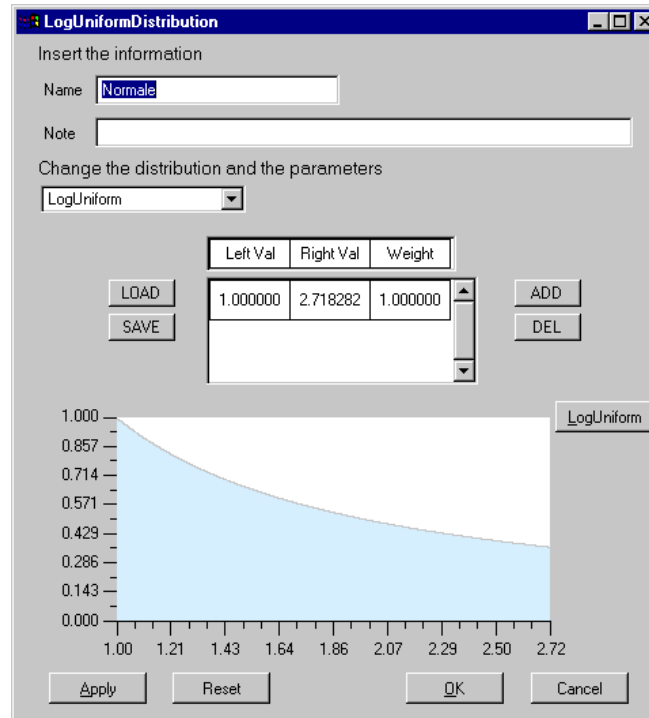


Figure 92 LogUniform distribution panel

**Mean Value ( $\mu$ ):** 
$$\sum_{i=1}^n \frac{RightVal_i - LeftVal_i}{\log(RightVal_i) - \log(LeftVal_i)}$$

**Standard deviation:**

$$\sqrt{\sum_{i=1}^n \left( \frac{RightVal_i^2 - LeftVal_i^2}{2 \cdot (\log(RightVal_i) - \log(LeftVal_i))} \right) + \mu^2 - 2\mu \cdot \frac{RightVal_i - LeftVal_i}{\log(RightVal_i) - \log(LeftVal_i)}}$$

## Weibull distribution

The density function of the Weibull distribution has the following expression:

$$f(x) = \frac{\beta}{n} * \left[ \frac{x-b}{n} \right]^{\beta-1} \cdot \exp \left[ - \left( \frac{x-b}{n} \right)^{\beta} \right]$$

### Distribution parameters

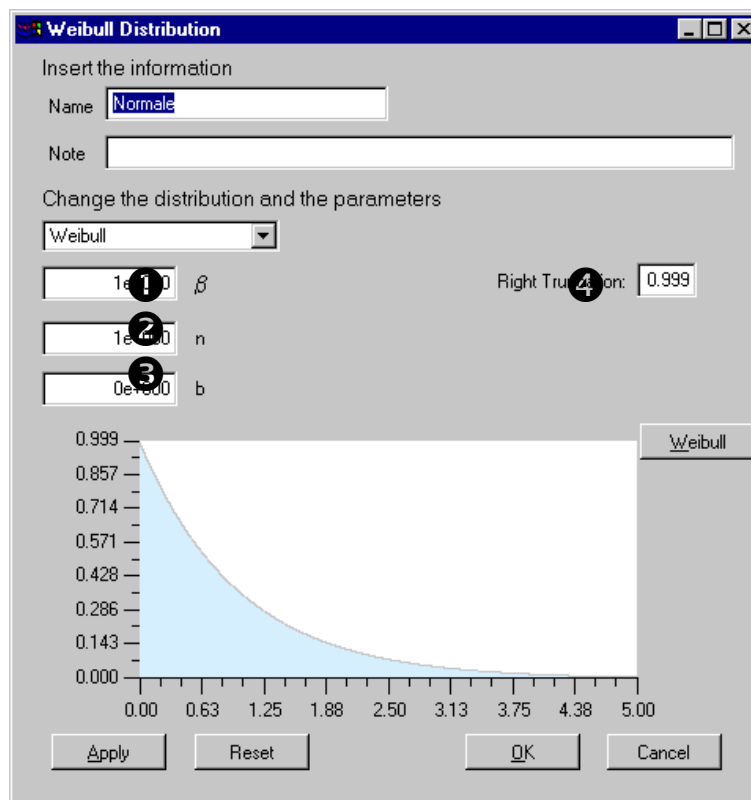


Figure 93 Weibull distribution panel

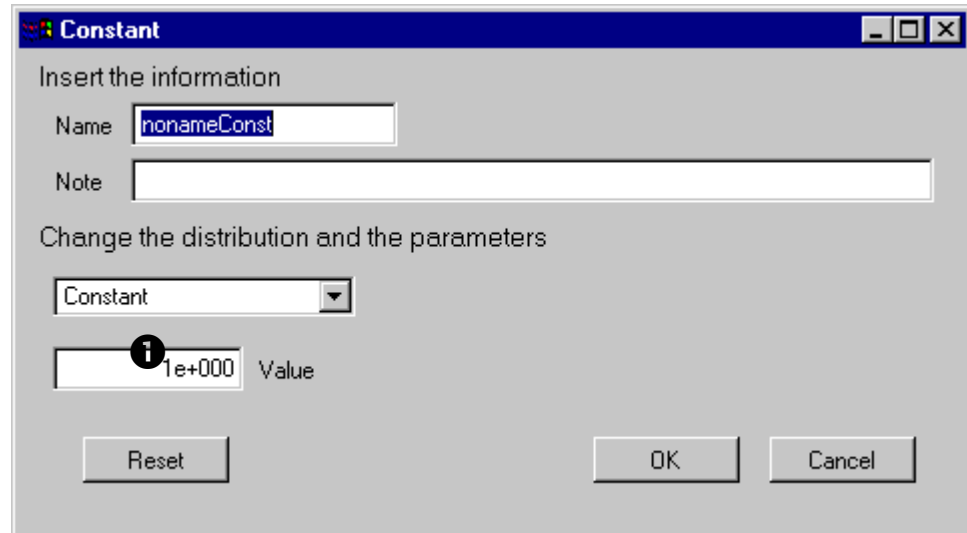
- ❶  $\beta$  value with  $\beta > 0$ ; the default value for  $\beta$  is 1.
- ❷  $n$  value with  $n > 0$ ; the default value for  $n$  is 1.
- ❸  $b$  value with  $b \geq 0$ ; the default value for  $b$  is 0.
- ❹ Right truncation value; the default value is 0.999

**Mean value:**  $n \cdot \Gamma \left( 1 + \frac{1}{\beta} \right) + b$

**Standard deviation:**  $\sqrt{n^2 \cdot \left[ \Gamma \left( 1 + \frac{2}{\beta} \right) - \Gamma^2 \left( 1 + \frac{1}{\beta} \right) \right]}$

## Constant factor

The user may insert constant factors using this panel. Constant factors are excluded by the sample generation process.



*Figure 94 Constant distribution panel*

- 1 This field specifies the value of the constant factor; the default value for a constant is 1.

## Exponential distribution

The density function of the Exponential distribution has the following expression:

$$f(x) = \lambda \cdot \exp[-\lambda \cdot (x - b)]$$

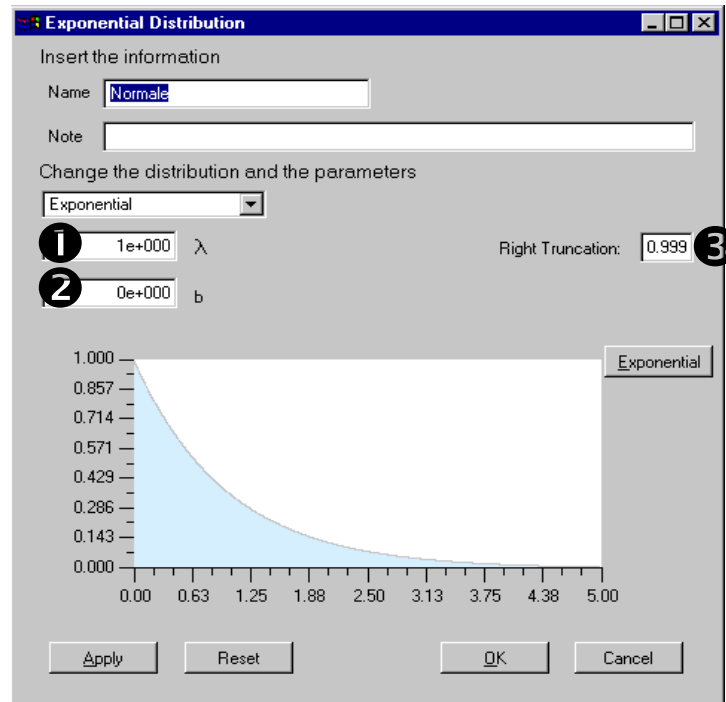


Figure 95 Exponential distribution panel

### Distribution parameters

- ①  $\lambda$  value with  $\lambda > 0$ ; the default value for  $\lambda$  is 1.
- ②  $b$  value with  $b > 0$  and  $x \geq b$ ; the default value for  $b$  is 0.
- ③ Right truncation value; the default value is 0.999.

**Mean value:**  $\frac{1}{\lambda} - b$

**Standard deviation:**  $\frac{1}{\lambda^2}$

## Gamma distribution

The density function of the Gamma distribution has the following expression:

$$f(x) = \frac{\lambda^r}{\Gamma(r)} * (x - b)^{r-1} * \exp(-\lambda * (x - b))$$

Distribution  
parameters

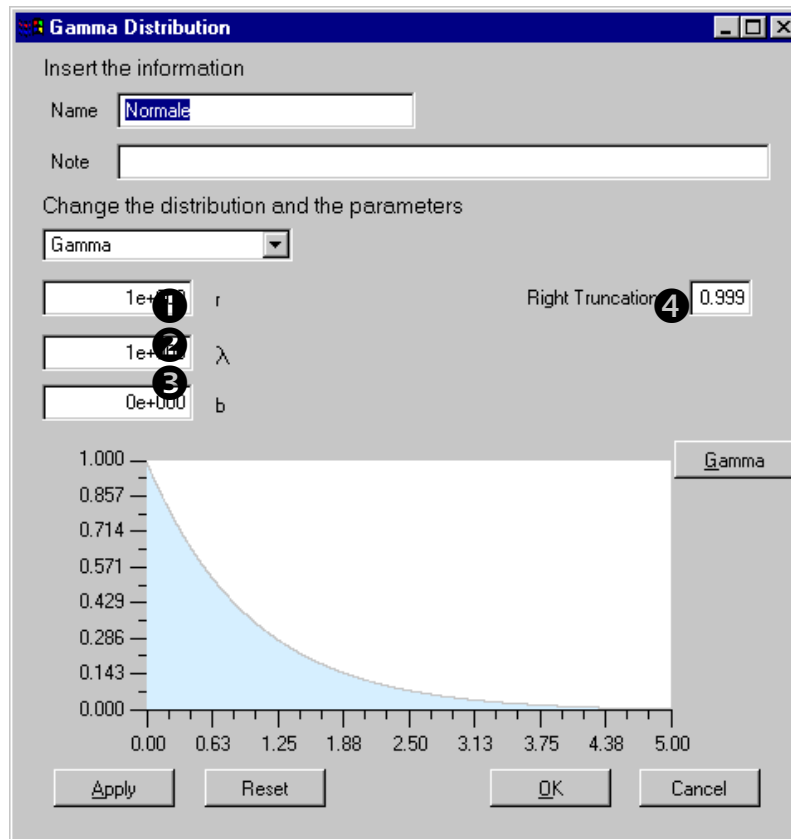


Figure 96 Gamma distribution panel

- ❶ r value with  $r > 0$ ; the default value for r is 1.
- ❷  $\lambda$  value with  $\lambda > 0$ ; the default value for  $\lambda$  is 1.
- ❸ b value with  $b \geq 0$  &  $x \geq b$ ; the default value for b is 0.
- ❹ Right truncation value; the default value is 0.999.

Mean value:  $\frac{r}{\lambda} + b$

Standard deviation:  $\sqrt{\frac{r}{\lambda^2}}$

## Beta distribution

The density function of the Beta distribution density function has the following expression:

$$f(x) = \frac{1}{B(\alpha, \beta)} * \frac{1}{b-a} * \left[ \frac{x-a}{b-a} \right]^{\alpha-1} * \left[ \frac{b-x}{b-a} \right]^{\beta-1}$$

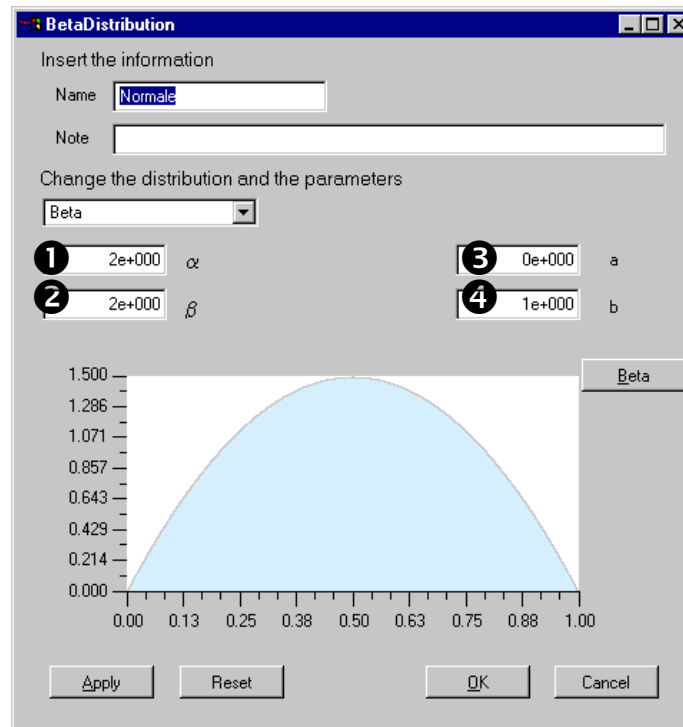


Figure 97 Beta distribution panel

### Distribution parameters

- ❶  $\alpha$  value with  $\alpha > 0$ ; the default value for  $\alpha$  is 2.
- ❷  $\beta$  value with  $\beta > 0$ ; the default value for  $\beta$  is 2.
- ❸  $a$  value with  $a < b$ ; the default value for  $a$  is 0.
- ❹  $b$  value; the default value for  $b$  is 1.

**Mean value:**  $\frac{\alpha}{\alpha + \beta} * (b - a)$

**Standard deviation:**  $\sqrt{\frac{\alpha * \beta}{(\alpha + \beta + 1) * (\alpha + \beta)^2} * (b - a)^2}$

## Triangular distribution

The density function of the Triangular distribution has the following expression:

$$f(x) = \begin{cases} \frac{2 * (x - \alpha)}{(\beta - \alpha) * (\gamma - \alpha)} & \alpha \leq x \leq \beta \\ \frac{2 * (\gamma - x)}{(\gamma - \beta) * (\gamma - \alpha)} & \beta \leq x \leq \gamma \end{cases}$$

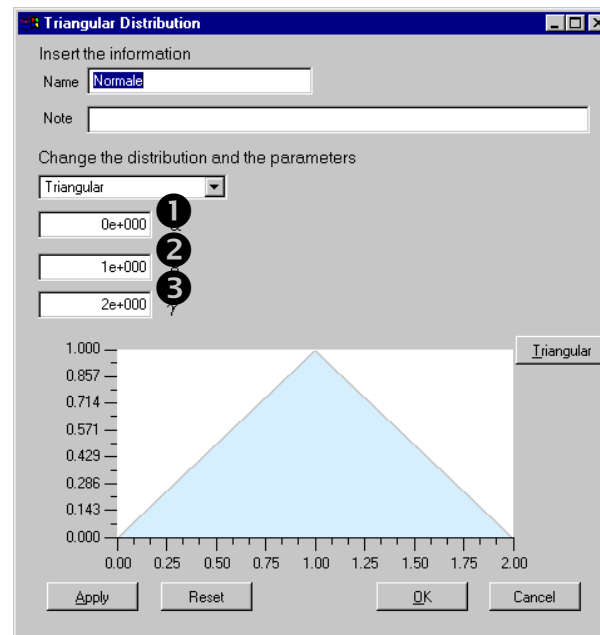


Figure 98 Triangular distribution panel

### Distribution parameters

- ❶  $\alpha$  value; the default value for  $\alpha$  is 0.
- ❷  $\beta$  value; the default value for  $\beta$  is 1.
- ❸  $\gamma$  value with  $\alpha \leq \gamma < \beta$  or  $\alpha < \gamma \leq \beta$ ; the default value for  $\gamma$  is 0.5.

**Height of  $\beta$  point (h):**  $\frac{2}{(\gamma - \alpha)}$

**Mean value ( $\mu$ ):**  $\frac{h}{3(\beta - \alpha)} \cdot [\beta^3 - \alpha^3] - \frac{\alpha \cdot h}{2(\beta - \alpha)} [\beta^2 - \alpha^2] + \frac{-h}{3(\gamma - \beta)} [\gamma^3 - \beta^3] + \frac{1}{2} \left( \frac{\beta \cdot h}{(\gamma - \beta)} + h \right) \cdot [\gamma^2 - \beta^2]$

**Standard deviation:**

$$\left( \frac{h}{4(\beta - \alpha)} [\beta^4 - \alpha^4] - \frac{\alpha \cdot h}{3(\beta - \alpha)} [\beta^3 - \alpha^3] + \frac{-h}{4(\gamma - \beta)} [\gamma^4 - \beta^4] + \frac{1}{3} \left( \frac{\beta \cdot h}{\gamma - \beta} + h \right) \cdot [\gamma^3 - \beta^3] - \mu^2 \right)^{1/2}$$

## Relation

This panel represents a special case among the input factors selection panels; the user can create a relation between inputs factors using the expression editor.

### Panel description

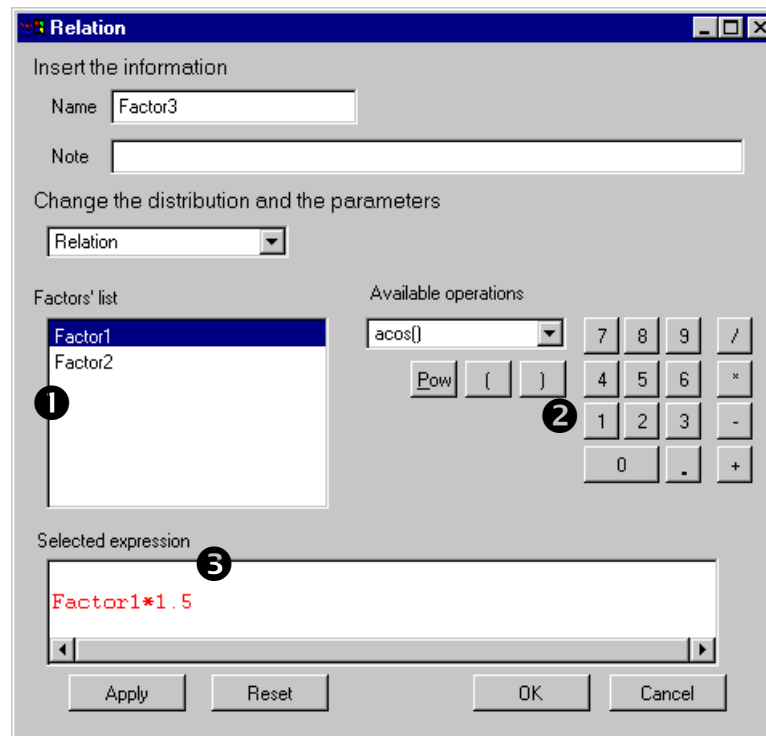


Figure 99 Relation panel

- ❶ **Factors list.** This field shows the available inputs factors; by double clicking an input factor, it is possible to insert that factor in the expression visualized in ❸.
- ❷ **Available operations.** In this section of the panel the user can select some functions and basic operations to apply to the inputs factors. This section has the same functionality of a calculator with field ❸ as display.
- ❸ **Expression field.** This field displays the current expression; it is possible to insert the expression through “Available operations” or directly through the keyboard.

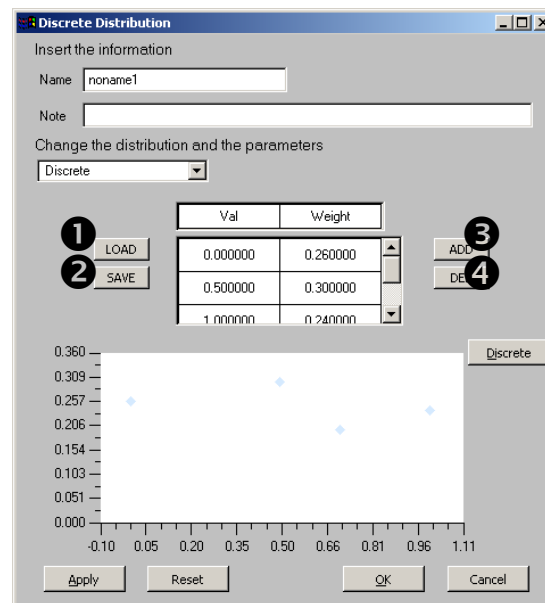


## Discrete distribution

The density function of the discrete distribution has the following expression:

$$f(x) = \text{Weight}_i \cdot I_{(x_1..x_n)}$$

where  $I_{(x_1..x_n)}$  is 1 in the x's points 0 otherwise.



### Buttons description

Figure 100 Uniform distribution panel

- ❶ **LOAD button.** The user can select this button to load a set of points for the current discrete distribution. This list of points will overwrite any previous list of points present in the matrix.
- ❷ **SAVE button.** This button allows the user to save in a file the current points for the discrete distribution.
- ❸ **ADD button.** This button is used to insert a new point for the current discrete distribution. For each interval, the user has to insert the value of the point and the relative weight of the point. Points can't overlap and the sum of the weights must be equal to 1.
- ❹ **DEL button.** With this button the user may delete any point present in the matrix. The user must select one interval before pressing the DEL button. After deleting an interval, the weight of the remaining elements must be corrected.

**Parameters area**

This area contains the parameters that characterise the discrete distribution. Weight<sub>*i*</sub> is the weight of point *i* the sum of weights must be equal to 1.

By double clicking an item in the 'Parameters area' the user can modify its value .

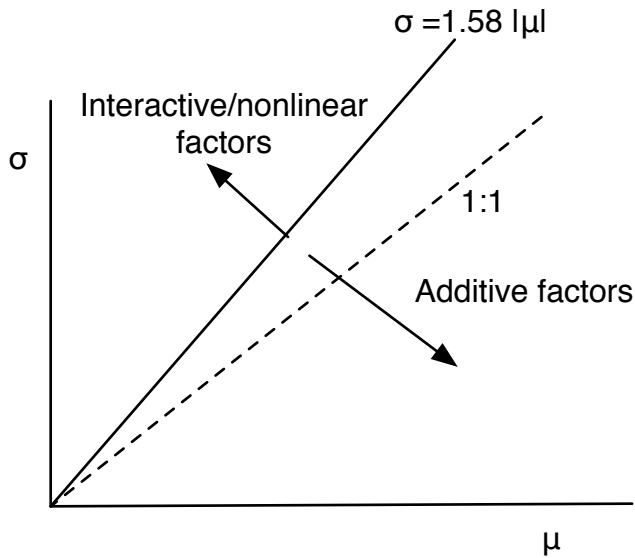
**Mean Value:**  $\sum_{i=1}^n w_i * x_i$  for each x in which the distribution is defined

**Standard deviation:**  $\sqrt{\sum_i (x_i - \mu_x)^2 * w_i}$

APPENDIX B:  
DEFINITIONS OF INTERACTION MEASURES IN EE METHOD AND NOTES

# INTERACTION EFFECTS IN MORRIS GRAPHS

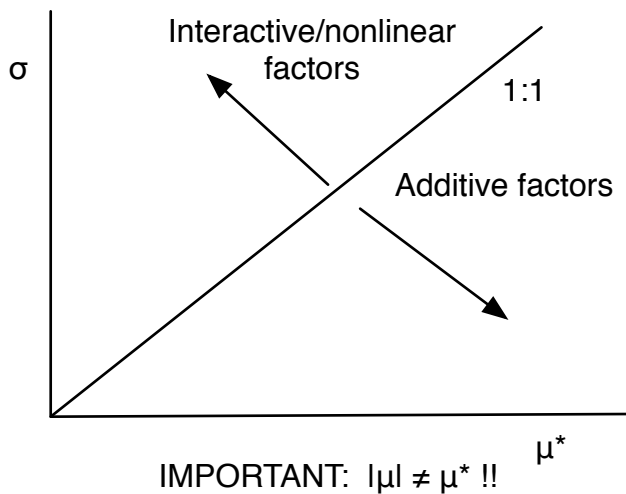
## MORRIS (1991) PROPOSAL (for $\mu$ )



$|\mu| = 2SE$   
 $SE = \sigma / \sqrt{r}$  ;  $r = \text{no. of Morris trajectories}$   
 IF  $r=4$ ,  $\sqrt{r}=2$ ,  $SE = \sigma/2$   
 $|\mu| = \sigma \Rightarrow 1:1 !!!$   
 $|\mu| = 2 * \sigma / \sqrt{r}$   
 $r=10$ ;  $2/\sqrt{r}=0.6325$   
 $\sigma = 1.58 |\mu|$

Muñoz-Carpena, R., Z. Zajac and Y.M. Kuo. 2007. Evaluation of water quality models through global sensitivity and uncertainty analyses techniques: application to the vegetative filter strip model VFMOD-W. *Trans. ASABE*, 50 (5) (2007), pp. 1719–1732  
 Chu-Agor, M.L., R. Muñoz-Carpena, G. Kiker, A. Emanuelsson and I. Linkov. 2011. Exploring sea level rise vulnerability of coastal habitats through global sensitivity and uncertainty analysis. *Env. Model. & Software* 26(5):593-604. doi:10.1016/j.envsoft.2010.12.003.

## OUR PROPOSAL (Muñoz-Carpena, 2007; Chu-Agor et al., 2011) (for $\mu^*$ )



$CV = \sigma / \mu^*$   
 $100 \Rightarrow \mu^* = \sigma$

Morris, M.D. 1991. Factorial sampling plans for preliminary computational experiments *Technometrics*, 33 (2) (May 1991), pp. 161–174

IMPORTANT:  $|\mu| \neq \mu^* !!$

## OTHER NOTES - Number of model runs (from Saltelli et al., 2004)

$N = \text{number of samples}$ ;  $k = \text{number of factors}$ ;  $M$  is the sample size in the MonteCarlo simulation,  $N \approx 500/1000$ ;  $r$  is no. Morris trajectories, generally sufficient at  $r=10$  (Campolongo et al., 1997)

Sobol: Original (Simlab v2.2)  $N = (2k + 2)M$ ; Mod. Sobol (R pkg, Saltelli, 2002)  $N = (K+2)M$

FAST:  $N \approx kM$

Morris:  $N = r(k + 1)$

Example:  $k = 20 \rightarrow N_{\text{Sobol1}} = 21000 - 42000$ ;  $N_{\text{Sobol2}} = 11000 - 22000$  ;  $N_{\text{FAST}} = 10000 - 20000$  ;

$N_{\text{Morris}} = 210$

APPENDIX C:  
INPUT FACTORS FILE FORMAT (.FAC)  
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## APPENDIX C

This section describes the file formats that are created during the SimLab working sessions.

### INPUT FACTORS FILE FORMAT (.FAC)

Input factors are generated in the first step of the Monte Carlo analysis. For each factor the user selects a range and a distribution type with distribution specific parameters; these information are saved in a file having *.fac* extension.

The *.fac* file contains the following information:

**default truncations values** that the user can change using the default truncations window;

**total number of inputs factors;**

then, for each input factor, the file contains:

**factor type;**

**factor name;**

**factor notes;**

**factor specific parameters** (dependent on the factor type).

Again, for each factor, is listed the relative dependence tree correlation information:

**Dependence tree correlation value** for the factor;

**Dependence tree parent** of the factor in the correlation tree (-1 for item without parents);

**number of children** in the dependence correlation tree;

for each child: his **position** in the list of factors;

all the values in the **Iman Conover correlation matrix**.

**Stein** correlatin information

The correlation method selected by the user: 0 dependence tree, 1 Iman Conover, 2 stein correlation 3 no correlation

The following is an example of a file *.fac*:

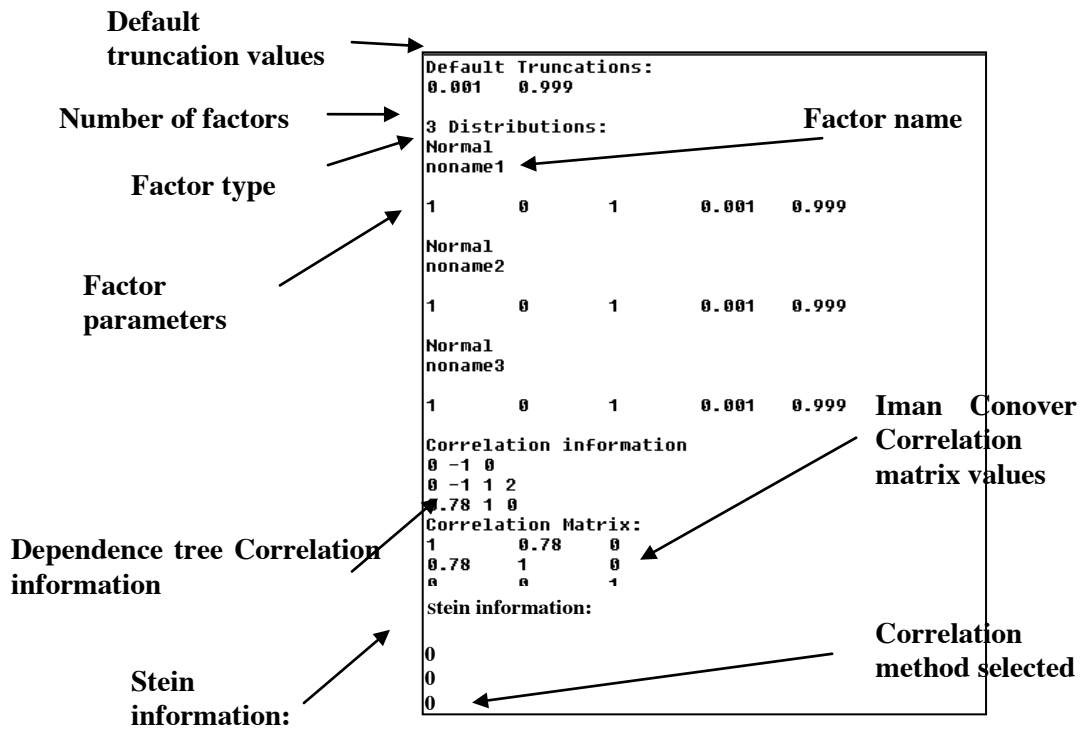


Figure 110 fac file example